

# MEMS Module

User's Guide

# MEMS Module User's Guide

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# Introduction

This user's guide describes the MEMS Module. The *MEMS Module User's Guide* introduces the modeling stages in COMSOL Multiphysics® and this module and serves as a reference for more advanced modeling techniques and details about the physics interfaces.

In this chapter:

- [About the MEMS Module](#)
- [Overview of the User's Guide](#)

# About the MEMS Module

In this section:

- [About MEMS](#)
- [About the MEMS Module](#)
- [The MEMS Module Physics Interface Guide](#)
- [Common Physics Interface and Feature Settings and Nodes](#)
- [Coupling to Other Physics Interfaces](#)
- [Where Do I Access the Documentation and Application Libraries?](#)



[The Physics Interfaces and Building a COMSOL Multiphysics Model in the \*COMSOL Multiphysics Reference Manual\*](#)

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## *About MEMS*

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The field of MEMS evolved as engineers and scientists explored new avenues to make use of the fabrication technologies developed by the microelectronics industry. These technologies enabled complex micron and submicron structures to be integrated with electronic systems and batch fabricated at low cost. Mechanical devices fabricated using these technologies have become known as *microelectromechanical systems* (MEMS) or alternatively as microsystems. A proper description of these devices usually requires multiple physical effects to be incorporated.

At the microscale, different physical effects become important to those dominant at macroscopic scales. Inertial forces, which scale with the volume of the system, become comparatively less important than effects that scale more favorably when the system size is reduced, such as electrostatic forces. Consequently electrostatically actuated devices have been developed to measure acceleration and rotation with high accuracy in a small package. These accelerometers and gyroscopes have found widespread application in the automotive industry (where they are used to deploy airbags), in industrial applications (as sensors), and in consumer applications (where smartphones have driven rapid growth in the use of MEMS devices in recent years). Capacitive sensing has also led to widespread adoption of capacitive pressure sensors, which have largely superseded the piezoresistive pressure sensors that were some of the first MEMS devices to come to market. Piezoelectric MEMS devices have also become

common with the widespread adoption of FBAR (thin-film bulk acoustic resonator) technology in mobile communication applications. Although there are few commercially important devices that employ thermal actuation (largely due to the high power consumption of such devices), thermal phenomena, such as packaging-induced thermal stresses, are often important in the design of MEMS devices. Finally, for resonant MEMS devices such as accelerometers, damping phenomena are important and there is a need for detailed modeling of phenomena such as thin film damping. Very high quality factor resonators are often used in MEMS timing applications, and for these devices the quality factor can be limited by thermoelasticity: the intrinsic coupling of the thermal and structural domains that exists as a result of the laws of thermodynamics.

Microfluidic systems are often included within the field of MEMS and represent a growing market for MEMS devices. For modeling microfluidics devices, the dedicated Microfluidics Module contains tailored physics interfaces for the simulation of microfluidic devices, including creeping flow, multiphase flow, electrokinetic effects, and slip flow.

### *About the MEMS Module*

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The MEMS Module is a collection of physics interfaces for the simulation of MEMS devices. It has a range of tools to address the specific challenges of modeling microsystems. It includes physics interfaces to model electromechanics (used for modeling electrostatically actuated structures), solid mechanics, piezoelectricity, piezoresistivity, and electrical circuits (which can be straightforwardly coupled to domain models). There are several predefined interfaces to model thermal-structural interactions, including the Thermoelasticity interface (for modeling damping in high quality factor resonators), Joule Heating with Thermal Expansion (for modeling thermal actuators), and the Thermal Stress interface (used for modeling thermal stresses when thermal gradients are present within devices). The Fluid-Structure Interaction interface implements a fully bidirectional coupling between fluid flow and structural motion, including the viscous, pressure, and inertial fluid forces as well as momentum transfer from the solid to the fluid. Finally the Thin Film-Flow interfaces allow thin layers of fluid to be modeled in an efficient manner and can be straightforwardly coupled to structural displacement to model damping phenomena, even under rarefied conditions.

COMSOL Multiphysics is uniquely transparent because the model equations are always visible and you have complete freedom in the definition of phenomena that are not predefined in the module.

The MEMS Module Applications Libraries and supporting documentation explain how to use the physics interfaces to model a range of MEMS devices.



- [Coupling to Other Physics Interfaces](#)
- [Physics and Scaling for MEMS Devices](#)
- [The MEMS Module Study Capabilities by Physics Interface](#)

### *The MEMS Module Physics Interface Guide*

The MEMS Module extends the functionality of the physics interfaces of the base package for COMSOL Multiphysics. The details of the physics interfaces and study types for the MEMS Module are listed in the table. The functionality of the COMSOL Multiphysics base package is given in the *COMSOL Multiphysics Reference Manual*.



In the *COMSOL Multiphysics Reference Manual*:

- [Studies and Solvers](#)
- [The Physics Interfaces](#)
- For a list of all the core physics interfaces included with a COMSOL Multiphysics license, see [Physics Interface Guide](#).

| PHYSICS INTERFACE                                                                                | ICON                                                                                | TAG  | SPACE DIMENSION | AVAILABLE STUDY TYPE                                                                                                           |
|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|------|-----------------|--------------------------------------------------------------------------------------------------------------------------------|
|  <b>AC/DC</b> |                                                                                     |      |                 |                                                                                                                                |
| Electric Currents <sup>1</sup>                                                                   |  | ec   | all dimensions  | stationary; stationary source sweep; frequency domain; time dependent; small signal analysis, frequency domain; eigenfrequency |
| Electric Currents in Shells                                                                      |  | ecis | 3D              | stationary; frequency domain; time dependent; eigenfrequency                                                                   |
| Electric Currents in Layered Shells                                                              |  | ecis | 3D              | stationary; frequency domain; time dependent; eigenfrequency                                                                   |

| PHYSICS INTERFACE                                                                                                     | ICON                                                                                | TAG  | SPACE DIMENSION         | AVAILABLE STUDY TYPE                                                                                                                           |
|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|------|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrical Circuit                                                                                                    |    | cir  | Not space dependent     | stationary; frequency domain; time dependent; small signal analysis, frequency domain; eigenfrequency                                          |
| Electrostatics <sup>1</sup>                                                                                           |    | es   | all dimensions          | stationary; time dependent; stationary source sweep; eigenfrequency; frequency domain; small signal analysis, frequency domain; eigenfrequency |
|  <b>Elastic Waves</b>                |                                                                                     |      |                         |                                                                                                                                                |
| Elastic Waves, Time Explicit                                                                                          |    | elte | 3D, 2D, 2D axisymmetric | time dependent                                                                                                                                 |
|  <b>Fluid Flow</b>                   |                                                                                     |      |                         |                                                                                                                                                |
|  <b>Single-Phase Flow</b>            |                                                                                     |      |                         |                                                                                                                                                |
| Laminar Flow <sup>1</sup>                                                                                             |    | spf  | 3D, 2D, 2D axisymmetric | stationary; time dependent                                                                                                                     |
|  <b>Fluid-Structure Interaction</b> |                                                                                     |      |                         |                                                                                                                                                |
| Fluid-Solid Interaction <sup>2</sup>                                                                                  |  | —    | 3D, 2D, 2D axisymmetric | stationary; time dependent                                                                                                                     |
| Fluid-Solid Interaction, Fixed Geometry <sup>2</sup>                                                                  |  | —    | 3D, 2D, 2D axisymmetric | stationary; stationary, one way; time dependent; time dependent, one way                                                                       |
| Conjugate Heat Transfer, Fluid-Solid Interaction <sup>2</sup>                                                         |  | —    | 3D, 2D, 2D axisymmetric | stationary; time dependent;                                                                                                                    |
| Fluid-Solid Interaction, Two-Phase Flow, Phase Field <sup>2, 6</sup>                                                  |  | —    | 3D, 2D, 2D axisymmetric | time dependent; time dependent with phase initialization                                                                                       |
| Fluid-Solid Interaction, Two-Phase Flow, Phase Field, Fixed Geometry <sup>2, 6</sup>                                  |  | —    | 3D, 2D, 2D axisymmetric | time dependent; time dependent with phase initialization                                                                                       |

| PHYSICS INTERFACE                                                                                                | ICON                                                                              | TAG   | SPACE DIMENSION         | AVAILABLE STUDY TYPE                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-------|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <b>Thin-Film Flow</b>          |                                                                                   |       |                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Thin-Film Flow, Shell                                                                                            |  | tffs  | 3D                      | stationary; time dependent; frequency domain; eigenfrequency                                                                                                                                                                                                                                                                                                                                                                                                     |
| Thin-Film Flow, Domain                                                                                           |  | tff   | 2D                      | stationary; time dependent; frequency domain; eigenfrequency                                                                                                                                                                                                                                                                                                                                                                                                     |
| Thin-Film Flow, Edge                                                                                             |  | tffs  | 2D and 2D axisymmetric  | stationary; time dependent; frequency domain; eigenfrequency                                                                                                                                                                                                                                                                                                                                                                                                     |
|  <b>Electromagnetic Heating</b> |                                                                                   |       |                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Joule Heating <sup>1,2</sup>                                                                                     |  | —     | all dimensions          | stationary; time dependent; small-signal analysis; frequency domain                                                                                                                                                                                                                                                                                                                                                                                              |
|  <b>Structural Mechanics</b>    |                                                                                   |       |                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Solid Mechanics <sup>1</sup>                                                                                     |  | solid | 3D, 2D, 2D axisymmetric | stationary; eigenfrequency; eigenfrequency, prestressed; mode analysis; time dependent; time dependent, modal; time dependent, prestressed, modal; time dependent, modal reduced-order model; frequency domain; frequency domain, modal; frequency domain, prestressed; frequency domain, prestressed, modal; frequency domain, modal reduced-order model; frequency domain, AWE reduced-order model; response spectrum; random vibration (PSD); linear buckling |



| PHYSICS INTERFACE                                  | ICON                                                                                | TAG | SPACE DIMENSION         | AVAILABLE STUDY TYPE                                                                                                                                                                                                                                                                                         |
|----------------------------------------------------|-------------------------------------------------------------------------------------|-----|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Thermal Stress, Solid <sup>2</sup>                 |    | —   | 3D, 2D, 2D axisymmetric | stationary; time dependent                                                                                                                                                                                                                                                                                   |
| Joule Heating and Thermal Expansion <sup>2</sup>   |    | —   | 3D, 2D, 2D axisymmetric | stationary; time dependent                                                                                                                                                                                                                                                                                   |
| Thermoelasticity                                   |    | —   | 3D, 2D, 2D axisymmetric | eigenfrequency; frequency domain; time dependent                                                                                                                                                                                                                                                             |
| Electromechanics                                   |    | —   | 3D, 2D, 2D axisymmetric | stationary; eigenfrequency, prestressed; time dependent; frequency domain, prestressed                                                                                                                                                                                                                       |
| Electromechanics, Boundary Elements                |    | —   | 3D, 2D                  | stationary; eigenfrequency, prestressed; time dependent; frequency domain, prestressed                                                                                                                                                                                                                       |
| Piezoelectricity <sup>2</sup>                      |    | —   | 3D, 2D, 2D axisymmetric | stationary; eigenfrequency; eigenfrequency, prestressed; time dependent; time dependent, modal; time dependent, prestressed, modal; frequency domain; frequency domain, modal; frequency domain, prestressed; frequency domain, prestressed, modal; small-signal analysis, frequency domain; linear buckling |
| Piezoelectricity, Layered Shell <sup>2, 3, 5</sup> |  | —   | 3D                      | stationary; eigenfrequency; time dependent; frequency domain                                                                                                                                                                                                                                                 |
| Magnetostriction <sup>2,3</sup>                    |  | —   | 3D, 2D, 2D axisymmetric | stationary; eigenfrequency; time dependent; frequency domain; small-signal analysis, frequency domain; eigenfrequency, prestressed; frequency domain, prestressed                                                                                                                                            |

| PHYSICS INTERFACE                                                                                         | ICON                                                                              | TAG | SPACE DIMENSION         | AVAILABLE STUDY TYPE                                                                                                                                                                                              |
|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ferroelectroelasticity <sup>2,</sup>                                                                      |  | —   | 3D, 2D, 2D axisymmetric | stationary; time dependent; frequency domain                                                                                                                                                                      |
| Electrostriction <sup>2,</sup>                                                                            |  | —   | 3D, 2D, 2D axisymmetric | stationary; time dependent; frequency domain                                                                                                                                                                      |
|  <b>Piezoresistivity</b> |                                                                                   |     |                         |                                                                                                                                                                                                                   |
| Piezoresistivity, Domain Currents                                                                         |  | —   | 3D                      | stationary; eigenfrequency; time dependent; time dependent, modal; frequency domain; frequency domain, modal; small-signal analysis, frequency domain; eigenfrequency, prestressed; frequency domain, prestressed |
| Piezoresistivity, Shell <sup>4</sup>                                                                      |  | —   | 3D                      | stationary; time dependent; time dependent, modal; frequency domain; frequency domain, modal; small-signal analysis, frequency domain; eigenfrequency, prestressed; frequency domain, prestressed                 |

| PHYSICS INTERFACE                                                                                                                                                                                                                                                                                                                                                                                                              | ICON                                                                              | TAG | SPACE DIMENSION | AVAILABLE STUDY TYPE                                                                                                                                                                                                                         |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Piezoresistivity,<br>Boundary Currents                                                                                                                                                                                                                                                                                                                                                                                         |  | —   | 3D              | stationary; eigenfrequency;<br>time dependent; time<br>dependent, modal;<br>frequency domain;<br>frequency domain, modal;<br>small-signal analysis,<br>frequency domain;<br>eigenfrequency,<br>prestressed; frequency<br>domain, prestressed |
| <sup>1</sup> This physics interface is included with the core COMSOL package but has added functionality for this module.<br><sup>2</sup> This physics interface is a predefined multiphysics coupling that automatically adds all the physics interfaces and coupling features required.<br><sup>3</sup> Requires the addition of the AC/DC Module.<br><sup>4</sup> Requires the addition of the Structural Mechanics Module. |                                                                                   |     |                 |                                                                                                                                                                                                                                              |

### *Common Physics Interface and Feature Settings and Nodes*

There are several common settings and sections available for the physics interfaces and feature nodes. Some of these sections also have similar settings or are implemented in the same way no matter the physics interface or feature being used. There are also some physics feature nodes that display in COMSOL Multiphysics.

In each module's documentation, only unique or extra information is included; standard information and procedures are centralized in the *COMSOL Multiphysics Reference Manual*.

|                                                                                     |                                                                                                                                                                                                                                                                                                       |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | In the <i>COMSOL Multiphysics Reference Manual</i> see <a href="#">Table 2-4</a> for links to common sections and <a href="#">Table 2-5</a> to common feature nodes. You can also search for information: press F1 to open the <b>Help</b> window or Ctrl+F1 to open the <b>Documentation</b> window. |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

### *Coupling to Other Physics Interfaces*

The MEMS Module connects to COMSOL Multiphysics and other add-on modules in the COMSOL Multiphysics product line. You can view and modify the models in

terms of the underlying PDEs. [Table 1-1](#) summarizes the most important MEMS couplings and other common devices you can model using this module.

The first column of the table lists phenomena, couplings, and devices that are often associated with the word electromechanical in the narrow and literal meaning of MEMS. The devices in this category are usually various kinds of actuators and sensors. The microfluidic devices, although using some of the same manufacturing and miniaturizing techniques, form a totally different application area. The *Fluid-Structure Interaction* column lists various techniques and phenomena that are useful for both electromechanical and microfluidic applications, where movement and deformation of solids are of concern.

This table, however, shows only the tip of the iceberg — our view of the most important applications where you can use the MEMS Module. In your hands, the multiphysics combinations and applications are unlimited.

TABLE 1-1: EXAMPLES OF COUPLED PHENOMENA AND DEVICES YOU CAN MODEL USING THE MEMS MODULE

|                        | ELECTROMECHANICAL                                                                                                                                                               | FLUID-STRUCTURE INTERACTION                                 |
|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|
| PHENOMENA/<br>COUPLING | Electro-structural<br>Electro-thermal<br>Thermo-mechanical<br>Thermal-electric-structural<br>Piezoelectric<br>Piezoresistive<br>Prestressed modal analysis<br>Stress stiffening | Moving boundary using ALE technique<br>Squeeze-film damping |
| DEVICES                | Cantilever beams<br>Comb drives<br>Resonators<br>Micromirrors<br>Thermomechanical actuators<br>Inertial sensors<br>Pressure sensors                                             | Mechanical pumps and valves                                 |

THE MEMS MODULE STUDY CAPABILITIES BY PHYSICS INTERFACE

This section lists the physics interfaces, the physical quantities they solve for, and the standard abbreviation each one uses. The physical quantities in these physics interfaces are:

- The *structural displacements* or the *velocity components*  $u$ ,  $v$ , and  $w$
- The *film pressure variation*,  $p_f$
- The *electric scalar potential*,  $V$
- The *concentration*,  $c$

Table 1-2 lists the physics interfaces specific to MEMS modeling and this module.

|                                                                                   |                                                                                                                                                                                                                                  |
|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | When using the axisymmetric physics interfaces, the horizontal axis represents the $r$ direction and the vertical axis the $z$ direction. The geometry in the right half plane must be created, that is, only for positive $r$ . |
|  | <a href="#">Studies and Solvers</a> in the <i>COMSOL Multiphysics Reference Manual</i>                                                                                                                                           |

TABLE 1-2: MEMS MODULE INTERFACE DEPENDENT VARIABLES AND PRESET STUDY OPTIONS

| PHYSICS INTERFACE  | NAME | DEPENDENT<br>VARIABLES | PRESET STUDY OPTIONS |                |                      |                |                                            |                  |                           |                                         |                                            |
|--------------------|------|------------------------|----------------------|----------------|----------------------|----------------|--------------------------------------------|------------------|---------------------------|-----------------------------------------|--------------------------------------------|
|                    |      |                        | STATIONARY           | TIME DEPENDENT | TIME-DEPENDENT MODAL | EIGENFREQUENCY | SMALL-SIGNAL ANALYSIS,<br>FREQUENCY DOMAIN | FREQUENCY DOMAIN | FREQUENCY-DOMAIN<br>MODAL | PRESTRESSED ANALYSIS,<br>EIGENFREQUENCY | PRESTRESSED ANALYSIS,<br>FREQUENCY, DOMAIN |
| AC/DC              |      |                        |                      |                |                      |                |                                            |                  |                           |                                         |                                            |
| Electrostatics     | es   | V                      | √                    | √              |                      |                |                                            |                  |                           |                                         |                                            |
| Electric Currents  | ec   | V                      | √                    |                |                      |                |                                            |                  |                           |                                         |                                            |
| Electrical Circuit | cir  | none                   | √                    | √              |                      |                |                                            | √                |                           |                                         |                                            |
| FLUID FLOW         |      |                        |                      |                |                      |                |                                            |                  |                           |                                         |                                            |

TABLE I-2: MEMS MODULE INTERFACE DEPENDENT VARIABLES AND PRESET STUDY OPTIONS

| PHYSICS INTERFACE                              | NAME  | DEPENDENT VARIABLES | PRESET STUDY OPTIONS |                |                      |                |                                         |                  |                        |                                      |                                        |
|------------------------------------------------|-------|---------------------|----------------------|----------------|----------------------|----------------|-----------------------------------------|------------------|------------------------|--------------------------------------|----------------------------------------|
|                                                |       |                     | STATIONARY           | TIME DEPENDENT | TIME-DEPENDENT MODAL | EIGENFREQUENCY | SMALL-SIGNAL ANALYSIS, FREQUENCY DOMAIN | FREQUENCY DOMAIN | FREQUENCY-DOMAIN MODAL | PRESTRESSED ANALYSIS, EIGENFREQUENCY | PRESTRESSED ANALYSIS, FREQUENCY DOMAIN |
| Thin-Film Flow, Shell and Thin-Film Flow, Edge | tffs  | $p_f$               | ✓                    | ✓              |                      | ✓              |                                         | ✓                |                        |                                      |                                        |
| Thin-Film Flow, Domain                         | tff   | $p_f$               | ✓                    | ✓              |                      | ✓              |                                         | ✓                |                        |                                      |                                        |
| Fluid-Structure Interaction                    | —     | $u, v, w$<br>$p$    | ✓                    | ✓              |                      |                |                                         |                  |                        |                                      |                                        |
| Fluid-Structure Interaction, Fixed Geometry    | —     | $u, v, w$<br>$p$    | ✓                    | ✓              |                      |                |                                         |                  |                        |                                      |                                        |
| <b>STRUCTURAL MECHANICS</b>                    |       |                     |                      |                |                      |                |                                         |                  |                        |                                      |                                        |
| Solid Mechanics                                | solid | $u, v, w$           | ✓                    | ✓              | ✓                    | ✓              | ✓                                       | ✓                | ✓                      | ✓                                    | ✓                                      |
| Piezoelectricity                               | —     | $u, v, w$<br>$V$    | ✓                    | ✓              | ✓                    | ✓              | ✓                                       | ✓                | ✓                      | ✓                                    | ✓                                      |
| Thermal Stress                                 | —     | $u, v, w$<br>$T$    | ✓                    | ✓              | ✓                    |                |                                         |                  |                        | ✓                                    | ✓                                      |
| Thermoelasticity                               | te    | $u, v, w$<br>$T$    |                      | ✓              |                      | ✓              |                                         | ✓                |                        |                                      |                                        |
| Joule Heating and Thermal Expansion            | —     | $u, v, w, T, V$     | ✓                    | ✓              | ✓                    |                | ✓                                       |                  |                        | ✓                                    | ✓                                      |
| Electromechanics                               | emi   | $u, v, w$<br>$V$    | ✓                    | ✓              |                      |                |                                         |                  |                        | ✓                                    | ✓                                      |
| Piezoresistivity, Domain Currents              | pzrd  | $u, v, w$<br>$V$    | ✓                    | ✓              | ✓                    |                | ✓                                       | ✓                | ✓                      | ✓                                    | ✓                                      |

TABLE 1-2: MEMS MODULE INTERFACE DEPENDENT VARIABLES AND PRESET STUDY OPTIONS

| PHYSICS INTERFACE                   | NAME | DEPENDENT VARIABLES  | PRESET STUDY OPTIONS |                |                      |                |                                         |                  |                        |                                      |                                         |
|-------------------------------------|------|----------------------|----------------------|----------------|----------------------|----------------|-----------------------------------------|------------------|------------------------|--------------------------------------|-----------------------------------------|
|                                     |      |                      | STATIONARY           | TIME DEPENDENT | TIME-DEPENDENT MODAL | EIGENFREQUENCY | SMALL-SIGNAL ANALYSIS, FREQUENCY DOMAIN | FREQUENCY DOMAIN | FREQUENCY-DOMAIN MODAL | PRESTRESSED ANALYSIS, EIGENFREQUENCY | PRESTRESSED ANALYSIS, FREQUENCY. DOMAIN |
| Piezoresistivity, Boundary Currents | pzrb | $u, v, w$<br>$V$     | √                    | √              | √                    |                | √                                       | √                | √                      | √                                    | √                                       |
| Piezoresistivity, Shell             | pzrs | $u, v, w$<br>$V, ar$ | √                    | √              | √                    |                | √                                       | √                | √                      | √                                    | √                                       |

*Where Do I Access the Documentation and Application Libraries?*

A number of internet resources have more information about COMSOL, including licensing and technical information. The electronic documentation, topic-based (or context-based) help, and the application libraries are all accessed through the COMSOL Desktop.

|                                                                                     |                                                                                                                                                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | If you are reading the documentation as a PDF file on your computer, the <a href="#">blue links</a> do not work to open an application or content referenced in a different guide. However, if you are using the Help system in COMSOL Multiphysics, these links work to open other modules, application examples, and documentation sets. |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

**THE DOCUMENTATION AND ONLINE HELP**

The *COMSOL Multiphysics Reference Manual* describes the core physics interfaces and functionality included with the COMSOL Multiphysics license. This book also has instructions about how to use COMSOL Multiphysics and how to access the electronic Documentation and Help content.

*Opening Topic-Based Help*

The Help window is useful as it is connected to the features in the COMSOL Desktop. To learn more about a node in the Model Builder, or a window on the Desktop, click

to highlight a node or window, then press F1 to open the Help window, which then displays information about that feature (or click a node in the Model Builder followed by the **Help** button (  ). This is called *topic-based* (or *context*) *help*.

|                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Win                                            | <p>To open the <b>Help</b> window:</p> <ul style="list-style-type: none"><li>• In the <b>Model Builder</b>, <b>Application Builder</b>, or <b>Physics Builder</b> click a node or window and then press F1.</li><li>• On any toolbar (for example, <b>Home</b>, <b>Definitions</b>, or <b>Geometry</b>), hover the mouse over a button (for example, <b>Add Physics</b> or <b>Build All</b>) and then press F1.</li><li>• From the <b>File</b> menu, click <b>Help</b> (  ).</li><li>• In the upper-right corner of the COMSOL Desktop, click the <b>Help</b> (  ) button.</li></ul> |
| Mac                                            | <p>To open the <b>Help</b> window:</p> <ul style="list-style-type: none"><li>• In the <b>Model Builder</b> or <b>Physics Builder</b> click a node or window and then press F1.</li><li>• On the main toolbar, click the <b>Help</b> (  ) button.</li><li>• From the main menu, select <b>Help&gt;Help</b>.</li></ul>                                                                                                                                                                                                                                                                                                                                                    |
| Linux                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <p><i>Opening the Documentation Window</i></p> |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Win                                            | <p>To open the <b>Documentation</b> window:</p> <ul style="list-style-type: none"><li>• Press Ctrl+F1.</li><li>• From the <b>File</b> menu select <b>Help&gt;Documentation</b> (  ).</li></ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Mac                                            | <p>To open the <b>Documentation</b> window:</p> <ul style="list-style-type: none"><li>• Press Ctrl+F1.</li><li>• On the main toolbar, click the <b>Documentation</b> (  ) button.</li><li>• From the main menu, select <b>Help&gt;Documentation</b>.</li></ul>                                                                                                                                                                                                                                                                                                                                                                                                        |
| Linux                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |



THE APPLICATION LIBRARIES WINDOW

Each model or application includes documentation with the theoretical background and step-by-step instructions to create a model or application. The models and applications are available in COMSOL Multiphysics as MPH files that you can open for further investigation. You can use the step-by-step instructions and the actual models as templates for your own modeling. In most models, SI units are used to describe the relevant properties, parameters, and dimensions, but other unit systems are available.

Once the Application Libraries window is opened, you can search by name or browse under a module folder name. Click to view a summary of the model or application and its properties, including options to open it or its associated PDF document.

|                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                     | <a href="#">The Application Libraries Window</a> in the <i>COMSOL Multiphysics Reference Manual</i> .                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| <p><i>Opening the Application Libraries Window</i></p> <p>To open the <b>Application Libraries</b> window (  ):</p> |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|                                                                                                                     | <ul style="list-style-type: none"><li>From the <b>Home</b> toolbar, <b>Windows</b> menu, click (  ) <b>Applications Libraries</b>.</li><li>From the <b>File</b> menu select <b>Application Libraries</b>.</li></ul> <p>To include the latest versions of model examples, from the <b>File&gt;Help</b> menu, select (  ) <b>Update COMSOL Application Library</b>.</p> |
| <br>                           | <p>Select <b>Application Libraries</b> from the main <b>File&gt;</b> or <b>Windows&gt;</b> menus.</p> <p>To include the latest versions of model examples, from the <b>Help</b> menu select (  ) <b>Update COMSOL Application Library</b>.</p>                                                                                                                                                                                                         |

CONTACTING COMSOL BY EMAIL

For general product information, contact COMSOL at [info@comsol.com](mailto:info@comsol.com).

COMSOL ACCESS AND TECHNICAL SUPPORT

To receive technical support from COMSOL for the COMSOL products, please contact your local COMSOL representative or send your questions to

support@comsol.com. An automatic notification and a case number are sent to you by email. You can also access technical support, software updates, license information, and other resources by registering for a COMSOL Access account.

**COMSOL ONLINE RESOURCES**

|                            |                                                                                                |
|----------------------------|------------------------------------------------------------------------------------------------|
| COMSOL website             | <a href="http://www.comsol.com">www.comsol.com</a>                                             |
| Contact COMSOL             | <a href="http://www.comsol.com/contact">www.comsol.com/contact</a>                             |
| COMSOL Access              | <a href="http://www.comsol.com/access">www.comsol.com/access</a>                               |
| Support Center             | <a href="http://www.comsol.com/support">www.comsol.com/support</a>                             |
| Product Download           | <a href="http://www.comsol.com/product-download">www.comsol.com/product-download</a>           |
| Product Updates            | <a href="http://www.comsol.com/support/updates">www.comsol.com/support/updates</a>             |
| COMSOL Blog                | <a href="http://www.comsol.com/blogs">www.comsol.com/blogs</a>                                 |
| Discussion Forum           | <a href="http://www.comsol.com/community">www.comsol.com/community</a>                         |
| Events                     | <a href="http://www.comsol.com/events">www.comsol.com/events</a>                               |
| COMSOL Application Gallery | <a href="http://www.comsol.com/models">www.comsol.com/models</a>                               |
| COMSOL Video Gallery       | <a href="http://www.comsol.com/video">www.comsol.com/video</a>                                 |
| Support Knowledge Base     | <a href="http://www.comsol.com/support/knowledgebase">www.comsol.com/support/knowledgebase</a> |

# Overview of the User's Guide

The *MEMS Module User's Guide* gets you started with modeling MEMS systems using COMSOL Multiphysics. The information in this guide is specific to this module. Instructions how to use COMSOL in general are included with the *COMSOL Multiphysics Reference Manual*.



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As detailed in the section [Where Do I Access the Documentation and Application Libraries?](#) this information can also be searched from the COMSOL Multiphysics software **Help** menu.

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## TABLE OF CONTENTS, GLOSSARY, AND INDEX

Use the [Contents](#), [Glossary of Terms](#), and [Index](#) to help you navigate through this guide.

## MEMS MODELING

[Creating and Analyzing MEMS Models](#) familiarizes you with modeling procedures useful when working with this module and MEMS applications such as microactuators and microsensors. Because the module is fully integrated with COMSOL Multiphysics, the design and analysis process is similar to the one you use in the base environment. The MEMS-specific modeling aspects should prove valuable during the modeling phase. There is also a short section (with model examples) about the materials databases available with this module.

## THE AC/DC BRANCH

[AC/DC Interfaces](#) chapter describes the physics interfaces for modeling conducting and nonconducting materials, including the enhanced versions of the Electrostatics and Electric Currents interfaces. It also has all the information about the Electrical Circuit interface. The Magnetic Fields interface is also included as part of the COMSOL Multiphysics base package, but this is detailed in the *COMSOL Multiphysics Reference Manual*.

## THE FLUID FLOW BRANCH

The types of momentum transport that you can simulate include laminar and thin-film flow. The Laminar Flow interface is available with the base license and is described in the *COMSOL Multiphysics Reference Manual*. [Fluid Flow Interfaces](#) chapter describes the Thin-Film Flow and Fluid-Structure Interaction interfaces.

The [Thin-Film Flow Interfaces](#) can be added either singularly or in combination with other physics interfaces such as mass and energy transfer. The Thin-Film Flow, Shell interface is for 3D models, the Thin-Film Flow, Edge interface is for 2D and 2D axisymmetric models, and the Thin-Film Flow, Domain interface is for 2D models.

The [Fluid-Solid Interaction Interface](#) (in the *Structural Mechanics Module User's Guide*) is an interface found under the Fluid Flow branch. It has the equations and physics for fluid-structure interaction, solving for the displacements, fluid velocity, and fluid pressure. You have access to all functionality from the Solid Mechanics interface and Single-Phase Flow interfaces for modeling the solid and fluid domains. From the Laminar Flow (the default) and Solid Mechanics submenus on the solid and boundary level you can access materials, sources, loads, and boundary conditions for the individual physics interfaces.

[Fluid-Structure Interaction, Fixed Geometry](#) multiphysics coupling (in the *Structural Mechanics Module User's Guide*) can be used to model phenomena where a fluid and a deformable solid structure affect each other. Both the fluid loading on the structure and the structural velocity transmission to the fluid can be taken into account. The interface models situations where the displacements of the solid are assumed to be small enough for the geometry of the fluid domain to be considered as fixed during the interaction.

## THE STRUCTURAL MECHANICS BRANCH

[Structural Mechanics Interfaces](#) chapter describes the Solid Mechanics, Piezoelectricity, Thermal Stress, Joule Heating and Thermal Expansion, and Electromechanics interfaces.

### *The Solid Mechanics Interface*

The [Electromechanics Interface](#) has the equations and physics features for stress analysis and general linear solid mechanics, solving for the displacements.

### *The Piezoelectricity Interface*

The [Piezoelectricity Interface](#) combines piezoelectricity with solid mechanics and electrostatics for modeling of piezoelectric devices where all or some of the domains contain a piezoelectric material. The piezoelectric coupling can be on stress-charge or strain-charge form.

### *The Thermal Stress Interface*

The [Electromechanics Interface](#) combines Solid Mechanics and Heat Transfer for modeling stress analysis and general linear and nonlinear solid mechanics by solving for the displacements.

#### *The Joule Heating and Thermal Expansion Interface*

[The Joule Heating and Thermal Expansion Interface](#) combines solid mechanics using a thermal linear elastic material with an electromagnetic Joule heating model. This is a multiphysics combination of solid mechanics, electric currents, and heat transfer for modeling of, for example, thermoelectromechanical (TEM) applications.

#### *The Electromechanics Interface*

[The Electromechanics Interface](#) combines solid mechanics and electrostatics with a moving mesh to model the deformation of electrostatically actuated structures. The physics interface is also compatible with piezoelectric materials.

#### *The Thermoelasticity Interface*

[The Thermoelasticity Interface](#) combines the Solid Mechanics and Thermal Stress interfaces, together with the thermoelastic coupling terms. These coupling terms result in local cooling of material under tension and heating of material that is compressed. The resulting irreversible heat transfer between warm and cool regions of the solid produces mechanical losses, which can be important, particularly for small structures.

### **THE PIEZORESISTIVITY BRANCH**

These physics interfaces are appropriate for modeling piezoresistivity under various assumptions.

[The Piezoresistivity, Domain Currents Interface](#) is appropriate for situations when the thickness of the conducting and piezoresistive layers are both resolved by the mesh.

[The Piezoresistivity, Boundary Currents Interface](#) should be used when the thicknesses of the conducting and piezoresistive layers are much smaller than those of the structural layers (this is often the case in practice).

[The Piezoresistivity, Shell Interface](#) is used when the structural layer is thin enough to be treated by the shell interface, but the conducting and piezoresistive layers are still much thinner than the structural layers.



# Creating and Analyzing MEMS Models

This chapter gives an overview of the physics interfaces and features available for modeling MEMS devices in COMSOL Multiphysics®.

In this chapter:

- [Physics and Scaling for MEMS Devices](#)
- [General Tools for MEMS Modeling](#)
- [Structural Mechanics](#)
- [Electrostatics](#)
- [Piezoresistivity](#)
- [Thermal Effects in MEMS Devices](#)
- [Microfluidics](#)
- [Connecting to Electrical Circuits](#)
- [SPICE Import and Export](#)

# Physics and Scaling for MEMS Devices

Microelectromechanical systems (MEMS) is a term that covers a broad range of manufactured mechanical components characterized by a small size. Many of these devices are fabricated with micron-scale dimension and represent mixed mechanical/electrical systems, although the term now encompasses systems that do not necessarily contain electrical parts, such as microfluidic devices. Thousands of MEMS devices can be batch fabricated on a single wafer, using technologies derived from the semiconductor industry. As a result of the smaller size and reduced manufacturing costs, MEMS-based equivalents of macroscopic devices such as accelerometers have been able to penetrate new markets. Additionally, MEMS technology has enabled entirely new devices to be created, such as the micromirror arrays that enable Texas Instruments' DLP projectors.



The [Physics Interfaces](#) and [Building a COMSOL Multiphysics Model](#) in the *COMSOL Multiphysics Reference Manual*

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The smaller size of MEMS devices has important effects on the physical processes that govern their operation ([Ref. 1](#)). In general, as the length scale ( $L$ ) of the device is reduced, the scaling of a physical effect with respect to  $L$  determines its relative importance (see [Table 2-1](#)). The inertial force required to produce a fixed acceleration of a solid body scales volumetrically as  $L^3$ . The scaling of other forces in comparison to this inertial force has important consequences for MEMS devices. For example, the effective spring constant for a body scales as  $L^1$ . The spring stiffness therefore decreases much more slowly than the system mass as the size of the system is reduced, resulting in higher resonant frequencies for smaller devices (resonant frequency scales as  $L^{-1}$ ). This means that micromechanical systems typically have higher operating frequencies and faster response times than macroscopic systems.



See [Structural Mechanics](#) for more information about modeling the mechanics of MEMS devices.

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Electrostatic forces scale favorably as the device dimensions are reduced (for example, the force between parallel plates with a fixed applied voltage scales as  $L^0$ ) (see [Table 2-1](#)). Additionally, electrostatic actuators consume no DC power and can be



manufactured using processes that are compatible with standard semiconductor foundries. In comparison, magnetic actuators scale less favorably (for example, the force between wires carrying a fixed current density scales as  $L^4$ ) and can involve materials that are incompatible with standard semiconductor processing. In some cases magnetic actuators or sensors require a DC bias current, which increases power consumption. These factors explain the prevalence of electrostatic actuation and sensing and the absence of magnetically actuated commercial MEMS devices.

TABLE 2-1: SCALING OF VARIOUS PHYSICAL PHENOMENA WITH DECREASING LENGTH (L) AND THE CONSEQUENCES FOR MEMS DEVICES

| PROPERTY                                                  | LENGTH SCALING | CONSEQUENCES                                                                                                                 |
|-----------------------------------------------------------|----------------|------------------------------------------------------------------------------------------------------------------------------|
| Volume                                                    | $L^3$          | Surface related properties increase in importance relative to volumetric properties, Surface area to volume ratios are high. |
| Area                                                      | $L^2$          |                                                                                                                              |
| Inertial Forces                                           | $L^3$          | How other forces scale with respect to inertial forces determines how effective device actuation is.                         |
| Spring Constant                                           | $L^1$          | Spring constant to mass ratio is reduced. Higher resonant frequencies, faster response times.                                |
| Resonant Frequency                                        | $L^{-1}$       |                                                                                                                              |
| Electrostatic force (parallel plates, constant voltage)   | $L^0$          | Electrostatic actuation becomes more efficient and is widely used in MEMS devices.                                           |
| Magnetic force (parallel wires, constant current density) | $L^4$          | Magnetic actuation scales poorly; there are no commercial magnetically actuated devices.                                     |
| Piezoelectric force (constant voltage)                    | $L^1$          | Piezoelectric actuation is efficient (manufacturing difficulties have hindered commercial adoption).                         |
| Thermal force (constant temperature difference)           | $L^2$          | Thermal actuation is efficient and fast. However, power consumption is typically greater than other methods.                 |
| Thermal time scale                                        | $L^2$          |                                                                                                                              |
| Squeeze film damping force                                | $L^1$          | Squeeze film damping becomes relatively more important.                                                                      |

Electrostatically actuated and sensed MEMS devices dominate the market for inertial sensors (usually employed in the automobile and consumer electronics industries). Magnetic MEMS devices can also be modeled in COMSOL Multiphysics, but since

these are less common, the AC/DC Module is required in addition to the MEMS Module.



See [Electrostatics](#) for information about how to model electrostatic phenomena in MEMS devices.

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Piezoelectric forces also scale well as the device dimension is reduced (the force produced by a constant applied voltage scales as  $L^1$ ). Furthermore, piezoelectric sensors and actuators are predominantly linear and do not consume DC power in operation. Piezoelectrics are more difficult to integrate with standard semiconductor processes, but significant progress has been made with commercial successes in the market (for example, Avago Technologies (formerly Agilent/HP) FBAR filters). High frequency FBAR resonators fabricated from aluminum nitride thin films on silicon wafers are now widely used as filters used in consumer devices such as mobile phones.



#### Modeling Piezoelectric Problems

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Thermal forces scale as  $L^2$ , assuming that the forces are generated by a fixed temperature change. This scaling is still favorable in comparison to inertial forces, and the thermal time scale also scales well (as  $L^2$ ), making thermal actuators faster on the microscale (although thermal actuators are typically slower than capacitive or piezoelectric actuators). Thermal actuators are also easy to integrate with semiconductor processes although they usually consume large amounts of power and thus have had a limited commercial applicability. Thermal effects play an important role in the manufacture of many commercial MEMS technologies with thermal stresses in deposited thin films being critical for many applications.



See [Thermal Effects in MEMS Devices](#), which discusses thermal actuation and stresses in more detail.

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The interaction of MEMS devices with a fluid leads to a range of microfluidic devices. COMSOL also has the Microfluidics Module, which is geared to model microfluidic devices, but some functionality to model fluids is included with the MEMS Module. In particular, the interaction of moving components with a fluid can be modeled using the Fluid-Structure Interaction Interface. In addition to modeling microfluidic actuators, this multiphysics interface can be used to model the damping of moving

structures in an air ambient. Damping in MEMS devices is often more conveniently modeled by treating the air as a thin layer and solving the Reynolds equations (or a modified form). These equations are also included in this module. The damping forces scale as  $L^1$  and are often important for MEMS devices, frequently leading to a requirement for vacuum packaging.



## Microfluidics

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This discussion has focused on actuators; however, many of the actuators discussed can also be used as sensors. Many MEMS devices (for example, gyroscopes and resonant sensors) require both actuators and sensors to be integrated into the same device. Electrostatic, magnetic, piezoelectric, and even thermal devices have all been employed as MEMS sensors. Another commonly used sensing mechanism found in commercial MEMS devices is that of piezoresistivity. The piezoresistive effect refers to the change in a material's conductivity that occurs in response to an applied stress. Piezoresistors are relatively easy to manufacture using common semiconductor processes and are inherently shielded from electromagnetic interference, and it is usually straightforward to implement electronics to interface with them. Pressure sensors based on the piezoresistive effect were some of the first MEMS devices to be mass produced. Piezoresistive devices do, however, usually consume more power and generate more electrical noise than capacitive sensors, which are displacing piezoresistive devices in some applications.



## Piezoresistivity

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# General Tools for MEMS Modeling

Several tools are required to model MEMS devices in addition to the application-specific physics interfaces. These are discussed in the following sections:

- [Infinite Elements and Perfectly Matched Layers](#)
- [Electrical Circuits](#)
- [Reduced-Order Modeling and Equivalent Circuits](#)
- [Importing Mask Data](#)
- [About the Material Libraries for the MEMS Module](#)

## *Infinite Elements and Perfectly Matched Layers*

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*Infinite elements* and *perfectly matched layers* (PMLs) are frequently required when modeling MEMS devices.

- Infinite elements are used in stationary or transient computations enabling a (finite sized) region of the model to represent a region stretching out to infinity. This applies to problems where the solution varies without oscillation in the infinite domain, a typical MEMS application is to compute the capacitance of a structure in a surrounding air ambient.
- Perfectly matched layers enable outgoing waves in a frequency domain model to be perfectly adsorbed. A typical MEMS application is to use PMLs to compute the anchor losses for a vibrating structure.



[Infinite Elements, Perfectly Matched Layers, and Absorbing Layers](#) in the *COMSOL Multiphysics Reference Manual*

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## *Electrical Circuits*

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Many MEMS devices include accompanying electrical circuits, either integrated on the same chip or, increasingly, through connections to an adjacent chip that is packaged with the device. COMSOL Multiphysics includes tools to connect physical finite

element models to electrical circuits as well as an Electric Circuits interface to model the circuits themselves.



The [Connecting to Electrical Circuits](#) section discusses how to use COMSOL Multiphysics in conjunction with external circuits.

### *Reduced-Order Modeling and Equivalent Circuits*

Reduced-order modeling seeks to reduce the number of degrees of freedom in a physical model, whilst still retaining the essential physics. It is frequently used in the design of resonant MEMS devices, which are usually designed to operate with the system vibrating in a particular mode. For a lightly damped resonant system driven at one of its resonant frequencies, it is reasonable to consider only the contributions to the system of a small number ( $m$ ) of modes within the signal bandwidth. In some cases a single mode is sufficient. A system with  $n$  degrees of freedom has mass, stiffness, and damping matrices of size  $n$ -by- $n$ . A reduced-order representation of the system considering  $m$  modes has size  $m$ -by- $m$ . The reduction in complexity of the system, and the computational speed up is therefore significant when  $m \ll n$ . Determining a suitable reduced-order model of a complex system is a common simulation goal for MEMS designers. Frequently this is implemented as an equivalent circuit that can easily be integrated with SPICE models of the system as a whole. This section describes the theory of the reduced-order system and gives guidelines on how to obtain reduced-order models from a COMSOL Multiphysics model.

#### **THE MODAL COORDINATE SYSTEM**

Consider a mechanical system, with  $n$  degrees of freedom, described by an equation of the form

$$M\ddot{\mathbf{u}} + D\dot{\mathbf{u}} + K\mathbf{u} = \mathbf{F} \quad (2-1)$$

where  $\mathbf{u}$  is the displacement vector (size:  $n$ -by-1),  $K$  is the stiffness matrix (size:  $n$ -by- $n$ ),  $D$  is the damping matrix (size:  $n$ -by- $n$ ), and  $M$  is the mass matrix (size:  $n$ -by- $n$ ). In the frequency domain the problem takes the form

$$-\omega^2 M \mathbf{u}_0 + i\omega D \mathbf{u}_0 + K \mathbf{u}_0 = \mathbf{F}$$

where  $\mathbf{u} = \mathbf{u}_0 e^{i\omega t}$ .

Initially consider the system in the absence of damping and forces. The undamped system has  $n$  eigenvalues  $\omega_i$ , which satisfy the equation

$$K\hat{\mathbf{u}}_i = \omega_i^2 M\hat{\mathbf{u}}_i \quad (2-2)$$

These eigenvectors are orthogonal with respect to  $M$ , as can be seen from the following construction, based on Equation 2-2:

$$\begin{aligned} \hat{\mathbf{u}}_j^T K\hat{\mathbf{u}}_i - \omega_i^2 \hat{\mathbf{u}}_j^T M\hat{\mathbf{u}}_i &= 0 \\ \hat{\mathbf{u}}_i^T K\hat{\mathbf{u}}_j - \omega_j^2 \hat{\mathbf{u}}_i^T M\hat{\mathbf{u}}_j &= 0 \\ (\hat{\mathbf{u}}_i^T K\hat{\mathbf{u}}_j - \omega_j^2 \hat{\mathbf{u}}_i^T M\hat{\mathbf{u}}_j)^T &= \hat{\mathbf{u}}_j^T K\hat{\mathbf{u}}_i - \omega_j^2 \hat{\mathbf{u}}_j^T M\hat{\mathbf{u}}_i = 0 \end{aligned}$$

using the results  $M^T = M$ , and  $K^T = K$ , which apply for physical reasons. Subtracting the first equation from the third gives:

$$-(\omega_j^2 - \omega_i^2) \hat{\mathbf{u}}_j^T M\hat{\mathbf{u}}_i = 0$$

so provided that the eigenfrequency are different:

$$\hat{\mathbf{u}}_j^T M\hat{\mathbf{u}}_i = 0 \quad i \neq j, \omega_i \neq \omega_j \quad (2-3)$$

Note that the above equations also imply

$$\hat{\mathbf{u}}_j^T K\hat{\mathbf{u}}_i = 0 \quad i \neq j, \omega_i \neq \omega_j \quad (2-4)$$

Next the following  $n$ -by- $n$  matrix is constructed, with columns taken from the  $n$  eigenvectors:

$$U = \begin{bmatrix} \hat{\mathbf{u}}_1 & \hat{\mathbf{u}}_2 & \dots & \hat{\mathbf{u}}_n \end{bmatrix}$$

Then consider the following matrix:

$$U^T M U = \begin{bmatrix} \hat{\mathbf{u}}_1^T M \hat{\mathbf{u}}_1 & \hat{\mathbf{u}}_1^T M \hat{\mathbf{u}}_2 & & \\ \hat{\mathbf{u}}_2^T M \hat{\mathbf{u}}_1 & \hat{\mathbf{u}}_2^T M \hat{\mathbf{u}}_2 & & \\ & & \ddots & \\ & & & \hat{\mathbf{u}}_{n-1}^T M \hat{\mathbf{u}}_{n-1} & \hat{\mathbf{u}}_{n-1}^T M \hat{\mathbf{u}}_n \\ & & & \hat{\mathbf{u}}_n^T M \hat{\mathbf{u}}_{n-1} & \hat{\mathbf{u}}_n^T M \hat{\mathbf{u}}_n \end{bmatrix}$$

From Equation 2-3 it is clear that this is a diagonal matrix. Similarly from Equation 2-4 it is clear that  $U^T K U$  is also diagonal.

From the properties of the eigenvectors it is possible to expand any function in terms of the eigenvectors. Thus the displacement  $\mathbf{u}$  can be written as:

$$\mathbf{u} = \sum_{i=1}^n a_i \hat{\mathbf{u}}_i$$

This equation can also be expressed in the form:

$$\mathbf{u} = U \mathbf{a} \quad (2-5)$$

where  $\mathbf{a}$  is a column vector containing the coefficients  $a_i$  as rows. In general  $\mathbf{a}$  is time dependent.

Now consider the original equation: Equation 2-1. First substitute for  $\mathbf{u}$  using Equation 2-5. Then transform the equation to the *modal coordinate system* by premultiplying by  $U^T$ . This gives:

$$U^T M U \ddot{\mathbf{a}} + U^T D U \dot{\mathbf{a}} + U^T K U \mathbf{a} = U^T \mathbf{F} \quad (2-6)$$

It has already been established that the matrices  $U^T M U$  and  $U^T K U$  are diagonal, and frequently a damping model is chosen that results in a diagonal damping matrix. For example, in Rayleigh damping  $D = \alpha M + \beta K$ , where  $\alpha$  and  $\beta$  are constants. Alternatively, a damping ratio,  $\xi_i$ , is assigned to each mode.

## EIGENVALUE SCALING AND EQUIVALENT ELECTRICAL AND MECHANICAL SYSTEMS

The precise form of Equation 2-6 is determined by the normalization adopted for the eigenfunctions. In structural applications the eigenfunctions are often normalized such that  $U^T M U = I$ . This is referred to as *mass matrix* scaling in the eigenvalue solver. In this case Equation 2-2 gives

$$\hat{\mathbf{u}}_i^T \hat{\mathbf{K}} \hat{\mathbf{u}}_i = \omega_i^2 \hat{\mathbf{u}}_i^T \hat{\mathbf{M}} \hat{\mathbf{u}}_i = \omega_i^2$$

so that

$$\mathbf{U}^T \mathbf{K} \mathbf{U} = \text{diag}(\omega_i^2)$$

where  $\text{diag}(\omega_i^2)$  is the diagonal matrix with diagonal elements  $\omega_i^2$ . Similarly, if damping ratios for each mode are defined, the damping matrix can be expressed in the form

$$\mathbf{U}^T \mathbf{D} \mathbf{U} = \text{diag}(2\xi_i \omega_i)$$

Thus if *mass matrix* scaling is used Equation 2-6 takes the form

$$\ddot{\mathbf{a}} + \text{diag}(2\xi_i \omega_i) \dot{\mathbf{a}} + \text{diag}(\omega_i^2) \mathbf{a} = \mathbf{U}^T \mathbf{F} \quad (2-7)$$

In MEMS applications it is common to scale the eigenvectors so that the point of maximum displacement has unit displacement magnitude. This is referred to as *max* scaling in the eigenvalue solver. For an individual mode this scaling has a simple physical interpretation — the corresponding component of  $\mathbf{a}$ ,  $a_i$ , is the amplitude of the  $i$ th mode, measured at the point of maximum displacement, when the mode is driven by the force  $\mathbf{F}$ . In this case Equation 2-6 takes the form

$$\text{diag}(m_{\text{eff}, i}) \ddot{\mathbf{a}} + \text{diag}(c_{\text{eff}, i}) \dot{\mathbf{a}} + \text{diag}(k_{\text{eff}, i}) \mathbf{a} = \mathbf{U}^T \mathbf{F} \quad (2-8)$$

Here  $m_{\text{eff}, i}$  is the effective mass of the  $i$ th mode,  $c_{\text{eff}, i} = 2m_{\text{eff}, i}\xi_i\omega_i$  is the effective damping parameter for the mode, and  $k_{\text{eff}, i}$  is the effective spring constant. Each element of the vector  $\mathbf{U}^T \mathbf{F}$  gives the force component that acts on each of the respective modes.

For electromechanical systems it is common to express the force term,  $\mathbf{U}^T \mathbf{F}$ , in terms of a driving voltage,  $V$ , applied to a terminal in the system. Given this:

$$\mathbf{U}^T \mathbf{F} = \boldsymbol{\eta} V$$

here the vector  $\boldsymbol{\eta}$  has components  $\eta_i$  which correspond to the *electromechanical coupling factor* for each of the modes in the system. Equation 2-8 now takes the form

$$\text{diag}(m_{\text{eff}, i}) \ddot{\mathbf{a}} + \text{diag}(c_{\text{eff}, i}) \dot{\mathbf{a}} + \text{diag}(k_{\text{eff}, i}) \mathbf{a} = \boldsymbol{\eta} V \quad (2-9)$$



To obtain the electromechanical coupling coefficients for a set of modes, it is possible to apply a 1 V signal to the system and then compute the induced forces:  $U^T \mathbf{F} = \boldsymbol{\eta}$ . Reciprocally, energy conserving transducers also have the property that the current that flows into the transducer when it is operating in a particular mode ( $i_{mot,i}$ ) is related to the displacement through the equation

$$i_{mot,i} = \eta_i \dot{a}_i$$

So Equation 2-9 can be rewritten in the form

$$\text{diag}\left(\frac{m_{\text{eff},i}}{\eta_i^2}\right) \frac{d\mathbf{i}}{dt} + \text{diag}\left(\frac{c_{\text{eff},i}}{\eta_i^2}\right) \mathbf{i} + \text{diag}\left(\frac{k_{\text{eff},i}}{\eta_i^2}\right) \int \mathbf{i} dt = \mathbf{V} \quad (2-10)$$

For each mode, the terms on the left of Equation 2-10 can be identified with a resistor capacitor and inductor, such that the mechanical system behaves like a set of parallel series *LCR* circuits. The equivalent modal resistances, capacitances, and inductances are given by:

$$L_i = \frac{m_{\text{eff},i}}{\eta_i^2}$$

$$R_i = \frac{c_{\text{eff},i}}{\eta_i^2}$$

$$C_i = \frac{\eta_i^2}{k_{\text{eff},i}}$$

For a given mode, these quantities are frequently referred to as the *motional inductance*, *resistance*, and *capacitance*.

## REDUCED-ORDER MODELS

The preceding discussion did not consider how to reduce the number of degrees of freedom in the system. For systems in which the vector  $U^T \mathbf{F}$  has only a few significant components (for example, components  $i = 1, \dots, m$  where  $m \ll n$ ) the following approximation can be made:

$$\mathbf{u} \approx \sum_{i=1}^m a_i \hat{\mathbf{u}}_i$$

The expression for  $\mathbf{u}$  in matrix becomes:

$$\mathbf{u} = U' \mathbf{a}'$$

where  $U'$  is now an  $m$ -by- $n$  and  $\mathbf{a}'$  is a vector with  $m$  components. The equation system in modal coordinates now takes the form

$$U'^T M U' \ddot{\mathbf{a}}' + U'^T D U' \dot{\mathbf{a}}' + U'^T K U' \mathbf{a}' = U'^T \mathbf{F} \quad (2-11)$$

The matrices  $U'^T M U'$ ,  $U'^T D U'$ , and  $U'^T K U'$  now have dimensions  $m$ -by- $m$ . Similarly the vector  $U'^T \mathbf{F}$  has  $m$  components. This results in a significant reduction in the system complexity.

### REDUCED-ORDER MODELS WITH PHYSICAL DAMPING

If physically relevant damping is present in the system, the above theory must be modified as the damping matrix is no longer diagonal in the modal coordinate system. COMSOL can still handle this case as the modal solver does not make the assumption that any of the matrices are diagonal. In this case the eigenvalues become complex and the eigenvectors split into right and left eigenvectors. The right eigenvectors  $U^r$  are solutions of the equation:

$$-\omega_i^2 \hat{M} \hat{\mathbf{u}}_{r,i} + i \omega_i \hat{D} \hat{\mathbf{u}}_{r,i} + K \hat{\mathbf{u}}_{r,i} = \mathbf{F}$$

As in the previous section, for a reduced set of modes, it is assumed that:

$$\mathbf{u} = U_r' \mathbf{a}'$$

where  $U_r'$  is the  $n$ -by- $m$  matrix containing the right eigenvectors chosen for the modal analysis. Once again  $\mathbf{a}'$  is a vector with  $m$  components. The system in modal coordinates takes the form

$$U_l'^T M U_r' \ddot{\mathbf{a}}' + U_l'^T D U_r' \dot{\mathbf{a}}' + U_l'^T K U_r' \mathbf{a}' = U_l'^T \mathbf{F}$$

where  $U_l'$  is the  $n$ -by- $m$  matrix containing the left eigenvectors chosen for the modal analysis.

The matrices  $U_l'^T M U_r'$ ,  $U_l'^T D U_r'$ , and  $U_l'^T K U_r'$  are no longer necessarily diagonal. The modal solver accepts any linearly independent set of vectors to project the solution vector and equations onto and constructs the reduced-order system accordingly.

## ACCESSING THE REDUCED-ORDER MODEL MATRICES

The **Model Reduction** and **Modal Reduced Order Model** study steps have the property that they can assemble the modal matrices and make them available for output. In the **Model Reduction** node, the **Store reduced matrices** check box must be selected.

After the model has solved, right-click the **Results>Derived Values** node and select **System Matrices**. In the output section choose the **Matrix** to display in the list. The mass matrix corresponds to the matrix  $U_l^T M U_r$ , the stiffness matrix corresponds to  $U_l^T K U_r$ , and the damping matrix corresponds to  $U_l^T D U_r$ . The vector  $U_l^T \mathbf{F}$  is available as the load vector. These matrices are given in a format that respects the normalization of the preceding **Eigenvalue Solver**. To change this select the **Eigenvalue Solver** node, and change the **Scaling of Eigenvectors** setting under the **Output** section. Use the **Max** setting if an equivalent Mass-Spring-Damper system is required, in which case the modal amplitude corresponds to the maximum displacement of the mode.

To convert this into an equivalent circuit representation, see the discussion in the section [Eigenvalue scaling and Equivalent Electrical and Mechanical Systems](#).

## Importing Mask Data

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The semiconductor processes used to manufacture MEMS devices are usually specified layer by layer through the definition of a mask set. It is often convenient to use these mask sets when building models of the 3D devices in COMSOL Multiphysics.



Use the ECAD Import Module to import mask data into COMSOL Multiphysics. See the *ECAD Import Module User's Guide* or go to <https://www.comsol.com/ecad-import-module/> for more information about this and other COMSOL products.

## About the Material Libraries for the MEMS Module

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The MEMS Module includes these material libraries:

- *MEMS*, an extended solid materials library with metals, semiconductors, insulators, and polymers common in MEMS devices.
- *Piezoelectric*, with over 20 common piezoelectric materials. The materials include temperature-dependent fluid dynamic and thermal properties.
- *Piezoresistivity*, with four materials each with seven material properties.

|                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                      |
|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>In the <i>COMSOL Multiphysics Reference Manual</i>:</p> <ul style="list-style-type: none"> <li>• <a href="#">MEMS Material Library</a></li> <li>• <a href="#">Piezoelectric Materials Library</a></li> <li>• <a href="#">Piezoresistivity Materials Library</a></li> <li>• <a href="#">Materials</a></li> </ul>                                                                                   |
|  | <p>For an example of the MEMS materials database, see <i>Microresistor Beam</i>: Application Library path <b>MEMS_Module/Actuators/microresistor_beam</b>.</p>                                                                                                                                                                                                                                       |
|  | <p>For examples of the Piezoelectric materials database, see:</p> <ul style="list-style-type: none"> <li>• <i>Piezoelectric Shear-Actuated Beam</i>: Application Library path <b>MEMS_Module/Piezoelectric_Devices/shear_bender</b></li> <li>• <i>Piezoceramic Tube</i>: Application Library path <b>MEMS_Module/Piezoelectric_Devices/piezoceramic_tube</b></li> </ul>                              |
|  | <p>For examples of the Piezoresistivity materials database, see:</p> <ul style="list-style-type: none"> <li>• <i>Piezoresistive Pressure Sensor</i>: Application Library path <b>MEMS_Module/Sensors/piezoresistive_pressure_sensor</b></li> <li>• <i>Multiphysics Interfaces and Couplings</i>: Application Library path <b>MEMS_Module/Sensors/piezoresistive_pressure_sensor_shell</b></li> </ul> |

# Structural Mechanics

Many of the COMSOL Multiphysics structural mechanics physics interfaces are available in the MEMS Module and are found under the **Structural Mechanics** branch () when adding a physics interface.

Many important aspects of the creation of structural mechanics models are covered in the chapter [Structural Mechanics Modeling](#) in the *Structural Mechanics Module User's Guide*. The following sections are of special importance for MEMS modeling;

- [Selecting the Physics Interface](#)
- [Applying Loads](#)
- [Defining Constraints](#)
- [Calculating Reaction Forces](#)
- [Modeling Piezoelectric Problems](#)
- [Mechanical Damping and Losses](#)
- [Modeling Geometric Nonlinearity](#)
- [Contact Modeling](#)
- [Springs and Dampers](#)
- [Defining Multiphysics Models](#)
- [Thermally Coupled Problems](#)
- [Solver Settings](#)



In the *Structural Mechanics Module User's Guide*

- [The Solid Mechanics Interface](#)
- [Structural Mechanics Theory](#)



The links to external guides, such as the *Structural Mechanics Module User's Guide*, do not work in the PDF, only from the online help in COMSOL Multiphysics.

## *Damping and Losses*

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For frequency domain (eigenfrequency or frequency domain studies) and transient simulations it is often necessary to include damping in the model. This is particularly important for resonant MEMS devices.

Within COMSOL Multiphysics, damping can be modeled explicitly by coupling the relevant physics interfaces into the model. Examples of such couplings include:

- Modeling the movement of the structure through a fluid directly by means of a complete fluid-structure interaction model. This can be done using the Fluid-Structure Interaction interface.
- Modeling thin films of a fluid using [The Thin-Film Flow Interfaces](#), or by means of the thin film damping boundary condition, integrated into the structural mechanics physics interfaces.
- Modeling thermoelastic damping explicitly by including heat transfer and the relevant thermodynamics in the model. See [The Thermoelasticity Interface](#).
- Modeling acoustic losses through anchor structures in the frequency domain using a perfectly matched layer.



[Infinite Elements, Perfectly Matched Layers, and Absorbing Layers](#) in the *COMSOL Multiphysics Reference Manual*

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- Modeling losses through anchor structures in the time domain using a spring damper system.



In the *Structural Mechanics Module User's Guide*

- [The Fluid-Solid Interaction Interface](#)
  - [Mechanical Damping and Losses](#)
  - [Springs and Dampers](#)
-

# Electrostatics

Most MEMS devices meet the electroquasistatic criterion ([Ref. 2](#)) in which the wavelength of the applied fields is substantially larger than the modeled device. The electric field can therefore be treated as quasi static and [The Electrostatics Interface](#) or [The Electric Currents Interface](#) can be used.

In this section:

- [Electrostatics](#)
- [Electric Currents in Conductive Media](#)
- [Lumped Parameters](#)

## *Electrostatics*

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[The Electrostatics Interface](#) solves for the electric potential  $V$  using the equation

$$-\nabla \cdot (\epsilon \nabla V) = \rho$$

For most MEMS devices the details of the charge distribution,  $\rho$ , inside material are unimportant and the charge usually resides only on surfaces held at fixed potentials. The [Electric Potential](#), [Ground](#), and [Terminal](#) boundary conditions are usually used to fix the potential on the surfaces of a MEMS device. At symmetry boundaries the [Zero Charge](#) boundary condition applies. To represent infinite regions adjacent to the model a common approach is to use infinite elements. Note that it is possible to model electric circuits associated with a terminal, as described in the [Connecting to Electrical Circuits](#) section.



[Infinite Elements, Perfectly Matched Layers, and Absorbing Layers](#) in the  
*COMSOL Multiphysics Reference Manual*

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## **ELECTROSTATIC FORCES**

The Maxwell stress tensor is a general method for calculating electromagnetic forces and torques. Force and torque calculations using Maxwell's stress tensor are available in the Electrostatics interface. In electrostatics the force is calculated by integrating

$$\mathbf{n}_1 T_2 = -\frac{1}{2} \mathbf{n}_1 (\mathbf{E} \cdot \mathbf{D}) + (\mathbf{n}_1 \cdot \mathbf{E}) \mathbf{D}^T \quad (2-12)$$

on the surface of the object that the force acts on where  $\mathbf{E}$  is the electric field,  $\mathbf{D}$  the electric displacement, and  $\mathbf{n}_1$  the outward normal from the object.

In practice, electric fields are modeled not only in the air but also inside the solid materials. By entering the electromagnetic force variable name into the domain settings, the force calculations are activated, and the physics interface automatically generates new domain and boundary variables.



The form of the stress tensor in [Equation 2-12](#) assumes no material electrostriction. Support for isotropic electrostriction is included in [The Electromechanics Interface](#).

## CAPACITANCE CALCULATIONS

The capacitance of a system can be computed using the functionality built into the Terminal boundary condition. This is discussed in more detail in the section [Lumped Parameters](#).

### *Electric Currents in Conductive Media*

The [Electric Currents Interface](#) uses the equation

$$-\nabla \cdot (\sigma \nabla V - \mathbf{J}^e) = Q_j$$

where  $\sigma$  is the conductivity,  $\mathbf{J}^e$  is an externally generated current density, and  $Q_j$  is the volume current source, which is usually zero in MEMS applications. Current flow through the device is specified by means of the [Normal Current Density](#) and [Electric Insulation](#) physics nodes. The [Electric Potential](#), [Ground](#), and [Terminal](#) physics nodes are frequently employed to specify constant potential surfaces, which can also act as current sources or sinks.

Conductors in MEMS designs are often thin sheets. For cases in which large aspect ratio differences occur it is often convenient to represent thin layers using a planar approximation.



## RESISTANCE AND CONDUCTANCE CALCULATIONS

Use **Terminal** boundary conditions to calculate resistances or conductances of the system. For more details see the [Lumped Parameters](#) section.



*Thin-Film Resistance:* Application Library path  
**COMSOL\_Multiphysics/Electromagnetics/thin\_film\_resistance**

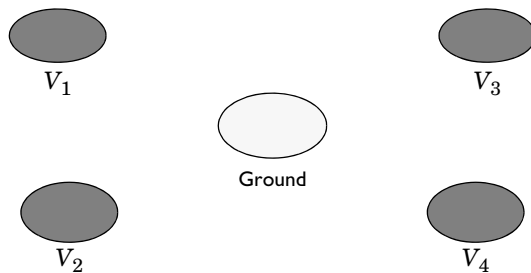
### *Lumped Parameters*

Lumped parameters are matrices describing electromagnetic properties such as resistance, capacitance, and inductance. In the time-harmonic case the lumped parameter matrix is either an impedance matrix or an admittance matrix depending on how the model is excited (current or voltage). In a static calculation only the resistive, capacitive, or inductive part of the lumped parameter matrix is obtained.

#### **CALCULATING LUMPED PARAMETERS WITH OHM'S LAW**

To calculate the lumped parameters, there must be at least two electrodes in the system, one of which must be grounded. Either a voltage or a current can be forced on the electrodes. After the simulation, extract the other property or the energy and use it when calculating the lumped parameter.

There are several available techniques to extract the lumped parameters. Which one to use depends on the physics interface, the parameter of interest, and how the model is solved. The overview of the techniques in this section use a 4-by-4 matrix example for the lumped parameter matrix. This represents a system of at least five electrodes, where four are used as terminals and the rest are grounded, as illustrated in [Figure 2-1](#).



*Figure 2-1: A five-electrode system with 4 terminals and one ground electrode.*

If a system specifies that all electrodes are terminals, the results are redundant matrix elements. This is better understood by considering a two-electrode system. If both

electrodes are declared as terminals, a 2-by-2 matrix is obtained for the system. This is clearly too many elements because there is only one unique lumped parameter between the terminals. If in addition one or more ground electrodes are declared, the system has three unique electrodes and the lumped parameter matrix becomes a 2-by-2 matrix.

### FORCED VOLTAGE

If voltages are applied to the terminals, the extracted currents represent elements in the admittance matrix,  $\mathbf{Y}$ . This matrix determines the relation between the applied voltages and the corresponding currents with the formula

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

so when  $V_1$  is nonzero and all other voltages are zero, the vector  $I$  is proportional to the first column of  $\mathbf{Y}$ .

In electrostatics the current is replaced with charge and the admittance matrix is replaced with the capacitance matrix

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

### FIXED CURRENT

It might be necessary to calculate the  $\mathbf{Z}$ -matrix in a more direct way. Similar to the  $\mathbf{Y}$  calculation, the  $\mathbf{Z}$  calculation can be done by forcing the current through one terminal at the time to a nonzero value while the others are set to zero. Then, the columns of the impedance matrix are proportional to the voltage values on all terminals:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

### FIXED CHARGE

The Electrostatics interface can use total charge instead of total current. This gives the inverted capacitance matrix in a similar manner as the **Z** and **Y** matrices.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix}^{-1} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_4 \\ Q_4 \end{bmatrix}$$

### CALCULATING LUMPED PARAMETERS USING THE ENERGY METHOD

When using this method the potential or the current is nonzero on one or two terminals at a time and the energy density is extracted and integrated over the whole geometry. The following formulas show how to calculate the capacitance matrix from the integral of the electric energy density.

$$C_{ii} = \frac{2}{V_i^2} \int_{\Omega} W_e d\Omega \quad V_j = \begin{cases} 0 & j \neq i \\ V_i & j = i \end{cases}$$

$$C_{ij} = \frac{1}{V_i V_j} \int_{\Omega} W_e d\Omega - \frac{1}{2} \left( \frac{V_i}{V_j} C_{ii} + \frac{V_j}{V_i} C_{jj} \right) \quad V_k = \begin{cases} 0 & k \neq i, j \\ V_i & k = i \\ V_j & k = j \end{cases}$$

### S-PARAMETERS

Scattering parameters (or S-parameters) are complex-valued, frequency-dependent matrices describing the transmission and reflection of electromagnetic waves at different ports of devices like filters, antennas, waveguide transitions, and transmission lines. S-parameters originate from transmission-line theory and are defined in terms of transmitted and reflected voltage waves. All ports are assumed to be connected to matched loads/feeds, that is, there is no reflection directly at a port.

For a device with  $n$  ports, the S-parameters are

$$S = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ S_{n1} & \cdot & \cdots & S_{nn} \end{bmatrix}$$

where  $S_{11}$  is the voltage reflection coefficient at port 1,  $S_{21}$  is the voltage transmission coefficient from port 1 to port 2, and so on. The time average power reflection/transmission coefficients are obtained as  $|S_{ij}|^2$ .

Now, for high-frequency problems, voltage is not a well-defined entity, and it is necessary to define the scattering parameters in terms of the electric field.

#### *S-Parameter Calculations*

The MEMS interfaces have built-in support for S-parameter calculations. In the Electric Currents and Electrostatics interfaces, use the *terminal* boundary feature with the *terminated* setting to approximate a connecting transmission line or a voltage source with a known internal impedance. For a terminal the voltage measurement is always with respect to ground so at least one *ground* feature is also required in the model.

#### *S-Parameter Variables*

This module automatically generates variables for the S-parameters. The port names (use numbers for sweeps to work correctly) determine the variable names. If, for example, there are two ports with the numbers 1 and 2 and Port 1 is the input, the software generates the variables  $S_{11}$  and  $S_{21}$ .  $S_{11}$  is the S-parameter for the reflected wave and  $S_{21}$  is the S-parameter for the transmitted wave. For convenience, two variables for the S-parameters on a dB scale,  $S_{11dB}$  and  $S_{21dB}$ , are also defined using the following relation:

$$S_{11dB} = 20\log_{10}(|S_{11}|)$$

The model and physics interface names also appear in front of the variable names so they can vary. The S-parameter variables are added to the predefined quantities in appropriate plot lists.

#### *Port/Terminal Sweeps and Touchstone Export*

The, [Manual Terminal Sweep Settings](#) section in the Electrostatics interface and the [Manual Terminal Sweep Settings](#) section in the Electric Currents interface describe how to cycle through the terminals, compute the entire S-matrix and export it to a Touchstone file.

### **LUMPED PARAMETER CONVERSION**

When the impedance matrix,  $\mathbf{Z}$ , or the admittance matrix,  $\mathbf{Y}$ , is available it is possible to calculate all other types of lumped parameter matrices from the relations below.

$$\begin{aligned}\mathbf{S} &= \mathbf{G}_{\text{ref}} \cdot (\mathbf{E} - (\mathbf{Z}_{\text{ref}}^* \cdot \mathbf{Y})) \cdot (\mathbf{E} + \mathbf{Z}_{\text{ref}} \cdot \mathbf{Y})^{-1} \cdot \mathbf{G}_{\text{ref}}^{-1}, \\ \mathbf{Z} &= \mathbf{Y}^{-1}, \quad \mathbf{L} = \frac{\text{Im}(\mathbf{Z})}{\omega}, \quad \mathbf{C} = \frac{\text{Im}(\mathbf{Y})}{\omega}, \\ \mathbf{R} &= \text{Re}(\mathbf{Z}), \quad \mathbf{G} = \text{Re}(\mathbf{Y})\end{aligned}$$

where  $\mathbf{L}$  is the inductance,  $\mathbf{C}$  is the capacitance,  $\mathbf{R}$  is the resistance, and  $\mathbf{G}$  is the conductance.  $\mathbf{S}$  is the S-parameter. The relations also include the following matrices

$$\mathbf{E} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{Z}_{\text{ref}} = \mathbf{E} \cdot Z_0$$

$$\mathbf{G}_{\text{ref}} = \mathbf{E} \cdot \frac{1}{2\sqrt{|\text{Re}(Z_0)|}}$$

where  $Z_0$  is the characteristic impedance.

You can compute conversions between the impedance matrix,  $\mathbf{Z}$ , the admittance matrix,  $\mathbf{Y}$ , and the S-parameter matrix  $\mathbf{S}$  in a results table using the **Settings** window for the **Global Matrix Evaluation** node, which you can add under **Results>Derived Values**.



[Global Matrix Evaluation](#) in the *COMSOL Multiphysics Reference Manual*

# Piezoresistivity

The *piezoresistive effect* describes the change in a material's conductivity when a stress is applied to the material. Unlike the piezoelectric effect, piezoresistivity is not reversible, so an applied current does not induce a stress (unless other secondary effects are present, such as heating). Piezoresistance is usually associated with semiconductor materials. In semiconductors, piezoresistance results from the strain-induced alteration of the material's band structure and the associated changes in carrier mobility and number density.

Piezoresistivity can be described in terms of a stress-induced change in the resistivity of the material. The relation between the electric field,  $\mathbf{E}$ , and the current,  $\mathbf{J}$ , becomes:

$$\mathbf{E} = \rho \cdot \mathbf{J} + \Delta\rho \cdot \mathbf{J}$$

where  $\rho$  is the resistivity and  $\Delta\rho$  is the induced change in the resistivity. In the general case,  $\rho$  and  $\Delta\rho$  are both rank-2 tensors (matrices). The change in resistance is related to the stress,  $\sigma$ , (for the piezoresistance form of the equations) or the strain,  $\epsilon$ , (for the elastoresistance form of the equations) by the constitutive relationship:

$$\begin{aligned}\Delta\rho &= \Pi \cdot \sigma && \text{(piezoresistance form)} \\ \Delta\rho &= \mathbf{M} \cdot \epsilon && \text{(elastoresistance form)}\end{aligned}\tag{2-13}$$

where  $\Pi$  is the piezoresistance tensor (SI unit:  $\text{Pa}^{-1}\Omega\cdot\text{m}$ ) and  $\mathbf{M}$  is the elastoresistance tensor (SI unit:  $\Omega\cdot\text{m}$ ). Note that both of these quantities are material properties.  $\Pi$  and  $\mathbf{M}$  are in this case rank-4 tensors; however, they can be represented as matrices if the resistivity, stress, and strain are converted to vectors within a reduced subscript notation.

In practice, piezoresistors are fabricated by doping a thin layer of a lightly doped wafer, either using the process of ion implantation or by diffusing dopant into the wafer from its surface at high temperatures. Both processes usually produce thin piezoresistors, typically 100s of nm thick in structures that are microns or tens of microns thick. These aspect ratios are challenging to resolve with a practical mesh, so the MEMS Module includes physics interfaces that make it possible to model the current conduction in a thin layer, represented by a boundary in the model geometry. The Piezoresistivity, Boundary Currents interface is appropriate for situations in which the thickness of the piezoresistive layer is much less than that of the structural layer. If the structural layer is also sufficiently thin that it can be represented using the Shell interface, then the Piezoresistivity, Shell interface can be used (requires the Structural Mechanics Module

in addition to the MEMS Module). This circumstance is frequently encountered in modeling pressure sensors, which usually have piezoresistors embedded near the edge of large membranes. Note that the Piezoresistive Layer is still assumed to be much thinner than the structural layer in this physics interface. Finally if both the conducting and structural layers are meshed through their thicknesses the Piezoresistivity, Domain Currents interface can be used. This physics interface allows for advanced modeling of, for example, nonuniform doping profiles in the piezoresistor at the expense of additional degrees of freedom in the model.



- [The Piezoresistivity, Domain Currents Interface](#)
- [The Piezoresistivity, Boundary Currents Interface](#)
- [The Piezoresistivity, Shell Interface](#)
- [Theory for the Piezoresistivity Interfaces](#)

# Thermal Effects in MEMS Devices

In this section:

- [About Thermal Effects in MEMS Devices](#)
- [Modeling Thermal Actuators](#)
- [Modeling Thermal Stresses](#)
- [Thermoelastic Damping](#)
- [Physics Interfaces for Modeling Heat Transfer in Solids](#)



[The Heat Transfer in Solids Interface](#) in the *COMSOL Multiphysics Reference Manual*

## *About Thermal Effects in MEMS Devices*

Heat transfer is characterized by three mechanisms: *conduction*, *convection*, and *radiation*. In MEMS actuators and sensors heat transfer by conduction is usually the dominant mechanism. Conductive heat transfer is diffusive and is driven by a temperature gradient. Within a solid the heat transfer equations take the following form:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \quad (2-14)$$

Here  $\rho$  is the density of the solid,  $C_p$  is its heat capacity,  $k$  is Boltzmann's constant,  $T$  is the temperature, and  $Q$  is a term that includes heat sources and sinks. The Heat Transfer in Solids interface solves [Equation 2-14](#), without additional coupling assumed.

[Equation 2-14](#) is solved in the Joule Heating interface, along with the equations for electric current flow. In this case the volumetric heat source  $Q$  takes the value:

$$Q = \mathbf{J} \cdot \mathbf{E} \quad (2-15)$$

where  $\mathbf{J}$  is the current density, and  $\mathbf{E}$  is the electric field. The electric field component in the direction of the current flow expresses the voltage drop per unit length of material in the direction of flow. Since the current density gives the current per unit area through a surface with normal parallel to the direction of flow, the quantity  $Q$  is



a power per unit volume, with dimensions  $\text{W}/\text{m}^3$ . The Joule Heating interface includes heat transfer and electromagnetic fields; in addition, solid mechanics is required to model thermal actuators. The MEMS Module includes [The Joule Heating and Thermal Expansion Interface](#) interface for this purpose.

### *Modeling Thermal Actuators*

---

To model thermal actuators, [The Joule Heating and Thermal Expansion Interface](#) is required. This multiphysics interface adds a Solid Mechanics interface, a Heat Transfer in Solids interface, and an Electric Currents interface. Joule heating and the resulting thermal expansion are included as multiphysics coupling nodes under Multiphysics in the model tree. Note that a reference temperature, at which the thermal strains are zero, must be added to the Thermal Expansion node. In the absence of thermal residual stresses this temperature should be specified as the operating temperature.



The [Modeling Thermal Stresses](#) section explains how to use this feature to include residual stresses in the film in addition to the thermal stresses generated by Joule heating.

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### *Modeling Thermal Stresses*

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Some MEMS devices are fabricated by sequential depositions of thin or thick films. This process introduces thermal residual stresses in the structures due to the mismatched thermal expansivity of the deposited layers and the substrate as well as the difference between the deposition and operating temperatures.

Thermal stresses in a single added layer can be modeled in multiphysics interfaces using a coupled multiphysics interface that include the Solid Mechanics interface by adding a [The Fluid-Solid Interaction Interface](#) subnode under the Multiphysics node (in the Solid Mechanics interface you can also add it as subnode to the material model). A reference temperature,  $T_{\text{ref}}$ , for zero thermal strain must be specified, and the operating temperature,  $T$ , is set by selecting a heat transfer interface in a multiphysics model, which sets up this temperature coupling automatically, or by selecting a temperature as a model input (that is, temperatures generated by other physics interfaces can be selected or a user-defined value or expression for the temperature can be supplied), if the thermal expansion is defined in the Solid Mechanics interface. If the device is operated at a constant temperature, then [The Solid Mechanics Interface](#) should be used with  $T$  specified as a user-defined constant value in the model input. If

temperature gradients resulting from external heat sources are present in the structure then [The Thermal Stress, Solid Interface](#) is the natural choice because this physics interface couples heat transfer with the Solid Mechanics interface (in this case you only need to specify the strain reference temperature  $T_{\text{ref}}$  in the Thermal Expansion subnode; the temperature coupling to the heat transfer interface is set up by the Thermal Stress multiphysics interface). Finally for Joule-heated structures, [The Joule Heating and Thermal Expansion Interface](#) make it possible to use arbitrary zero strain reference temperatures, which enables the inclusion of thermal stress in addition to the Joule heating effects. For this physics interface you only need to specify the strain reference temperature  $T_{\text{ref}}$  in the Thermal Expansion subnode as in the Thermal Stress interface.

Thermal stresses in multilayered structures can also be modeled. As an example, consider a trilayer structure (a substrate plus two deposited layers), modeled using the Solid Mechanics interface with a Thermal Expansion subnode. For the first added layer, the zero strain temperature should be set to the deposition temperature of this layer, but the solution temperature (set through the model input), should be set to the deposition temperature of the second layer. A second study step should then be added with the output of the first study step supplied as an initial stress (this requires two Solid Mechanics interfaces to be added to the model, and some adjustment of the solver settings). For the second study step the zero strain reference temperature is chosen as the deposition temperature of the second added layer and the solution (model input) temperature should be set to the operating temperature. This process can naturally be extended to any number of deposited layers.



*Thermal Stresses in a Layered Plate:* Application Library path  
**MEMS\_Module/Actuators/layered\_plate**

### *Thermoelastic Damping*

When the product of the coefficient of thermal expansion and the temperature of the structure at rest is large, mechanical vibrations cause significant oscillations of the temperature field. The resulting energy transfer from the mechanical domain to the thermal domain is called *thermoelastic damping*. [The Thermoelasticity Interface](#) provides a predefined multiphysics interface to model thermoelastic damping.

## Physics Interfaces for Modeling Heat Transfer in Solids

Table 2-2 gives a summary of the thermal physics interfaces showing which physics nodes are available in each interface.

TABLE 2-2: SUMMARY OF THE PHYSICS INTERFACES FOR MODELING HEAT TRANSFER AND THERMAL EXPANSION IN THE MEMS MODULE

| PHYSICS INTERFACE                   | ID    | HEAT TRANSFER INCLUDED | SOLID MECHANICS INCLUDED? | ELECTRIC CURRENTS AND JOULE HEATING INCLUDED? | MODELING THERMAL STRESSES                                                                 |
|-------------------------------------|-------|------------------------|---------------------------|-----------------------------------------------|-------------------------------------------------------------------------------------------|
| Heat Transfer in Solids             | ht    | Yes                    | No                        | No                                            | Not applicable — would need to add <b>Solid Mechanics</b> separately.                     |
| Solid Mechanics                     | solid | No                     | Yes                       | No                                            | Add <b>Thermal Expansion</b> node & specify $T_{\text{ref}}$ and $T$ .                    |
| Thermal Stress                      | —     | Yes                    | Yes                       | No                                            | Specify $T_{\text{ref}}$ in the <b>Thermal Expansion</b> node under <b>Multiphysics</b> . |
| Joule Heating                       | —     | Yes                    | No                        | Yes                                           | Not applicable — would need to add <b>Solid Mechanics</b> separately.                     |
| Joule Heating and Thermal Expansion | —     | Yes                    | Yes                       | Yes                                           | Specify $T_{\text{ref}}$ in the <b>Thermal Expansion</b> node under <b>Multiphysics</b> . |

# Microfluidics

COMSOL provides a dedicated Microfluidics Module that is designed for users developing microfluidic devices. This module includes features for modeling single-phase and multiphase flow, electrokinetics, flow in porous media, rarefied gas flows, and chemical transport.

In the MEMS Module, the microfluidics physics interfaces are focused on modeling the interaction of fluids with microstructures.

In this section:

- [Fluid-Structure Interaction](#)
- [Thin-Film Damping](#)

## *Fluid-Structure Interaction*

---

The Fluid-Structure Interaction interface can be used to compute the flow of a liquid or gas around a moving microstructure. A typical application is the simulation of microvalves. The physics interface can be used to model both turbulent and laminar flows at low Mach numbers.

The Fluid-Structure Interaction interface uses the arbitrary Lagrangian-Eulerian (ALE) method to combine the fluid flow equations, formulated using an Eulerian description and a spatial frame, with the solid mechanics equations, formulated using a Lagrangian description and a material (reference) frame. The Fluid-Structure Interaction couplings appear on the boundaries between the fluid and the solid.



- [Damping and Losses](#)
- [The Fluid-Solid Interaction Interface](#) (in the *Structural Mechanics Module User's Guide*)
- [The Piezoelectricity Interface](#) (in the *Structural Mechanics Module User's Guide*)

## *Thin-Film Damping*

---

In many MEMS devices a released structure moves relative to the substrate, compressing or shearing a thin layer of gas between the two structures. The fluid film

can be the dominant form of damping for the moving microstructure. If the film is compressed by a structure moving perpendicular to its plane, this type of damping is usually referred to as *squeeze-film damping*. Damping induced by motion of the structure parallel to the plane in which the fluid flows is called *slide-film damping*.

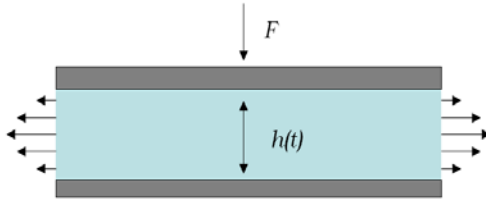


Figure 2-2: Diagram showing a circumstance in which squeeze-film damping applies.

It is often convenient to model the film using the Reynolds equation — enabling the 3D gas layer to be modeled on a 2D surface. The Reynolds equation applies for isothermal flows of a thin film in which the film height,  $h$ , is much less than a typical lateral dimension of the device,  $L$ . It must also be possible to neglect inertial flow effects in comparison to the viscous effects (for MEMS devices, this assumption is reasonable below MHz frequencies). Additionally, the curvature of the reference surface is neglected.

For isothermal, ideal gases the Reynolds equation can be simplified, leading to a modified Reynolds equation, formulated in the pressure only (the full Reynolds equation is formulated using both the pressure and the density). COMSOL Multiphysics includes both forms of the Reynolds equations in the Thin-Film Flow interfaces, and it is possible to switch between them using the Equation Type setting. Both forms of the equations include squeeze-film damping and slide-film damping.

The Thin-Film Flow interfaces are available as standalone physics interfaces that can be manually coupled to, for example, the physics interfaces in the Structural Mechanics branch. Thin-Film Damping has also been added as a boundary condition to the structural mechanics physics interfaces — these include Solid Mechanics, Piezoelectricity, Electromechanics, and Joule Heating and Thermal Expansion. The boundary condition automatically couples the damping forces to the model.

For gas damping, especially in vacuum packaged devices, the Knudsen number for the thin film gap is an important parameter to consider. This is the ratio of the gas mean free path to the gap height. Below Knudsen numbers of 0.01 it is necessary to use a slip boundary condition for the fluid by specifying a characteristic slip length. As the Knudsen number decreases further additional rarefaction effects need to be accounted

for. These can be included empirically in the Reynolds equation using models that require the mean free path and the tangential momentum accommodation coefficient (TMAC) to be specified. The TMAC is a measure of the mean fractional loss of tangential momentum of the gas molecules on collision with the walls — typical values for various gas surface combinations are available in [Ref. 1](#) (see Table 6 in this reference).



- [The Thin-Film Flow Interfaces](#)
  - [Theory for the Thin-Film Flow Interfaces](#)
- 

### *Reference for Thin-Film Damping*

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I. F. Sharipov, “Data on the Velocity Slip and Temperature Jump on a Gas-Solid Interface”, *J. Phys. Chem. Ref. Data*, vol. 40, no. 2, 023101, 2011.

# Connecting to Electrical Circuits

In this section:

- [About Connecting Electrical Circuits to Physics Interfaces](#)
- [Connecting Electrical Circuits Using Predefined Couplings](#)
- [Connecting Electrical Circuits by User-Defined Couplings](#)
- [Solving](#)
- [Postprocessing](#)

## *About Connecting Electrical Circuits to Physics Interfaces*

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This section describes the various ways electrical circuits can be connected to other physics interfaces in COMSOL Multiphysics. If you are not familiar with circuit modeling, it is recommended that you review the [Theory for the Electrical Circuit Interface](#).

In general electrical circuits connect to other physics interfaces via one or more of three special circuit features:

- [External I vs. U](#)
- [External U vs. I](#)
- [External I-Terminal](#)

These features either accept a voltage measurement from the connecting noncircuit physics interface and return a current from a or the Electrical Circuit interface or the other way around.



The “External” features are considered “ideal” current or voltage sources by the Electrical Circuit interface. Hence, you cannot connect them directly in parallel (voltage sources) or in series (current sources) with other ideal sources. This results in the error message *The DAE is structurally inconsistent*. A workaround is to provide a suitable parallel or series resistor, which can be tuned to minimize its influence on the results.

## *Connecting Electrical Circuits Using Predefined Couplings*

---

In addition to these circuit features, interfaces in the AC/DC Module, RF Module, MEMS Module, Plasma Module, and Semiconductor Module (the modules that include the Electrical Circuit interface) also contain features that provide couplings to the Electrical Circuit interface by accepting a voltage or a current from one of the specific circuit features ([External I vs. U](#), [External U vs. I](#), and [External I-Terminal](#)).

This coupling is typically activated when:

- A choice is made in the **Settings** window for the noncircuit physics interface feature, which then announces (that is, includes) the coupling to the Electrical Circuit interface. Its voltage or current is then included to make it visible to the connecting circuit feature.
- A voltage or current that has been announced (that is, included) is selected in a feature node's **Settings** window.

These circuit connections are supported in Terminals.

## *Connecting Electrical Circuits by User-Defined Couplings*

---

A more general way to connect a physics interface to the Electrical Circuit interface is to:

- Apply the voltage or current from the connecting “External” circuit feature as an excitation in the noncircuit physics interface.
- Define your own voltage or current measurement in the noncircuit physics interface using variables, coupling operators and so forth.
- In the **Settings** window for the Electrical Circuit interface feature, selecting the User-defined option and entering the name of the variable or expression using coupling operators defined in the previous step.

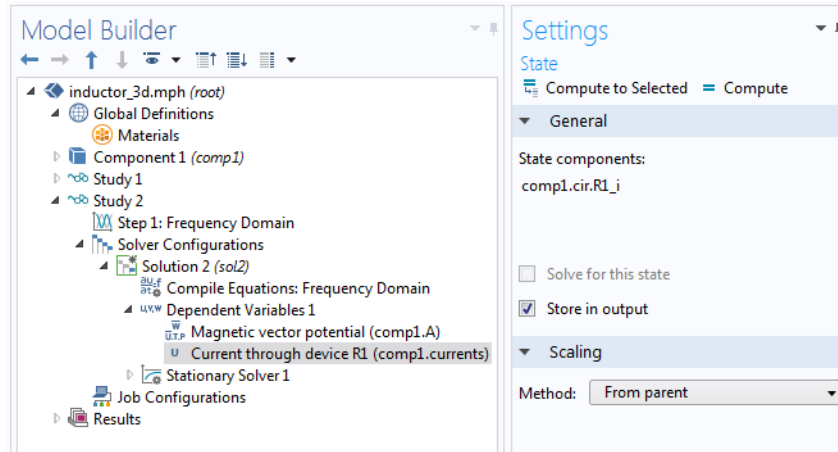
### **DETERMINING A CURRENT OR VOLTAGE VARIABLE NAME**

To determine a current or voltage variable name, look at the **Dependent Variables** node under the **Study** node. To do this:

- I In the **Model Builder**, right-click the **Study** node and select **Show Default Solver**.



- Expand the **Solver>Dependent Variables** node and click the state node, in this example, **Current through device R1 (comp1.currents)**. The variable name is shown in the **Settings** window for **State**.



Typically, voltage variables are named `cir.Xn_v` and current variables `cir.Xn_i`, where  $n$  is the “External” device number — 1, 2, and so on.

## Solving



Some modeling errors lead to the error message *The DAE is structurally inconsistent* being displayed when solving. This error typically occurs from having an open current loop, from connecting voltage sources in parallel, or connecting current sources in series.

In this respect, the predefined coupling features are also treated as (ideal) voltage or current sources. The remedy is to close current loops and to connect resistors in series with voltage sources or in parallel with current sources.

## Postprocessing

The Electrical Circuits interface, unlike most of the other physics interfaces, solves for a relatively large number of global dependent variables (such as voltages and currents),

instead of solving for a few space-varying fields (such as temperature or displacement). For this reason, the Electrical Circuit interface does not provide default plots when computing a study.

The physics interface defines a number of variables that can be used in postprocessing. All variables defined by the Electrical Circuit interface are of a global scope, and can be evaluated in a **Global Evaluation** node (under **Derived Values**). In addition, the time evolution or dependency on a parameter can be plotted in a **Global** plot (under a **ID Plot Group** node).

The physics interface defines a Node voltage variable for each electrical node in the circuit, with name `cir.v_name`, where `cir` is the physics interface Label and `<name>` is the node Name. For each two-pin component, the physics interface also defines variables containing the voltage across it and the current flowing through it.



In the *COMSOL Multiphysics Reference Manual*:

- [Derived Values, Evaluation Groups, and Tables](#) and [Global Evaluation](#)
- [Plot Groups and Plots](#) and [Global](#)

## References

1. V. Kaajakari, *Practical MEMS*, Small Gear Publishing, Las Vegas, 2009.
2. S.D. Senturia, *Microsystem Design*, Springer Science and Business Media, New York, 2001.
3. A.F. Bower, *Applied Mechanics of Solids*, CRC Press, Boca Raton, FL, 2010 (<http://www.solidmechanics.org>).

# SPICE Import and Export

The following text is a generic description of the SPICE Import and Export functionality available with various add-on products from COMSOL.

## *SPICE Import*

The circuit definition in COMSOL Multiphysics adheres to the SPICE format developed at the University of California, Berkeley ([Ref. 1](#)). SPICE netlists can be imported and the corresponding circuit nodes are generated in the COMSOL Multiphysics model. Most circuit simulators can export to this format or some version of it.

The Electrical Circuit interface supports the following device models:

TABLE 2-3: SUPPORTED SPICE DEVICE MODELS

| STATEMENT | DEVICE MODEL                                          |
|-----------|-------------------------------------------------------|
| R         | <a href="#">Resistor</a>                              |
| C         | <a href="#">Capacitor</a>                             |
| L         | <a href="#">Inductor</a>                              |
| V         | <a href="#">Voltage Source</a>                        |
| I         | <a href="#">Current Source</a>                        |
| E         | <a href="#">Voltage-Controlled Voltage Source</a>     |
| F         | <a href="#">Current-Controlled Current Source</a>     |
| G         | <a href="#">Voltage-Controlled Current Source</a>     |
| H         | <a href="#">Current-Controlled Voltage Source</a>     |
| D         | <a href="#">Diode</a>                                 |
| Q         | <a href="#">NPN BJT and PNP BJT</a>                   |
| M         | <a href="#">n-Channel MOSFET and p-Channel MOSFET</a> |
| X         | <a href="#">Subcircuit Instance</a>                   |

Statements corresponding to multiple devices are resolved by parsing the associated `.model` statement. The physics interface also supports the `.subckt` statement, which is represented in COMSOL by a [Subcircuit Definition](#) node, and the `.include` statement. SPICE commands are interpreted case-insensitively. The statement defining each device is also interpreted as the **Device name**.

According to SPICE specification, the first line in the netlist file is assumed to be the title of the netlist and it is ignored by the parser.

### *SPICE Export*

---

The **SPICE Export** functionality creates a SPICE netlist file containing a description of the circuit represented by the physics interface. This functionality can be accessed from the physics interface context menu (right-click the physics interface node and select **Export SPICE Netlist**). After specifying a filename, the circuit is exported and messages from the export process display in the **Messages** window. During the export process, a series of operations are performed:

- In order to avoid conflicts, each component must be identified by a unique **Device name**. If one or more components have the same device name, the export operation fails and an error message is displayed. All characters in a **Device name** that are not letters, digits or underscores are replaced by underscores.
- According to the SPICE specification, each circuit must have a node with name 0, which is assumed to be the only ground node. When exporting a circuit, any node with name 0 that is not connected to a **Ground** component is exported with a different node name. All nodes that are connected to a Ground components are exported as a merged node with name 0. The Messages window shows a log message if these operations are performed, showing the name of the renamed or merged nodes.
- All characters in node names that are not letters, digits or underscores are replaced by underscores.
- Some components (most notably, the **External** components used to couple to other physics interfaces) cannot be exported to a SPICE netlist. These components are ignored during the export process, and a message is shown in the Messages window. Note that this can change the exported circuit, since some components are then missing.
- Subcircuit definitions are added as `.subckt` statements in the netlist. Semiconductor devices (such as MOSFETs, BJTs, and diodes) are exported as a SPICE device with a corresponding `.model` statement.

The title of the exported netlist file is the model's filename, and the time, date, and version of COMSOL Multiphysics is added as a comment in the netlist file.

## *Reference*

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1. <http://bwrc.eecs.berkeley.edu/Classes/IcBook/SPICE/>



## AC/DC Interfaces

This chapter describes the physics interfaces found under the **AC/DC** branch .

In this chapter:

- [The Electrostatics Interface](#)
- [The Electrostatics, Boundary Elements Interface](#)
- [The Electric Currents Interface](#)
- [The Electrical Circuit Interface](#)
- [Theory for the Electrostatics Interface](#)
- [Theory for the Electric Currents Interface](#)
- [Theory for the Electrical Circuit Interface](#)

See the *COMSOL Multiphysics Reference Manual* for details about [The Magnetic Fields Interface](#) and the [Theory of Magnetic Fields](#).

# The Electrostatics Interface

The **Electrostatics (es)** interface (  ), found under the **AC/DC>Electric Fields and Currents** branch when adding a physics interface, is used to compute the electric field, electric displacement field, and potential distributions in dielectrics under conditions where the electric charge distribution is explicitly prescribed. The formulation is stationary except for use together with other physics interfaces. Eigenfrequency, frequency-domain, small-signal analysis, and time-domain modeling are supported in all space dimensions.

The physics interface solves Gauss' law for the electric field using the scalar electric potential as the dependent variable.

Charge Conservation is the main node, which adds the equation for the electric potential and has a Settings window for defining the constitutive relation for the electric displacement field and its associated properties such as the relative permittivity.

When this physics interface is added, these default nodes are also added to the **Model Builder** — **Charge Conservation**, **Zero Charge** (the default boundary condition), and **Initial Values**. Then, from the **Physics** toolbar, add other nodes that implement, for example, boundary conditions and space charges. You can also right-click **Electrostatics** to select physics features from the context menu.

### Physics-Controlled Mesh

The physics-controlled mesh is controlled from the **Mesh** node's **Settings** window (if the **Sequence type** is **Physics-controlled mesh**). There, in the table in the **Physics-Controlled Mesh** section, find the physics interface in the **Contributor** column and select or clear the check box in the **Use** column on the same table row for enabling (the default) or disabling contributions from the physics interface to the physics-controlled mesh.

Information from the physics, such as the presence of an infinite elements domain or periodic condition, will be used to automatically set up an appropriate meshing sequence.



In the *COMSOL Multiphysics Reference Manual* see the [Physics-Controlled Mesh](#) section for more information about how to define the physics-controlled mesh.



## SETTINGS

The **Label** is the default physics interface name.

The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the **name** string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `es`.

### CROSS-SECTION AREA (1D COMPONENTS)

For 1D components, enter a default value for the **Cross-section area**  $A$  (SI unit:  $\text{m}^2$ ). The default value of 1 is typically not representative for a thin domain. Instead it describes a unit thickness that makes the 1D equation identical to the equation used for 3D components. See also [Change Cross Section](#).

### THICKNESS (2D COMPONENTS)

For 2D components, enter a default value for the **Out-of-plane thickness**  $d$  (SI unit:  $\text{m}$ ). The default value of 1 is typically not representative for a thin dielectric medium, for example. Instead it describes a unit thickness that makes the 2D equation identical to the equation used for 3D components. See also [Change Thickness \(Out-of-Plane\)](#).

## MANUAL TERMINAL SWEEP SETTINGS

Enter a **Reference impedance**  $Z_{\text{ref}}$  (SI unit:  $\Omega$ ). The default is  $50\ \Omega$ .

Select the **Activate manual terminal sweep** check box to switch on the sweep and invoke a parametric sweep over the terminals. Enter a **Sweep parameter name** to assign a specific name to the variable that controls the terminal number solved for during the sweep. The **Sweep parameter name** must also be declared as a model parameter. The default is `PortName`.

The generated lumped parameters are in the form of capacitance matrix elements. The terminal settings must consistently be of either fixed voltage or fixed charge type.

The lumped parameters are subject to **Touchstone file export**. Enter a file path or **Browse** for a file. Select a **Parameter format (value pairs)** for the Touchstone export — **Magnitude and angle (MA)** (the default), **Magnitude in dB and angle (DB)**, or **Real and imaginary parts (RI)**. Select an option from the **If file exists** list — **Overwrite** or **Create new**. Create new is useful when the model is solved multiple times with different settings. Select a **Parameter to export**: **Z** (the default), **Y**, or **S**.

From the **Home** toolbar add a **Parameters** node and enter the chosen name and assign to it a temporary **Expression** of unity into the **Parameters** table. You can also right-click **Global Definitions** to add the node.

|                                                                                   |                                                                                                                                                                                                                                                                                                                                  |
|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>Only a temporary expression needs to be entered at this stage. During the analysis process, the solver assigns a proper value to this parameter. The generated lumped parameters are in the form of capacitance matrix elements. The terminal settings must consistently be of either fixed voltage or fixed charge type.</p> |
|  | <p>For most applications it is simpler to sweep over terminals using the Stationary Source Sweep study step. See <a href="#">Stationary Source Sweep</a> in the <i>COMSOL Multiphysics Reference Manual</i> and (for more details) <a href="#">Stationary Source Sweep</a> in the <i>AC/DC Module User's Guide</i>.</p>          |

## DEPENDENT VARIABLES

The dependent variable is the **Electric potential**  $V$ . You can change its name, which changes both the field name and the variable name. If the new name coincides with the name of another electric potential field in the model, the physics interfaces shares degrees of freedom. The new name must not coincide with the name of a field of another type or with a component name belonging to some other field.

## DISCRETIZATION

Select the shape order for the **Electric potential** dependent variable — **Linear**, **Quadratic** (the default), **Cubic**, **Quartic**, or **Quintic**. For more information about the **Discretization** section, see [Settings for the Discretization Sections](#) in the *COMSOL Multiphysics Reference Manual*.

|                                                                                     |                                                                                                                                                                                                                                                                                                               |
|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>In the <i>COMSOL Multiphysics Reference Manual</i>, see <a href="#">Table 2-4</a> for links to common sections and <a href="#">Table 2-5</a> to common feature nodes. You can also search for information: press F1 to open the <b>Help</b> window or Ctrl+F1 to open the <b>Documentation</b> window.</p> |
|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

|                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                                                                                                                                           | <ul style="list-style-type: none"><li>• <a href="#">Domain, Boundary, Edge, Point, and Pair Nodes for the Electrostatics Interface</a></li><li>• <a href="#">Theory for the Electrostatics Interface</a></li></ul>     |
|                                                                                                                                                                                                                                                                                           | <i>Electric Sensor</i> : Application Library path <b>COMSOL_Multiphysics/Electromagnetics/electric_sensor</b>                                                                                                          |
| <hr/>                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                        |
| <i>Domain, Boundary, Edge, Point, and Pair Nodes for the Electrostatics Interface</i>                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                        |
| <hr/>                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                        |
| <p>The Electrostatics interface has these domain, boundary, edge, point, and pair nodes available.</p>                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                        |
| <p><b>ABOUT THE BOUNDARY CONDITIONS</b></p>                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                        |
| <p>The relevant physics interface condition at interfaces between different media is</p>                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                        |
| $\mathbf{n}_2 \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                        |
| <p>In the absence of surface charges, this condition is fulfilled by the natural boundary condition</p>                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                        |
| $\mathbf{n} \cdot [(\epsilon_0 \nabla V - \mathbf{P})_1 - (\epsilon_0 \nabla V - \mathbf{P})_2] = -\mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = 0$                                                                                                                                                                                                                     |                                                                                                                                                                                                                        |
| <p><b>AVAILABLE NODES</b></p>                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                        |
| <p>These nodes, listed in alphabetical order, are available from the <b>Physics</b> ribbon toolbar (Windows users), <b>Physics</b> context menu (Mac or Linux users), or right-click to access the context menu (all users). Also see <a href="#">Table 3-1</a> for a list of interior and exterior boundary conditions, including edge, point, and pair availability.</p> |                                                                                                                                                                                                                        |
|                                                                                                                                                                                                                                                                                         | <p>In general, to add a node, go to the <b>Physics</b> toolbar no matter what operating system you are using. Subnodes are available by clicking the parent node and selecting it from the <b>Attributes</b> menu.</p> |

- Change Cross Section
- Change Thickness (Out-of-Plane)
- Charge Conservation
- Charge Conservation, Piezoelectric<sup>1,2</sup>
- Charge Conservation, Ferroelectric<sup>2,3</sup>
- Conduction Loss (Time-Harmonic)
- Dielectric Shielding
- Distributed Capacitance
- Electric Displacement Field
- Electric Potential
- Electrostatic Point Dipole
- External Surface Charge Accumulation
- Floating Potential
- Force Calculation
- Ground
- Initial Values
- Line Charge
- Line Charge (on Axis)
- Line Charge (Out-of-Plane)
- Periodic Condition
- Point Charge
- Point Charge (on Axis)
- Space Charge Density
- Surface Charge Density
- Terminal
- Thin Low Permittivity Gap
- Zero Charge (the default boundary condition)

<sup>1</sup> This feature is available with the Piezoelectricity multiphysics interface.

<sup>2</sup> Requires the Acoustics Module, MEMS Module, or the Structural Mechanics Module.

<sup>3</sup> This feature is available with the Ferroelectroelasticity multiphysics interface.

Table 3-1 lists the interior and exterior boundary conditions available with this physics interface. It also includes edge, point, and pair availability.

TABLE 3-1: INTERIOR AND EXTERIOR BOUNDARY CONDITIONS (INCLUDING EDGE, POINT, AND PAIR AVAILABILITY) FOR THE ELECTROSTATICS INTERFACE

| NODE                            | INTERIOR | EXTERIOR | ALSO AVAILABLE FOR       |
|---------------------------------|----------|----------|--------------------------|
| Change Cross Section            | x        | x        | pairs                    |
| Change Thickness (Out-of-Plane) | x        | x        | pairs                    |
| Dielectric Shielding            | x        | x        | pairs                    |
| Distributed Capacitance         | x        | x        | pairs                    |
| Electric Displacement Field     | x        | x        | pairs                    |
| Electric Potential              | x        | x        | edges, points, and pairs |

TABLE 3-1: INTERIOR AND EXTERIOR BOUNDARY CONDITIONS (INCLUDING EDGE, POINT, AND PAIR AVAILABILITY) FOR THE ELECTROSTATICS INTERFACE

| NODE                                 | INTERIOR | EXTERIOR | ALSO AVAILABLE FOR       |
|--------------------------------------|----------|----------|--------------------------|
| External Surface Charge Accumulation |          | x        | pairs                    |
| Floating Potential                   | x        | x        | pairs                    |
| Ground                               | x        | x        | edges, points, and pairs |
| Periodic Condition                   |          | x        | not applicable           |
| Surface Charge Density               | x        | x        | pairs                    |
| Terminal                             | x        | x        | domains                  |
| Thin Low Permittivity Gap            | x        |          | not applicable           |
| Zero Charge (the default)            | x        | x        | pairs                    |



For axisymmetric components, COMSOL Multiphysics takes the axial symmetry boundaries (at  $r = 0$ ) into account and automatically adds an **Axial Symmetry** node to the model that is valid on the axial symmetry boundaries only. There are also **Line Charge (on Axis)** and **Point Charge (on Axis)** available.



In the *COMSOL Multiphysics Reference Manual*, see [Table 2-4](#) for links to common sections and [Table 2-5](#) to common feature nodes. You can also search for information: press F1 to open the **Help** window or Ctrl+F1 to open the **Documentation** window.

### Charge Conservation

The **Charge Conservation** node adds the equations for charge conservation according to Gauss' law for the electric displacement field. It provides an interface for defining the constitutive relation and its associated properties such as the relative permittivity.

### MATERIAL TYPE

The **Material type** setting decides how materials behave and how material properties are interpreted when the mesh is deformed. Select **Solid** for materials whose properties change as functions of material strain, material orientation, and other variables evaluated in a material reference configuration (material frame). Select **Nonsolid** for materials whose properties are defined only as functions of the current local state at each point in the spatial frame, and for which no unique material reference

configuration can be defined. Select **From material** to pick up the corresponding setting from the domain material on each domain.

#### CONSTITUTIVE RELATION **D-E**

Select a **Dielectric model** to describe the macroscopic properties of the medium (relating the electric displacement **D** with the electric field **E**) and the applicable material properties, such as the relative permittivity. Select:

- **Relative permittivity** (the default) to use the constitutive relation  $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$ . Then the default is to take the **Relative permittivity**  $\epsilon_r$  (dimensionless) values **From material**. For **User defined**, select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** and enter values or expressions in the field or matrix. The default is 1.
- **Polarization** to use the constitutive relation  $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$ . Then enter the components based on space dimension for the **Polarization** vector **P** (SI unit: C/m<sup>2</sup>). The defaults are 0 C/m<sup>2</sup>.
- **Remanent electric displacement** to use constitutive relation  $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} + \mathbf{D}_r$ , where **D<sub>r</sub>** is the remanent displacement (the displacement when no electric field is present). Then the default is to take the **Relative permittivity**  $\epsilon_r$  (dimensionless) values **From material**. For **User defined**, select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** and enter values or expressions in the field or matrix. Then enter the components based on space dimension for the **Remanent electric displacement** **D<sub>r</sub>** (SI unit: C/m<sup>2</sup>). The defaults are 0 C/m<sup>2</sup>.

#### *Conduction Loss (Time-Harmonic)*



This feature requires the Acoustics Module, MEMS Module, or the Structural Mechanics Module. See the individual documentation for information.

The **Conduction Loss (Time-Harmonic)** subnode allows you to model possible conductive losses in a dielectric material. The effect is only active in a Eigenfrequency or Frequency response study.

## CONDUCTION CURRENT

By default, the **Electrical conductivity**  $\sigma$  for the media is defined **From material**. You can also select **User defined** or **Linearized resistivity**.

- For **User defined** select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** depending on the characteristics of the electrical conductivity, and then enter values or expressions for the **Electrical conductivity**  $\sigma$  in the field or matrix.
- For **Linearized resistivity** the default **Reference temperature**  $T_{\text{ref}}$ , and **Resistivity temperature coefficient**  $\alpha$ , and **Reference resistivity**  $\rho_0$  are taken **From material**, which means that the values are taken from the domain (or boundary) material.  $T$  is the current temperature, which can be a value that is specified as a model input or the temperature from a heat transfer interface. The definition of the temperature field appears in the **Model Inputs** section.

## LOCATION IN USER INTERFACE

### *Context Menus*

**Electrostatics>Charge Conservation>Conduction Loss (Time-Harmonic)**

### *Ribbon*

Physics tab with **Charge Conservation** node selected in the model tree:

**Attributes>Conduction Loss (Time-Harmonic)**

### *Initial Values*

---

The **Initial Values** node adds an initial value for the electric potential  $V$  that can serve as an initial condition for a transient simulation or as an initial guess for a nonlinear solver.

## INITIAL VALUES

Enter a value or expression for the initial value of the **Electric potential**  $V$  (SI unit: V). The default value is 0 V.

### *Space Charge Density*

---

The **Space Charge Density** node adds a space charge density  $\rho$ , which appears on the right-hand side of the equation that the physics interface defines.

## SPACE CHARGE DENSITY

Enter a value or expression for the **Space charge density**  $\rho_v$  (SI unit: C/m<sup>3</sup>). The default is 0 C/m<sup>3</sup>.

## Force Calculation

---

Use the **Force Calculation** node to define globally available force and torque variables for the selected domains.

### FORCE CALCULATION

Enter a **Force name**, which is then appended to global variables. The method used to compute forces and torques is integration of the Maxwell's stress tensor over the exterior surfaces of the set of domains. This feature also gives access to the normal component of the Maxwell stress tensor on the external surfaces. The computed force is made available as a global vector variable with name `es.Force<component>_<force name>`.

Enter a direction vector for the **Torque axis**  $\mathbf{r}_{ax}$  and coordinates for the **Torque rotation point**  $\mathbf{r}_0$ . A torque calculation about a given point (**Torque rotation point**) is made and defined as a global vector variable, `es.T<component>_<force name>`. The resulting torque component parallel to the given **Torque axis** is given as a global scalar variable, typically `es.Tax_<force name>`.

In frequency domain studies, the cycle-averaged force and torque variables are also defined, with names `es.Forceav<component>_<force name>`, `es.Tav<component>_<force name>` and `es.Taxav_<force name>`. The variables described are still defined and represent the instantaneous force and torque.



In small-signal analysis studies, no cycle-average variables are defined. Use the additional plot settings for the Harmonic Perturbation on the instantaneous variables to compute the quantities of interest. See [Harmonic Perturbation, Prestressed Analysis, and Small-Signal Analysis](#) in the *COMSOL Multiphysics Reference Manual*.



For more information on calculation of forces and torques, see [Electrostatics](#).



## ADVANCED SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

The **Compute both instantaneous and cycle-averaged variables in frequency domain** check box is selected by default. The check box controls which variables are defined by the Force Calculation feature in frequency-domain studies. When selected (the default setting in new models), the variables are defined as described above. This check box selected by default for backward compatibility. If the check box is cleared, only the cycle-averaged variables are computed, replicating the behavior of the Force Calculation feature in version 4.3 and earlier. The check box is cleared in existing Force Calculation features when opening models created in version 4.3 and earlier.

### *Zero Charge*

---

The **Zero Charge** node adds the condition that there is zero charge on the boundary so that  $\mathbf{n} \cdot \mathbf{D} = 0$ . This boundary condition is also applicable at symmetry boundaries where the potential is known to be symmetric with respect to the boundary. This is the default boundary condition at exterior boundaries. At interior boundaries, it means that no displacement field can penetrate the boundary and that the electric potential is discontinuous across the boundary.

### *Ground*

---

The **Ground** node implements ground (zero potential) as the boundary condition  $V = 0$ .

Ground means that there is a zero potential on the boundary. This boundary condition is also applicable at symmetry boundaries where the potential is known to be antisymmetric with respect to the boundary.

For some physics interfaces, also select additional **Ground** nodes from the **Edges** (3D components) or **Points** (2D and 3D components) submenus. For 2D axisymmetric components, it can be applied on the Symmetry axis.

## BOUNDARY, EDGE, OR POINT SELECTION



Beware that constraining the potential on edges or points in 3D or on points in 2D usually yields a current outflow that is mesh dependent.

---

## CONSTRAINT SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

### *Electric Potential*

---

The **Electric Potential** node provides an electric potential  $V_0$  as the boundary condition  $V = V_0$ .

Because the electric potential is being solved for in the physics interface, the value of the potential is typically defined at some part of the geometry. For some physics interfaces, also select additional **Electric Potential** nodes from the **Edges** (3D components) or **Points** (2D and 3D components) submenus. For 2D axisymmetric components, it can be applied on the symmetry axis.

## BOUNDARY, EDGE, OR POINT SELECTION



Beware that constraining the potential on edges or points in 3D or on points in 2D usually yields a current outflow that is mesh dependent.

## ELECTRIC POTENTIAL

Enter the value or expression for the **Electric potential**  $V_0$  (SI unit: V). The default is 0 V.

## CONSTRAINT SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

### *Surface Charge Density*

---

The **Surface Charge Density** node provides the following surface-charge boundary condition for exterior boundaries (left) and interior boundaries (right):

$$-\mathbf{n} \cdot \mathbf{D} = \rho_s, \quad \mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$$

Specify the surface charge density  $\rho_s$  at an outer boundary or at an interior boundary between two nonconducting media.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or click **Harmonic Perturbation** on the **Physics** toolbar. For more information, see

Harmonic Perturbation — Exclusive and Contributing Nodes in the *COMSOL Multiphysics Reference Manual*.

### **SURFACE CHARGE DENSITY**

Enter the value or expression for the **Surface charge density**  $\rho_s$  (SI unit: C/m<sup>2</sup>).

#### *External Surface Charge Accumulation*

---

The **External Surface Charge Accumulation** node implements the boundary condition

$$-\mathbf{n} \cdot \mathbf{D} = \rho_s$$

where  $\rho_s$  is the solution of the following distributed ODE on the boundary:

$$\frac{d\rho_s}{dt} = \mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e$$

where  $\mathbf{n} \cdot \mathbf{J}_i$  is the normal component of the total ion current density on the wall and  $\mathbf{n} \cdot \mathbf{J}_e$  is the normal component of the total electron current density on the wall, which are feature inputs.

### **MATERIAL TYPE**

The **Material type** setting decides how materials behave and how material properties are interpreted when the mesh is deformed. Select **Solid** for materials whose properties change as functions of material strain, material orientation, and other variables evaluated in a material reference configuration (material frame). Select **Nonsolid** for materials whose properties are defined only as functions of the current local state at each point in the spatial frame, and for which no unique material reference configuration can be defined. Select **From material** to pick up the corresponding setting from the domain material on each domain.

### **EXTERNAL SURFACE CHARGE ACCUMULATION**

Enter values or expressions for the **Normal ion current density**  $\mathbf{n} \cdot \mathbf{J}_i$  (SI unit: A/m<sup>2</sup>) and the **Normal electron current density**  $\mathbf{n} \cdot \mathbf{J}_e$  (SI unit: A/m<sup>2</sup>).

#### *Electric Displacement Field*

---

The **Electric Displacement Field** node adds the following electric-displacement boundary condition:

$$\mathbf{n} \cdot \mathbf{D} = \mathbf{n} \cdot \mathbf{D}_0$$

It specifies the normal component of the electric displacement field at a boundary.

### ELECTRIC DISPLACEMENT FIELD

Enter the coordinates of the **Boundary electric displacement field  $\mathbf{D}_0$**  (SI unit: C/m<sup>2</sup>).

### *Periodic Condition*

The **Periodic Condition** node defines periodicity or antiperiodicity between two boundaries. If required, activate periodic conditions on more than two boundaries, in which case the Periodic Condition tries to identify two separate surfaces that can each consist of several connected boundaries. For more complex geometries, it might be necessary to use the **Destination Selection** subnode. With this subnode the boundaries which constitute the source and destination surfaces can be manually specified. The **Destination Selection** subnode is available from the context menu (right-click the parent node) as well as from the **Physics** toolbar, **Attributes** menu.



When this feature is used in conjunction with a [Sector Symmetry](#) feature on connected boundaries, wherever the sector symmetry boundaries connect with the periodic boundaries, the same periodic condition feature cannot be used on both sides. At least two periodic condition features are required for the model to compute correctly.

### BOUNDARY SELECTION

When using nonconforming meshes on the source and destination of a periodic boundary pair, for numerical stability, a finer mesh should be applied on the destination side. Use conforming meshes if possible.

### PERIODIC CONDITION

Select a **Type of periodicity** — **Continuity** (the default), **Antiperiodicity**, or **Floquet periodicity**. Select:

- **Continuity** to make the electric potential periodic (equal on the source and destination).
- **Antiperiodicity** to make it antiperiodic.
- **Floquet periodicity** (only available with products supporting piezoelectric modeling). Specify the components of the **k-vector for Floquet periodicity  $\mathbf{k}_F$**  (SI unit: rad/m).

## CONSTRAINT SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

For information about the Orientation of Source section, see [Orientation of Source and Destination](#).

### *Thin Low Permittivity Gap*

---

Use the **Thin Low Permittivity Gap** node

$$\mathbf{n} \cdot \mathbf{D}_1 = \frac{\epsilon_0 \epsilon_r}{d} (V_1 - V_2)$$

$$\mathbf{n} \cdot \mathbf{D}_2 = \frac{\epsilon_0 \epsilon_r}{d} (V_2 - V_1)$$

to model a thin gap of a material with a small permittivity compared to the adjacent domains. The layer has the thickness  $d$  and the relative permittivity  $\epsilon_r$ . The indices 1 and 2 refer to the two sides of the boundary.

#### THIN LOW PERMITTIVITY GAP

The default is to take the **Relative permittivity**  $\epsilon_r$  (dimensionless) values **From material**. For **User defined**, enter a different value or expression. Enter a **Thickness**  $d$  (SI unit: m). The default is 5 mm.

### *Dielectric Shielding*

---

The **Dielectric Shielding** node adds dielectric shielding as a boundary condition. It describes a thin layer with thickness  $d_s$  and a bulk relative permittivity  $\epsilon_r$  that shields the electric field:

$$\mathbf{n} \cdot \mathbf{D} = -\nabla_t \cdot \epsilon_0 \epsilon_{rs} d_s \nabla_t V$$

Use this boundary condition when approximating a thin domain with a boundary to reduce the number of mesh elements.

#### MATERIAL TYPE

The **Material type** setting decides how materials behave and how material properties are interpreted when the mesh is deformed. Select **Solid** for materials whose properties change as functions of material strain, material orientation and other variables evaluated in a material reference configuration (material frame). Select **Nonsolid** for

materials whose properties are defined only as functions of the current local state at each point in the spatial frame, and for which no unique material reference configuration can be defined. Select **From material** to pick up the corresponding setting from the domain material on each domain.

### ELECTRIC SHIELDING

The default is to take the **Relative permittivity**  $\epsilon_r$  (dimensionless) values **From material**. It takes it from the adjacent domains if not explicitly defined. For **User defined** select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** and enter values or expressions in the field or matrix. Enter a **Surface thickness**  $d_s$  (SI unit: m) of the shielding. The default is 1 m.

### *Terminal*

---

The **Terminal** node provides a boundary or domain condition for connection to external circuits, to transmission lines, or with a specified voltage or charge. By specifying zero charge, a floating potential condition is obtained.

The **Terminal** node also enables the computation of the lumped parameters of the system, such as capacitance.

### TERMINAL

Specify the terminal properties. Enter a unique **Terminal name** that will be used to identify the global variables (such as the terminal voltage or current) that are defined by the terminal. The **Terminal name** can contain alphanumeric characters, but it should be numeric when performing terminal sweeps.

Select a **Terminal type** — **Charge** (the default), **Voltage**, **Circuit**, or **Terminated**. Select:

- **Charge** to prescribe the total charge deposited on the terminal boundaries. Enter the total charge  $Q_0$ . The default is 0 C, which corresponds to a uncharged floating electrode.
- **Voltage** to specify a fixed electric potential at the terminal. Enter an electric potential  $V_0$ . The default is 1 V.
- **Circuit** to specify a terminal connected to an Electrical Circuit physics interface that models an external circuit. The Terminal node provides a current-voltage characteristic to the circuit.
- **Terminated** to connect the terminal to an impedance that might represent a load or a transmission line. When **Terminated** is selected, the scattering parameters

(S-parameters) are computed. The **Terminated** setting can only be used in frequency-domain studies.

- Enter a **Terminal power**  $P_0$  to specify the input power at this terminal from the transmission line. This excitation can be toggled using a port sweep.
- Select an option from the **Characteristic impedance from** list to define the value of the impedance — **Physics interface** or **User defined**. For **Physics interface** the **Reference impedance**  $Z_{\text{ref}}$  defined on the **Settings** window for the physics under Sweep Settings is used. For **User defined** enter a specific impedance  $Z_{\text{ref}}$  for this terminal. The default is 50  $\Omega$ .

#### *Initial values*

The initial values subsection is used to provide initial values for the internal state variables in the Terminal. These settings can be useful to provide an initial guess to the nonlinear solver or the initial value in a time-dependent study.

The **Initial value for voltage** is available for all Terminal types except Voltage. Enter an **Initial value for voltage**  $V_{\text{init}}$ .

The **Initial value for charge** is available for the Circuit excitation. It specifies the initial charge on the terminal when the circuit is connected. Enter an **Initial value for charge**  $Q_{\text{init}}$ .

#### **CONSTRAINT SETTINGS**

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

#### *Floating Potential*

The **Floating Potential** node is used when modeling a metallic electrode at floating potential. It applies a constant voltage  $V_0$  on the boundary (for domain features, this is the boundary enclosing the selected domain), such that the total normal electric displacement field  $\mathbf{D}$  equals a specific charge  $Q_0$ :

$$V = V_0$$

$$\int_{\partial\Omega} (\mathbf{D} \cdot \mathbf{n}) dS = Q_0,$$

where  $\partial\Omega$  represents the boundary and  $\mathbf{n}$  refers to the surface normal. The constant boundary voltage implies the tangential electric field equals zero; the electric field will be perpendicular to the boundary:

$$-\nabla_t V = \mathbf{E}_t = 0$$

$$\mathbf{n} \times \mathbf{E} = 0.$$

In case of  $Q_0 = 0$  (the default case), the boundary will behave as an unconnected, neutrally charged, good conductor under electrostatic conditions (a floating equipotential). Although locally the displacement field may vary, the total electric displacement field entering or leaving the boundary equals zero.

If the floating potential touches a point, boundary or domain feature that is not floating (a **Terminal** or **Ground** feature), the floating potential will acquire that feature's potential. If the floating potential is set to a certain charge, or connected to a circuit, it behaves like a terminal.

### FLOATING POTENTIAL

The **Floating potential identifier** text area shows the unique identifier for the floating potential feature. It is used to identify the global variables created by the node, such as the voltage. The **Floating potential group** check box on the **Settings** window for **Floating Potential** controls how potentials are assigned to boundary segments in the feature's boundary selection. If this check box is not selected, a single potential is applied to all boundaries in the selection. If the check box is selected, each group of contiguous boundaries in the selection is given a unique potential. This simplifies the setup of models with many floating electrodes. The values of the potential at each group of boundaries are then made available in postprocessing, collected in a vector variable.

The following options are not available if the **Floating potential group** check box is selected. Select a specification for the **Electric charge** — choose **User defined** to specify a total **Charge**  $Q_0$  deposited on the surface. Select **Circuit** to connect the floating potential to an Electrical Circuit.

#### *Initial Values*

The initial values subsection is used to provide initial values for the internal state variables in the Floating potential. These settings can be useful to provide an initial guess to the nonlinear solver or the initial value in a time-dependent study.

Enter an **Initial value for voltage**  $V_{\text{init}}$ .

The **Initial value for charge** is available for the Circuit excitation. It specifies the initial charge on the floating potential when the circuit is connected. Enter an **Initial value for charge**  $Q_{\text{init}}$ .



## CONSTRAINT SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.



Settings and Properties Windows for Feature Nodes in the *COMSOL Multiphysics Reference Manual*

### *Distributed Capacitance*

The **Distributed Capacitance** node adds a distributed capacitance boundary condition according to the following equations for exterior boundaries (left) and interior boundaries (right):

$$-\mathbf{n} \cdot \mathbf{D} = \epsilon_0 \epsilon_r \frac{V_{\text{ref}} - V}{d_s} \quad \mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \epsilon_0 \epsilon_r \frac{V_{\text{ref}} - V}{d_s}$$

Use this boundary condition to model a thin sheet or film of a dielectric material. The sheet has the relative permittivity  $\epsilon_r$  and the surface thickness  $d_s$ , and it is connected to the reference potential  $V_{\text{ref}}$ .

#### DISTRIBUTED CAPACITANCE

Enter the values or expressions for **Relative permittivity**  $\epsilon_r$  (dimensionless), **Surface thickness**  $d_s$  (SI unit: m), and **Reference potential**  $V_{\text{ref}}$ . The default value for the surface thickness is  $10^{-3}$  m (1 mm) and 0 V for the reference potential.

### *Line Charge*

For 3D components, use the **Line Charge** node to specify line charges along the edges of a geometry. Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

#### EDGE SELECTION



Beware that constraining the potential on edges usually yields a current outflow that is mesh dependent.

## LINE CHARGE

Enter a value or expression to apply a **Line charge**  $Q_L$  (SI unit: C/m). This source represents electric charge per unit length and the default is 0 C/m.



Line Charge (on Axis) and Line Charge (Out-of-Plane)

### *Line Charge (on Axis)*

For 2D axisymmetric components, use the **Line Charge (on Axis)** node to specify line charges along the symmetry axis.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or click **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

## LINE CHARGE (ON AXIS)

Enter a value or expression to apply a **Line charge**  $Q_L$  (SI unit: C/m). This source represents electric charge per unit length and the default is 0 C/m.



Line Charge and Line Charge (Out-of-Plane)

### *Line Charge (Out-of-Plane)*

For 2D and 2D axisymmetric components, points are selected and this is the same as a line out-of-plane.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

Use the **Line Charge (Out-of-Plane)** node to specify line charges along the points of a geometry for 2D and 2D axisymmetric components.

## POINT SELECTION



Beware that constraining the potential on points usually yields a current outflow that is mesh dependent.

### LINE CHARGE (OUT-OF-PLANE)

Enter a value or expression to apply a **Line charge**  $Q_L$  (SI unit: C/m). This source represents electric charge per unit length and the default is 0 C/m.



[Line Charge](#) and [Line Charge \(on Axis\)](#)

### *Point Charge*

The **Point Charge** node adds a point source to 3D components. The point charge represents an electric displacement field flowing out of the point.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

## POINT SELECTION



Beware that constraining the potential on points usually yields a current outflow that is mesh dependent.

### POINT CHARGE

Enter a value or expression to apply a **Point charge**  $Q_P$  (SI unit: C) to points. This source represents an electric displacement field flowing out of the point. The default is 0 C.



[Point Charge \(on Axis\)](#) and [Line Charge \(Out-of-Plane\)](#)

## Point Charge (on Axis)

---

The **Point Charge (on Axis)** node adds a point source to 2D axisymmetric components. The point charge represents an electric displacement field flowing out of the point.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

### POINT SELECTION



Beware that constraining the potential on points usually yields a current outflow that is mesh dependent.

---

### POINT CHARGE (ON AXIS)

Enter a value or expression to apply a **Point charge**  $Q_P$  (SI unit: C) to points on an axis. This source represents an electric displacement field flowing out of the point. The default is 0 C.



[Point Charge](#) and [Line Charge \(Out-of-Plane\)](#)

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## Change Cross Section

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This node is available with 1D components. This setting overrides the global **Cross-Section Area** setting made in any physics interface that uses this feature. For 2D components, see [Change Thickness \(Out-of-Plane\)](#).

Use the **Change Cross Section** node to set the cross-section area for specific geometric entities.

### CHANGE CROSS SECTION

Enter a value or expression for the **Cross-section area**  $A$ . The default value of 1 unit length is typically not representative for a thin domain. Instead it describes a unit thickness that makes the 1D equation identical to the equation used for 3D components.

### *Change Thickness (Out-of-Plane)*

---

This node is available for 2D components. This setting overrides the global **Thickness** setting made in any physics interface that uses this node. For 1D components, see [Change Cross Section](#).

Use the **Change Thickness (Out-of-Plane)** node to set the out-of-plane thickness for specific geometric entities.

#### **CHANGE THICKNESS (OUT-OF-PLANE)**

Enter a value or expression for the **Out-of-plane thickness**  $d$  (SI unit: m). The default value is, in most cases, 1 unit length, which is typically not representative for a thin domain. Instead it describes a unit thickness that makes the 2D equation identical to the equation used for 3D components.

### *Charge Conservation, Ferroelectric*

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This feature is available with the Ferroelectroelasticity multiphysics interface which requires the Acoustics Module, MEMS Module, or the Structural Mechanics Module. See [Ferroelectricity](#) and [Ferroelectroelasticity](#) for more information.

The **Charge Conservation, Ferroelectric** node is normally used together with a **Electrostriction** multiphysics coupling node and **Solid Mechanics** interface. The node is added by default to the **Electrostatics** interface when adding a Ferroelectroelasticity interface. It is also available from the context menu (right-click the **Electrostatics** interface parent node) or from the **Physics** toolbar.

### *Charge Conservation, Piezoelectric*

---



This feature is available with the Piezoelectricity interface, which requires the Acoustics Module, MEMS Module, or the Structural Mechanics Module. See the individual documentation for information.

The **Charge Conservation, Piezoelectric** node is normally used together with a **Piezoelectric Effect** multiphysics coupling node and a corresponding **Piezoelectric Material** node in the **Solid Mechanics** interface. The node is added by default to the

**Electrostatics** interface when adding a Piezoelectricity interface. It is also available from the context menu (right-click the **Electrostatics** interface parent node) or from the **Physics** toolbar.



When the **Charge Conservation, Piezoelectric** node is added to the electrostatics interface in the absence of an active **Piezoelectric Effect** multiphysics coupling node, the material behaves similarly to a **Charge Conservation** node, with electric properties corresponding to the relative permittivity entered (see below). The piezoelectric effect is *not* included in the corresponding equation system.

## ELECTRIC DISPLACEMENT

If the node is used together with an active **Piezoelectric Effect** multiphysics coupling node, then these settings are locked. Note that if they are unlocked, then the material behaves like a dielectric and *not* a piezoelectric. In this case, the default is to take the **Relative permittivity**  $\epsilon_{TS}$  (dimensionless) values **From material**. For **User defined**, select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** and enter values or expressions in the field or matrix.

### *Electrostatic Point Dipole*

Add an **Electrostatic Point Dipole** node to 3D and 2D components. Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or click **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

The **Electrostatic Point Dipole** represents the limiting case of zero separation distance between two equally strong point sources of opposing signs while maintaining the product between separation distance and source strength at a fixed value ( $p$ ). The dipole moment is a vector entity with positive direction from the negative charge to the positive one.

## ELECTROSTATIC POINT DIPOLE

Select a **Dipole specification** — **Magnitude and direction** (the default) or **Electric dipole moment**.

- For **Magnitude and direction** enter coordinates for the **Electric dipole moment direction**  $\mathbf{n}_p$  (dimensionless) and the **Electric dipole moment, magnitude**  $p$ .
- For **Electric dipole moment** enter coordinates for the **Electric dipole moment**  $\mathbf{p}$ .

# The Electrostatics, Boundary Elements Interface

The **Electrostatics, Boundary Elements (esbe)** interface () , found under the **AC/DC>Electric Fields and Currents** branch when adding a physics interface, is used for computing the potential distribution in dielectrics under conditions where the electric potential distribution on the boundaries is explicitly prescribed. The formulation is based on the boundary element method and the interface is available in 2D and 3D.

The physics interface solves Laplace’s equation for the electric potential using the scalar electric potential as the dependent variable

$$-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = 0 .$$



For a discussion about the boundary element method, see [Theory for the Boundary Elements PDE](#) in the *COMSOL Multiphysics Reference Manual*.

When this physics interface is added, these default nodes are also added to the **Model Builder** — **Charge Conservation, Zero Charge** (on exterior boundaries and in 3D also on interior edges) and **Initial Values**. Then, from the **Physics** toolbar, add other nodes that implement, for example, electric potential and surface charge density conditions. You can also right-click **Electrostatics, Boundary Elements** to select physics features from the context menu.



If both [The Electrostatics Interface](#) and [The Electrostatics, Boundary Elements Interface](#) are available, the [Electric Scalar-Scalar Potential Coupling](#) node is available from the **Multiphysics** menu in the **Physics** toolbar or by right-clicking the **Multiphysics Couplings** node in **Model Builder**.



The [Electrostatics Interface](#) and [The Electrostatics, Boundary Elements Interface](#) can also be coupled by using the same name for the dependent variable for both interfaces. Then [Electric Scalar-Scalar Potential Coupling](#) is not needed. How to set the name for the dependent variable is described in the [Dependent Variables](#) section.



### Physics-Controlled Mesh

The physics-controlled mesh is controlled from the **Mesh** node's **Settings** window (if the **Sequence type** is **Physics-controlled mesh**). There, in the table in the **Physics-Controlled Mesh** section, find the physics interface in the **Contributor** column and select or clear the check box in the **Use** column on the same table row for enabling (the default) or disabling contributions from the physics interface to the physics-controlled mesh.

Information from the physics will be used to automatically set up an appropriate mesh sequence.



In the *COMSOL Multiphysics Reference Manual* see the [Physics-Controlled Mesh](#) section for more information about how to define the physics-controlled mesh.

### DOMAIN SELECTION

From the **Selection** list, select any of the options — **Manual**, **All domains**, **All voids**, or **All domains and voids** (the default). The geometric entity list displays the selected domain entity numbers. Edit the list of selected domain entity numbers using the selection toolbar buttons to the right of the list or by selecting the geometric entities in the **Graphics** window. Entity numbers for voids can be entered by clicking the Paste () button in the selection toolbar and supplying the entity numbers in the in the dialog box. The entity number for the infinite void is 0, and finite voids have negative entity numbers.

Selections can also be entered using the **Selection List** window, available from the **Windows** menu on the **Home** toolbar.



For more information about making selections, see [Working with Geometric Entities](#) in the *COMSOL Multiphysics Reference Manual*.

### PHYSICS SYMBOLS

Select the **Enable physics symbols** check box to display symmetry planes (in 3D) and lines (in 2D) in the **Graphics** window, as specified in the [Symmetry](#) settings.

### THICKNESS (2D COMPONENTS)

For 2D components, enter a default value for the **Out-of-plane thickness**  $d$  (SI unit: m). The default value of 1 is typically not representative for a thin dielectric medium.

Instead it describes a unit thickness that makes the 2D equation identical to the equation used for 3D components.

### MANUAL TERMINAL SWEEP SETTINGS

Select the **Activate manual terminal sweep** check box to invoke a parametric sweep over terminals. Enter a **Sweep parameter name** to assign a specific name to the variable that controls the terminal number solved for during the sweep. The **Sweep parameter name** must also be declared as a model parameter. The default is PortName.



For most applications it is simpler to sweep over terminals using the Stationary Source Sweep study step. See [Stationary Source Sweep](#) in the *COMSOL Multiphysics Reference Manual* and (for more details) [Stationary Source Sweep](#) in the [Modeling with the AC/DC Module](#) chapter of this manual.



To correctly calculate the terminal charge and the corresponding capacitances, if voltage [Terminal](#) is used on boundaries between [The Electrostatics Interface](#) and [The Electrostatics, Boundary Elements Interface](#), let the dependent variable for [The Electrostatics, Boundary Elements Interface](#) be the same as the dependent variable for [The Electrostatics Interface](#) and disable [Electric Scalar-Scalar Potential Coupling](#). How to set the name for the dependent variable is described in the [Dependent Variables](#) section. Since the [Electric Scalar-Scalar Potential Coupling](#) is disabled, add manually a Fully Coupled node to the Stationary Solver below the Solution node in the Solver Configurations.

### SYMMETRY



For 3D components, from the **Condition for the  $x = x_0$  plane**, **Condition for the  $y = y_0$  plane**, and **Condition for the  $z = z_0$  plane** lists, choose **Off** (the default), **Symmetric**, or **Antisymmetric**. Then enter the value for the plane location  $x_0$ ,  $y_0$ , or  $z_0$  (SI unit: m) as required.



For 2D components, from the **Condition for the  $x = x_0$  plane** and **Condition for the  $y = y_0$  plane** lists, choose **Off** (the default), **Symmetric**, or **Antisymmetric**. Then enter the value for the plane location  $x_0$  or  $z_0$  (SI unit: m) as required.

## FAR-FIELD APPROXIMATION

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.



For more information about the **Far Field Approximation** settings, see [Far-Field Approximation Settings](#) in the *COMSOL Multiphysics Reference Manual*.

## INFINITY CONDITION



For 3D components, select the **Infinity condition — Total charge** (the default) or **Asymptotic value at infinity**. Specify the **Total charge**  $Q_{\text{tot}}$  (SI unit: C; the default value is 0 C) or **Electric potential at infinity**  $V_{\infty}$  (SI unit: V; the default value is 0 V). If there is an antisymmetric symmetry in the potential field, it acts as an added infinite ground plane with a fixed value of the electric potential. The value at infinity is fixed to 0 by the presence of the infinite ground plane, so for this case there is a fixed **Zero potential at infinity** condition.



For 2D components, select the **Infinity condition — Total charge** (the default) or **Value at reference distance**. Specify the **Total charge**  $Q_{\text{tot}}$  (SI unit: C; the default value is 0 C) or **Electric potential at reference distance**  $V_{\text{ref}}$  (SI unit: V; the default value is 0 V). If there is an antisymmetric symmetry in the potential field, it acts as an added ground line with a fixed value of the electric potential. The value at a reference distance is fixed to 0 by the presence of the ground line, so for this case there is a fixed **Zero potential at reference distance** condition.

## QUADRATURE

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.



For more information about the **Quadrature** settings, see [Quadrature](#) in the *COMSOL Multiphysics Reference Manual*.

## DISCRETIZATION

From the **Electric potential/Surface charge density** list, choose from predefined options for the boundary element discretization order for the electric potential variable and the surface charge density variable, respectively. The predefined options represent the suitable combinations of element orders such as **Quadratic/Linear** (the default).



For 3D components, the Line charge variable will have the same discretization order as the Electric potential variable.

The settings under **Value types when using splitting of complex variables** are important for sensitivity and optimization computations. See the description of the built-in operators `fsens` and `fsensimag`.

## DEPENDENT VARIABLES

The dependent variable (field variable) is for the **Electric potential**  $V$ . The name can be changed but the names of fields and dependent variables must be unique within a model.

### *Domain, Boundary, and Edge Nodes for the Electrostatics, Boundary Elements Interface*

The [Electrostatics, Boundary Elements Interface](#) has these domain, boundary, and edge nodes available from the **Physics** ribbon (Windows users), **Physics** context menu (Mac or Linux users), or by right-clicking the physics interface in **Model Builder** to access the context menu (all users).



In general, to add a node, go to the **Physics** toolbar, no matter what operating system you are using. Subnodes are available by clicking the parent node and selecting it from the **Attributes** menu.

## AVAILABLE NODES

These nodes and subnodes are described in this section:

- [Initial Values](#)
- [Charge Conservation](#)
- [Electric Potential](#)
- [Floating Potential](#)
- [Force Calculation](#)
- [Ground](#)
- [Surface Charge Density](#)
- [Terminal](#)
- [Zero Charge](#)

The [Zero Charge](#) node is the default boundary and edge condition available for this physics interface and described for the Electrostatics interface.

### *Initial Values*

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**Initial Values** adds an initial value for the electric potential that can serve as an initial condition for a transient simulation or as an initial guess for a nonlinear solver. Add more **Initial Values** nodes from the **Physics** toolbar, **Global** menu.

#### INITIAL VALUES

Enter a value or expression for the initial value of the **Electric potential**  $V$  (SI unit: V).

### *Charge Conservation*

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The **Charge Conservation** node adds the equations for charge conservation according to Gauss' law for the electric displacement field. It provides an interface for defining the constitutive relation defined by the relative permittivity.

#### CONSTITUTIVE RELATION D-E

Enter the **Relative permittivity**  $\epsilon_r$  (dimensionless) to describe the macroscopic properties of the medium. The default is to take the **Relative permittivity** values **From material**. For **User defined**, enter a value or expression in the field.



Notice that the boundary element method is based on the availability of an analytic Green's function for the domain. Thus, the **Relative permittivity** must evaluate to a constant value for each **Charge Conservation** node.

## Electric Potential

The **Electric Potential** node provides an electric potential  $V_0$  as the boundary condition  $V = V_0$ .



For more information about the Electric Potential condition, see [Electric Potential](#) in the documentation for the Electrostatics interface.



For 3D components, enter the **Edge radius** (SI unit: m) for the virtual tube surrounding the edge. The default value is 0.1 m. It is generally assumed that the edge radius is small in comparison to other geometrical measures of the model, such as the edge length and the distances between different edges in the geometry.

## Floating Potential

The **Floating Potential** node is used when modeling a metallic electrode at floating potential.



For more information about the Floating Potential condition, see [Floating Potential](#) in the documentation for the Electrostatics interface.



For 3D components, enter the **Edge radius** (SI unit: m) for the virtual tube surrounding the edge. The default value is 0.1 m. It is generally assumed that the edge radius is small in comparison to other geometrical measures of the model, such as the edge length and the distances between different edges in the geometry.

## Ground

The **Ground** node implements ground (zero potential) as the boundary condition  $V = 0$ .



For more information about the Ground condition, see [Ground](#) in the documentation for the Electrostatics interface.



For 3D components, enter the **Edge radius** (SI unit: m) for the virtual tube surrounding the edge. The default value is 0.1 m. It is generally assumed that the edge radius is small in comparison to other geometrical measures of the model, such as the edge length and the distances between different edges in the geometry.

### *Surface Charge Density*

The **Surface Charge Density** node provides the following surface-charge boundary condition for exterior boundaries (left) and interior boundaries (right):

$$-\mathbf{n} \cdot \mathbf{D} = \rho_s, \quad \mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$$

Specify the surface charge density  $\rho_s$  at an outer boundary or at an interior boundary between two nonconducting media.



For more information about the Surface Charge Density condition, see [Surface Charge Density](#) in the documentation for the Electrostatics interface.



For 3D components, enter the **Edge radius** (SI unit: m) for the virtual tube surrounding the edge. The default value is 0.1 m. It is generally assumed that the edge radius is small in comparison to other geometrical measures of the model, such as the edge length and the distances between different edges in the geometry. Enable **Compensate for tube volume** to allow for a potential gradient across the cross section of the virtual tube. This can be useful for establishing a zero surface charge density condition on the virtual tube periphery.

### *Terminal*

The **Terminal** node provides a boundary or domain condition for connection to external circuits, to transmission lines, or with a specified voltage or charge.



For more information about the Terminal condition, see [Terminal](#) in the documentation for the Electrostatics interface.

|                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>For 3D components, enter the <b>Edge radius</b> (SI unit: m) for the virtual tube surrounding the edge. The default value is 0.1 m. It is generally assumed that the edge radius is small in comparison to other geometrical measures of the model, such as the edge length and the distances between different edges in the geometry.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|  | <p>To correctly calculate the terminal charge and the corresponding capacitances, if voltage <b>Terminal</b> is used on boundaries between <a href="#">The Electrostatics Interface</a> and <a href="#">The Electrostatics, Boundary Elements Interface</a>, let the dependent variable for <a href="#">The Electrostatics, Boundary Elements Interface</a> be the same as the dependent variable for <a href="#">The Electrostatics Interface</a> and disable <a href="#">Electric Scalar-Scalar Potential Coupling</a>. How to set the name for the dependent variable is described in the <a href="#">Dependent Variables</a> section. Since the <a href="#">Electric Scalar-Scalar Potential Coupling</a> is disabled, add manually a Fully Coupled node to the Stationary Solver below the Solution node in the Solver Configurations.</p> |

### *Zero Charge*

The **Zero Charge** node adds the condition that there is zero charge on the boundary so that  $\mathbf{n} \cdot \mathbf{D} = 0$ . This is the default boundary condition on exterior boundaries and on edges embedded within a [Charge Conservation](#) feature.

### *Electric Scalar-Scalar Potential Coupling*

The **Electric Scalar-Scalar Potential Coupling** multiphysics node assures continuity of the electric potential across boundaries between [The Electrostatics Interface](#) and [The Electrostatics, Boundary Elements Interface](#). The **Electric Scalar-Scalar Potential Coupling** node is available from the **Multiphysics** menu in the **Physics** toolbar or by right-clicking the **Multiphysics Couplings** node in **Model Builder**, if both [The](#)



[Electrostatics Interface](#) and [The Electrostatics, Boundary Elements Interface](#) are available.



[The Electrostatics Interface](#) and [The Electrostatics, Boundary Elements Interface](#) can also be coupled by using the same name for the dependent variable for both interfaces. Then **Electric Scalar-Scalar Potential Coupling** is not needed. How to set the name for the dependent variable is described in the [Dependent Variables](#) section.



When using [The Electrostatics, Boundary Elements Interface](#) with iterative solvers, **Right Preconditioning** is preferred. Thus, it is advised to check that **Right Preconditioning** is used when combining the **Electric Scalar-Scalar Potential Coupling** with [The Electrostatics, Boundary Elements Interface](#) and other physics interfaces. How to define **Right Preconditioning** is described in [Iterative](#) in the *COMSOL Multiphysics Reference Manual*.

## BOUNDARY SELECTION

Select **Manual** or **All boundaries** from the **Selection** list. Make additional edits to the list of boundary entity numbers using the Selection toolbar buttons. When **All boundaries** is selected from the **Selection** list, the boundaries exterior to the Electrostatics interface that intersect the exterior boundaries to the Electrostatics, Boundary Elements interface are available in the boundary entity number list.

## COUPLED INTERFACES

- Select **Electrostatics, Boundary Elements** as **Primary interface** and **Electrostatics** and **Secondary interface**.

# The Electric Currents Interface

The **Electric Currents (ec)** interface () , under the **AC/DC>Electric Fields and Currents** branch when adding a physics interface, is used to compute electric field, current, and potential distributions in conducting media under conditions where inductive effects are negligible; that is, when the skin depth is much larger than the studied device.

Depending on the licensed products, stationary, frequency-domain, small-signal analysis, and time-domain modeling are supported in all space dimensions. In the time and frequency domains, capacitive effects are also accounted for.

The physics interface solves a current conservation equation based on Ohm's law using the scalar electric potential as the dependent variable.

**Current Conservation** is the main node, which adds the equation for the electric potential and provides a Settings window for defining the electrical conductivity as well as the constitutive relation for the electric displacement field and its associated material properties, such as the relative permittivity.

When this physics interface is added, these default nodes are also added to the **Model Builder** — **Current Conservation**, **Electric Insulation** (the default boundary condition), and **Initial Values**. Then, from the **Physics** toolbar, add other nodes that implement, for example, boundary conditions and current sources. You can also right-click **Electric Currents** to select physics features from the context menu.

## Physics-Controlled Mesh

The physics-controlled mesh is controlled from the **Mesh** node's **Settings** window (if the **Sequence type** is **Physics-controlled mesh**). There, in the table in the **Physics-Controlled Mesh** section, find the physics interface in the **Contributor** column and select or clear the check box in the **Use** column on the same table row for enabling (the default) or disabling contributions from the physics interface to the physics-controlled mesh.

Information from the physics, such as the presence of an infinite elements domain or periodic condition, will be used to automatically set up an appropriate meshing sequence.



In the *COMSOL Multiphysics Reference Manual* see the [Physics-Controlled Mesh](#) section for more information about how to define the physics-controlled mesh.

## SETTINGS

The **Label** is the default physics interface name.

The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the **name** string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `ec`.

### CROSS-SECTION AREA (1D)

Enter a default value for the **Cross-section area**  $A$  (SI unit:  $\text{m}^2$ ). The default value of 1 is typically not representative for a thin domain. Instead it describes a unit thickness that makes the 1D equation identical to the equation used for 3D components. See also [Change Cross Section](#) (described for the Electrostatics interface).

### THICKNESS (2D)

Enter a default value for the **Out-of-plane thickness**  $d$  (SI unit:  $\text{m}$ ) (see [Equation 3-2](#)). The default value of 1  $\text{m}$  is typically not representative for a thin dielectric medium, for example. Instead it describes a unit thickness that makes the 2D equation identical to the equation used for 3D components. See also [Change Thickness \(Out-of-Plane\)](#) (described for the Electrostatics interface).

## MANUAL TERMINAL SWEEP SETTINGS

Enter a **Reference impedance**  $Z_{\text{ref}}$  (SI unit:  $\Omega$ ). The default is 50  $\Omega$ .

Select the **Activate manual terminal sweep** check box to switch on the sweep and invoke a parametric sweep over the terminals. Enter a **Sweep parameter name** to assign a specific name to the variable that controls the terminal number solved for during the sweep. The default is `PortName`. The generated lumped parameters are in the form of capacitance matrix elements. The terminal settings must consistently be of either fixed voltage or fixed charge type.

The lumped parameters are subject to **Touchstone file export**. Enter a file path or **Browse** for a file. Select a **Parameter format (value pairs)** for the Touchstone export — **Magnitude and angle (MA)** (the default), **Magnitude in dB and angle (DB)**, or **Real and imaginary parts (RI)**. Select an option from the **If file exists** list — **Overwrite** or **Create**

**new.** Create new is useful when the model is solved multiple times with different settings. Select a **Parameter to export** — **Z** (the default), **Y**, or **S**.



For most applications it is simpler to sweep over terminals using the Stationary Source Sweep study step. See [Stationary Source Sweep](#) in the *COMSOL Multiphysics Reference Manual* and (for more details) [Stationary Source Sweep](#) in the *AC/DC Module User's Guide*.

**DEPENDENT VARIABLES**

The dependent variable is the **Electric potential** *V*. You can change its name, which changes both the field name and the variable name. If the new name coincides with the name of another electric potential field in the model, the physics interfaces share degrees of freedom. The new name must not coincide with the name of a field of another type or with a component name belonging to some other field.

**DISCRETIZATION**

Select the shape order for the **Electric potential** dependent variable — **Linear**, **Quadratic** (the default), **Cubic**, **Quartic**, or **Quintic**. For more information about the **Discretization** section, see [Settings for the Discretization Sections](#) in the *COMSOL Multiphysics Reference Manual*.



- [Domain, Boundary, Edge, Point, and Pair Nodes for the Electric Currents Interface](#)
- [Theory for the Electric Currents Interface](#)



*Pacemaker Electrode*: Application Library path **COMSOL\_Multiphysics/Electromagnetics/pacemaker\_electrode**

*Domain, Boundary, Edge, Point, and Pair Nodes for the Electric Currents Interface*

The Electric Currents interface has these domain, boundary, edge, point, and pair nodes available from the **Physics** ribbon toolbar (Windows users) or **Physics** context

menu (Mac or Linux users). You can also right-click to access the context menu (all users).



In general, to add a node, go to the **Physics** toolbar, no matter what operating system you are using. Subnodes are available by clicking the parent node and selecting it from the **Attributes** menu.

### ABOUT THE BOUNDARY CONDITIONS

The exterior and interior boundary conditions listed in [Table 3-1](#) are available. The relevant physics interface condition at interfaces between different media and interior boundaries is continuity; that is,

$$\mathbf{n}_2 \cdot (\mathbf{J}_1 - \mathbf{J}_2) = 0$$

which is the natural boundary condition.

### AVAILABLE NODES

These nodes are available for this physics interface, listed in alphabetical order. Also see [Table 3-1](#) for a list of interior and exterior boundary conditions, including edge, point, and pair availability.

- [Boundary Current Source](#)
- [Contact Impedance](#)
- [Current Conservation](#)
- [Current Source](#)
- [Distributed Impedance](#)
- [Electric Insulation](#)
- [Electric Point Dipole](#)
- [Electric Point Dipole \(on Axis\)](#)
- [Electric Shielding](#)
- [External Current Density](#)
- [Floating Potential](#)
- [Initial Values](#)
- [Line Current Source](#)
- [Line Current Source \(on Axis\)](#)
- [Normal Current Density](#)
- [Piezoresistive Material](#)<sup>1</sup>
- [Point Current Source](#)
- [Sector Symmetry](#)
- [Terminal](#)

<sup>1</sup>This feature is available with the Piezoresistivity, Domain Currents interface, which requires the MEMS Module.

These nodes are described for the Electrostatics interface:

- [Change Cross Section](#)
- [Change Thickness \(Out-of-Plane\)](#)
- [Electric Potential](#)
- [Force Calculation](#)
- [Ground](#)
- [Periodic Condition](#)



In the *COMSOL Multiphysics Reference Manual*, see [Table 2-4](#) for links to common sections and [Table 2-5](#) for common feature nodes. You can also search for information: press F1 to open the **Help** window or Ctrl+F1 to open the **Documentation** window.



For axisymmetric components, COMSOL Multiphysics takes the axial symmetry boundaries (at  $r = 0$ ) into account and automatically adds an **Axial Symmetry** node to the model that is valid on the axial symmetry boundaries only.

[Table 3-1](#) lists the interior and exterior boundary conditions available with this physics interface. It also includes edge, point, and pair availability.

TABLE 3-2: INTERIOR AND EXTERIOR BOUNDARY CONDITIONS (INCLUDING EDGE, POINT, AND PAIR AVAILABILITY) FOR THE ELECTRIC CURRENTS INTERFACE

| NODE                    | INTERIOR | EXTERIOR | ALSO AVAILABLE FOR       |
|-------------------------|----------|----------|--------------------------|
| Boundary Current Source | x        |          | pairs                    |
| Contact Impedance       | x        |          | pairs                    |
| Distributed Impedance   | x        | x        | not applicable           |
| Electric Insulation     | x        | x        | pairs                    |
| Electric Potential      | x        | x        | edges, points, and pairs |
| Electric Shielding      | x        | x        | pairs                    |
| Floating Potential      | x        | x        | pairs                    |
| Ground                  | x        | x        | edges, points, and pairs |
| Normal Current Density  |          | x        | not applicable           |
| Periodic Condition      |          | x        | not applicable           |
| Terminal                | x        | x        | pairs, domains           |

## Current Conservation

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The **Current Conservation** node adds the continuity equation for the electrical potential and provides an interface for defining the electric conductivity as well as the constitutive relation and the relative permittivity for the displacement current.

### MATERIAL TYPE

The **Material type** setting decides how materials behave and how material properties are interpreted when the mesh is deformed. Select **Solid** for materials whose properties change as functions of material strain, material orientation, and other variables evaluated in a material reference configuration (material frame). Select **Non-solid** for materials whose properties are defined only as functions of the current local state at each point in the spatial frame, and for which no unique material reference configuration can be defined. Select **From material** to pick up the corresponding setting from the domain material on each domain.

### CONSTITUTIVE RELATION JC-E

By default, the **Electrical conductivity**  $\sigma$  (SI unit: S/m) for the media is defined **From material**. Or select **User defined** or **Linearized resistivity**.

#### *User Defined*

For **User defined** select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** depending on the characteristics of the electrical conductivity, and then enter values or expressions for the electrical conductivity  $\sigma$  in the field or matrix. The default is 0 S/m. If type of temperature dependence is used other than a linear temperature relation, enter any expression for the conductivity as a function of temperature.

#### *Linearized Resistivity*

Select **Linearized resistivity** for a temperature-dependent conductivity (this occurs in, for example, Joule heating, and is also called resistive heating). The equation describing the conductivity:

$$\sigma = \frac{1}{\rho_0(1 + \alpha(T - T_{\text{ref}}))}$$

where  $\rho_0$  is the resistivity at the reference temperature  $T_{\text{ref}}$ , and  $\alpha$  is the temperature coefficient of resistance, which describes how the resistivity varies with temperature.

The default **Reference resistivity**  $\rho_0$  (SI unit:  $\Omega \cdot \text{m}$ ), **Reference temperature**  $T_{\text{ref}}$  (SI unit: K), and **Resistivity temperature coefficient**  $\alpha$  (SI unit:  $1/\text{K}$ ) are taken **From material**, which means that the values are taken from the domain (or boundary)

material.  $T$  is the current temperature, which can be a value that is specified as a model input or the temperature from a heat transfer interface. The definition of the temperature field is in the **Model Inputs** section.

To specify other values for any of these properties, select **User defined** from the list and then enter a value or expression for each. The default values are:

- 1  $\Omega\cdot\text{m}$  for the Reference resistivity
- 273.15 K for the Reference temperature, and
- 0 1/K for the Resistivity temperature coefficient

### CONSTITUTIVE RELATION D-E

Select a **Dielectric model** to describe the macroscopic properties of the medium (relating the electric displacement  $\mathbf{D}$  with the electric field  $\mathbf{E}$ ) and the applicable material properties, such as the relative permittivity. For a description of the constitutive relations **Relative permittivity**, **Polarization**, and **Remanent electric displacement**, see **Electric Field** as described for the [Charge Conservation](#) node for the Electrostatics interface. The constitutive relations specific to Electric Currents are:

- **Dielectric losses:** uses the constitutive relation  $\mathbf{D} = \epsilon_0(\epsilon' + \epsilon'')\mathbf{E}$ . Specify that the **Relative permittivity (real part)**  $\epsilon'$  (dimensionless) and the **Relative permittivity (imaginary part)**  $\epsilon''$  (dimensionless) must be taken **From material** or be **User defined**. For **User defined**, select **Isotropic**, **Diagonal**, **Symmetric**, or **Full** and enter values or expressions in the field or matrix. The default is 1.
- **Loss tangent, loss angle:** uses the constitutive relation  $\mathbf{D} = \epsilon_0\epsilon'(1+j\tan\delta)\mathbf{E}$ . Specify the **Relative permittivity (real part)**  $\epsilon'$  (dimensionless) and **Loss angle**  $\delta$  (SI unit: rad).
- **Loss tangent, dissipation factor:** uses the constitutive relation  $\mathbf{D} = \epsilon_0\epsilon'(1+j\tan\delta)\mathbf{E}$ . Specify the **Relative permittivity (real part)**  $\epsilon'$  (dimensionless) and the **Dissipation factor**  $\tan\delta$  (dimensionless).

### *Initial Values*

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The **Initial Values** node adds an initial value for the electric potential that can serve as an initial condition for a transient simulation or as an initial guess for a nonlinear solver. If more than one set of initial values is required, from the **Physics** toolbar, add other nodes that implement, for example, boundary conditions and current sources. Add more **Initial Values** nodes from the **Physics** toolbar.



## INITIAL VALUES

Enter a value or expression for the initial value of the **Electric potential**  $V$  (SI unit: V). The default value is 0 V.

### *External Current Density*

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The **External Current Density** node adds an externally generated current density  $\mathbf{J}_e$ , which appears in Ohm's law

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$

and in the equation that the physics interface defines.

The external current density does not contribute to the losses (due to Joule heating), since there is no electric field associated with it. To include the contribution to the losses from the external current density, select the **Add contribution of the external current density to the losses** check box. Then select an option from the **External losses** list — **From domain conductivity** (the default) or **User defined**. If **From domain conductivity** is selected, the heat source is computed using the conductivity specified in the material model feature (such as **Current Conservation**) that is applied in the domain. For **User defined**, enter a value for  $Q_e$  (SI unit: W/m<sup>3</sup>) to specify a user-defined heat source.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

## EXTERNAL CURRENT DENSITY

Based on space dimension, enter the coordinates ( $\mathbf{x}$ ,  $\mathbf{y}$ , and  $\mathbf{z}$  for 3D components, for example) of the **External current density**  $\mathbf{J}_e$  (SI unit: A/m<sup>2</sup>). The defaults are 0 A/m<sup>2</sup>.

### *Current Source*

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The **Current Source** node adds a distributed current source  $Q_j$  in the equation that the physics interface defines. Use this node with caution as it can violate the current conservation law that is inherent in Maxwell-Ampère's law.

Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see

### CURRENT SOURCE

Enter a value or expression for the **Current source**  $Q_j$  (SI unit: A/m<sup>3</sup>). The default is 0 A/m<sup>3</sup>.

### *Electric Insulation*

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The **Electric Insulation** node, which is the default boundary condition, adds electric insulation as the boundary condition:

$$\mathbf{n} \cdot \mathbf{J} = 0$$

This boundary condition means that no electric current flows into the boundary. At interior boundaries, it means that no current can flow through the boundary and that the electric potential is discontinuous across the boundary. It is also applicable at symmetric boundaries where the potential is known to be symmetric with respect to the boundary.

Electric insulation as the default boundary condition is not applicable to interior boundaries. To add electric insulation to an interior boundary, add an **Electric Insulation** node in addition to the one that represents the default boundary condition.

### *Floating Potential*

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The **Floating Potential** node is used when modeling a metallic electrode at floating potential. It applies a constant voltage  $V_0$  on the boundary (for domain features, this is the boundary enclosing the selected domain), such that the total normal electric current density  $\mathbf{J}$  equals a specific current  $I_0$ :

$$V = V_0$$
$$\int_{\partial\Omega} (-\mathbf{n} \cdot \mathbf{J}) dS = I_0,$$

where  $\Omega$  represents the boundary and  $\mathbf{n}$  refers to the surface normal. The constant boundary voltage implies the tangential electric field equals zero; the electric field will be perpendicular to the boundary:

$$-\nabla_t V = \mathbf{E}_t = 0$$

$$\mathbf{n} \times \mathbf{E} = 0.$$

In case of  $I_0 = 0$  (the default case), the boundary will behave as an unconnected perfect conductor (a floating equipotential). This is a good approximation when the conductivity of the electrode is many orders of magnitude larger than that of the surrounding medium. Although locally the current density may vary, the total current entering or leaving the boundary equals zero.

If the floating potential touches a point, boundary or domain feature that is not floating (a **Terminal** or **Ground** feature), the floating potential will acquire that feature's potential. If the floating potential is set to a certain current, or connected to a circuit, it behaves like a terminal.

The **Harmonic Perturbation** subnode (it is of the exclusive type) is available from the context menu (right-click the parent node) or on the **Physics** toolbar, click the **Attributes** menu and select **Harmonic Perturbation**. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

## FLOATING POTENTIAL

The Floating potential identifier text area shows the unique identifier for the floating potential feature. It is used to identify the global variables created by the node, such as the voltage. The **Floating potential group** check box on the **Settings** window for **Floating Potential** controls how potentials are assigned to boundary segments in the feature's boundary selection. If this check box is not selected, a single potential is applied to all boundaries in the selection. If the check box is selected, each group of contiguous boundaries in the selection is given a unique potential. This simplifies the setup of models with many floating electrodes. The values of the potential at each group of boundaries are then made available in postprocessing, collected in a vector variable.

The following options are not available if the **Floating potential group** check box is selected. Select a specification for the **Floating potential current** — choose **User defined** (the default) to specify a total **Current**  $I_0$  (SI unit: A) that flows from the electrode. The default is 0 A, corresponding to an unconnected electrode. Select **Circuit** to connect the floating potential to an Electrical Circuit interface.

### Initial values

The initial values subsection is used to provide initial values for the internal state variables in the Floating Potential. These settings can be useful to provide an initial guess to the nonlinear solver or the initial value in a time-dependent study when the

initial values of the other dependent variables (such as the electric potential) are computed from a separate physics or study. In most cases, the default values are appropriate.

Enter an **Initial value for voltage**  $V_{\text{init}}$  (SI unit: V). The default is 0 V.

#### CONSTRAINT SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.



Settings and Properties Windows for Feature Nodes in the *COMSOL Multiphysics Reference Manual*

### *Boundary Current Source*

The **Boundary Current Source** node adds a current source  $Q_j$  on the boundary.

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = Q_j$$

It is applicable to interior boundaries that represent either a source or a sink of current. Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or click **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

#### BOUNDARY CURRENT SOURCE

Enter a value or expression for the **Boundary current source**  $Q_j$  (SI unit: A/m<sup>2</sup>). The default is 0 A/m<sup>2</sup>.

### *Normal Current Density*

The **Normal Current Density** node is applicable to exterior boundaries that represent either a source or a sink of current. It provides a condition for specifying the normal current density as an inward or outward current flow:

$$-\mathbf{n} \cdot \mathbf{J} = J_n$$

Or alternatively, as a current density  $\mathbf{J}_0$ :

$$\mathbf{n} \cdot \mathbf{J} = \mathbf{n} \cdot \mathbf{J}_0$$

The normal current density is positive when the current flows inward in the domain. Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

## NORMAL CURRENT DENSITY

Select a **Type** — **Inward current density** (the default) or **Current density**.

- For **Inward current density** enter a value or expression for the **Normal current density**  $J_n$  (SI unit: A/m<sup>2</sup>). Use a positive value for an inward current flow or a negative value for an outward current flow. The default is 0 A/m<sup>2</sup>.
- For **Current density** enter values or expressions for the components of the **Current density**  $\mathbf{J}_0$  (SI unit: A/m<sup>2</sup>). The defaults are 0 A/m<sup>2</sup>.

## Distributed Impedance

The **Distributed Impedance** node adds a distributed impedance boundary condition to a model.

The **Harmonic Perturbation** subnode (it is of the exclusive type) is available from the context menu (right-click the parent node) or on the **Physics** toolbar, click the **Attributes** menu and select **Harmonic Perturbation**. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

Use this boundary condition to model a thin sheet of a resistive material connected to a reference potential  $V_{\text{ref}}$ .

The layer impedance can be specified either with the bulk material conductivity  $\sigma_s$ , the relative permittivity  $\epsilon_r$  and layer thickness  $d_s$ , or directly with the surface resistance  $\rho_s$  and capacitance  $C_s$ . Assuming DC currents, the equation is:

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = \frac{\sigma_s}{d_s} (V - V_{\text{ref}})$$

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = \frac{1}{\rho_s} (V - V_{\text{ref}})$$

For the Frequency Domain and Time Dependent study types, this boundary condition is slightly more sophisticated and accounts also for capacitive coupling. The equations are:

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = \frac{(\sigma + j\omega\epsilon_0\epsilon_r)}{d_s}(V - V_{\text{ref}})$$

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = \left(\frac{1}{r_s} + j\omega C_s\right)(V - V_{\text{ref}})$$

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = \frac{1}{d_L} \left( \sigma(V - V_{\text{ref}}) + \epsilon_0\epsilon_r \frac{\partial}{\partial t}(V - V_{\text{ref}}) \right)$$

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = \left( \frac{1}{\rho_s}(V - V_{\text{ref}}) + C_s \frac{\partial}{\partial t}(V - V_{\text{ref}}) \right)$$

#### DISTRIBUTED IMPEDANCE

Enter the reference potential  $V_{\text{ref}}$  (SI unit: V). The default is 0 V.

Select a potentially complex-valued **Layer specification** — **Thin layer** (the default) or **Surface impedance**.

- For **Thin layer**, enter values or expressions for the:
  - **Surface thickness**  $d_s$  (SI unit: m). The default is  $5 \cdot 10^{-3}$  m (5 mm).
  - **Electrical conductivity**  $\sigma$  (SI unit: S/m) and **Relative permittivity**  $\epsilon_r$  (dimensionless). The defaults take values **From material**. For **User defined**, enter different values or expressions. The default electrical conductivity is  $1 \cdot 10^{-2}$  S/m and the default relative permittivity is 1.
- For **Surface impedance**, enter values or expressions for the **Surface resistance**  $\rho_s$  (SI unit:  $\Omega \cdot \text{m}^2$ ) and the **Surface capacitance**  $C_s$  (SI unit: F/m<sup>2</sup>). The default surface impedance is  $1 \cdot 10^{-8}$   $\Omega \cdot \text{m}^2$  and the default surface capacitance is 0 F/m<sup>2</sup>.

## Terminal

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The **Terminal** node provides a boundary or domain condition for connection to external circuits, to transmission lines, or with a specified voltage or current. By specifying zero current, a floating potential condition is obtained.



In most cases, it is not recommended to include the interior of good conductors in the simulation. When using the **Terminal** on the domain level, the interior unknowns for the electric potential are replaced by a single constant, thus avoiding numerical problems arising from a very high material contrast. If one instead uses the **Terminal** on the boundary level, it is recommended to exclude the interior of the associated conductor from the domain selection for the main Electric Currents node.

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The **Terminal** node also enables the computation of the lumped parameter of the system, such as the impedance.

The **Harmonic Perturbation** subnode (it is of the exclusive type) is available from the context menu (right-click the parent node) or on the **Physics** toolbar, click the **Attributes** menu and select **Harmonic Perturbation**. The **Harmonic Perturbation** subnode only has effect if **Current** or **Voltage** are selected as terminal type. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

### TERMINAL

Specify the terminal's properties. The **Terminal name** identifies the terminal and the variables it creates. The name should be numeric for sweeps to work properly.

Select a **Terminal type** — **Current** (the default), **Voltage**, **Circuit**, **Terminated**, or **Power**.



The **Circuit** and **Power** types cannot be used together with a terminal sweep.

---

Select:

- **Current** to specify a total current flowing from the terminal. Enter the current  $I_0$  (SI unit: A). The default is 0 A for an open circuit.

- **Voltage** to specify a fixed electric potential at the terminal. Enter the value of the electric potential  $V_0$  (SI unit: V). The default is 1 V.
- **Circuit** to specify a terminal connected to an Electrical Circuit interface that models an external circuit.
- **Terminated** to connect the terminal to an impedance that might represent a load or a transmission line. When **Terminated** is selected, the scattering parameters (S-parameters) are computed.
  - Enter a **Terminal power**  $P_0$  (SI unit: W) to specify the input power at this terminal from the transmission line. This excitation can be toggled using a terminal sweep. The default is 1 W.
  - Select an option from the **Characteristic impedance from** list to define the value of the impedance — **Physics interface** (the default) or **User defined**. For **Physics interface** the **Reference impedance**  $Z_{\text{ref}}$  defined on the **Settings** window for the physics interface under Sweep Settings is used. For **User defined** enter a specific impedance  $Z_{\text{ref}}$  (SI unit:  $\Omega$ ) for this terminal. The default is 50  $\Omega$ .
- **Power** to specify a fixed electrical power for the terminal. The power is computed as the product of the terminal current and voltage and, in frequency domain, is the cycle-averaged power. When **Power** is selected:
  - Enter a **Terminal power**  $P_0$  (SI unit: W) to specify the input power at this terminal. The default is 1 W.



Using Power excitation causes the equation system to become nonlinear. COMSOL Multiphysics automatically adjusts the solver settings when Power is selected.

Be aware that, in general, the values of the voltage and the current might not uniquely be determined by this constraint and may depend on the initial value provided for the current and voltage variables. Particularly in the frequency domain, the absolute phase of the quantities can be arbitrary. This indeterminacy can have an impact on the solution process. See [Compile Equations](#) in the *COMSOL Multiphysics Reference Manual* for a possible solution to this problem.

### Initial Values

The initial values subsection is used to provide initial values for the internal state variables in the Terminal. These settings can be useful to provide an initial guess to the nonlinear solver or the initial value in a time-dependent study when the initial values



of the other dependent variables (such as the electric potential) are computed from a separate physics or study. In most cases, the default values are appropriate.

The **Initial value for voltage** is available for all Terminal types except Voltage. Enter an **Initial value for voltage**  $V_{\text{init}}$  (SI unit: V). The default is 0 V.

The **Initial value for current** is available for Power only. In this case, it provides an initial guess for the nonlinear solver, and should not be set to zero. The initial value provided may affect the solution. Enter an **Initial value for current**  $I_{\text{init}}$  (SI unit: A). The default is 1 mA.

## CONSTRAINT SETTINGS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

### *Electric Shielding*

---

The **Electric Shielding** node provides an electric shielding boundary condition. Use this node to model a thin layer of a highly conductive medium that shields the electric field. The sheet has the electrical conductivity  $\sigma_s$  and the surface thickness  $d$ .

The condition is represented by the following equation for interior boundaries and (setting  $\mathbf{J}_2 = 0$ ) exterior boundaries assuming DC currents

$$\mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) = -\nabla_t \cdot d(\sigma_s \nabla_t V)$$

For the frequency domain and Time Dependent study types, also displacement currents are accounted for via the bulk relative permittivity of the sheet;  $\epsilon_{rs}$  and the conservation laws change to:

$$\begin{aligned} \mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) &= -\nabla_t \cdot d((\sigma_s + j\omega\epsilon_0\epsilon_{rs})\nabla_t V) \\ \mathbf{n} \cdot (\mathbf{J}_1 - \mathbf{J}_2) &= -\nabla_t \cdot d\left(\sigma_s \nabla_t V + \epsilon_0\epsilon_{rs} \frac{\partial}{\partial t} \nabla_t V\right) \end{aligned}$$

Use this boundary condition when approximating a thin domain with a boundary to reduce the number of mesh elements. The **Electric Field** and **Conduction Current** sections are the same as for [Current Conservation](#).

## THICKNESS

Enter a value or expression for the **Surface thickness**  $d_s$  (SI unit: m). The default is 1 cm.

## Contact Impedance

---

Use the **Contact Impedance** node on interior boundaries to model a thin layer of resistive material. It can also be added as a pair using a **Pair Contact Impedance** node. The feature allows specifying the contact impedance either by entering the properties of the material together with the layer thickness, or by entering the impedance properties of the thin layer directly.

The feature, in stationary studies, applies the following conditions that relate the normal electric current density with the jump in the electric potential:

$$\mathbf{n} \cdot \mathbf{J}_1 = \frac{\sigma}{d_s}(V_1 - V_2)$$

$$\mathbf{n} \cdot \mathbf{J}_2 = \frac{\sigma}{d_s}(V_2 - V_1)$$

$$\mathbf{n} \cdot \mathbf{J}_1 = \frac{1}{\rho_s}(V_1 - V_2)$$

$$\mathbf{n} \cdot \mathbf{J}_2 = \frac{1}{\rho_s}(V_2 - V_1)$$

The first two equations refer to a layer impedance specified using the bulk material conductivity  $\sigma_s$  and the layer thickness  $d_s$ , while the last two equations refer to the case in which the surface resistance  $\rho_s$  is specified. The indices 1 and 2 refer to the two sides of the boundary. These parameters work the same as with [Distributed Impedance](#).

For the frequency domain and Time Dependent study types, this boundary condition is slightly more sophisticated and accounts also for capacitive coupling. The bulk material relative permittivity  $\epsilon_r$  or the layer capacitance  $C_s$  can be specified.

The equations used in Frequency Domain studies are:

$$\mathbf{n} \cdot \mathbf{J}_1 = \frac{(\sigma + j\omega\epsilon_0\epsilon_r)}{d_s}(V_1 - V_2)$$

$$\mathbf{n} \cdot \mathbf{J}_2 = \frac{(\sigma + j\omega\epsilon_0\epsilon_r)}{d_s}(V_2 - V_1)$$

$$\mathbf{n} \cdot \mathbf{J}_1 = \left(\frac{1}{\rho_s} + j\omega C_s\right)(V_1 - V_2)$$

$$\mathbf{n} \cdot \mathbf{J}_2 = \left(\frac{1}{\rho_s} + j\omega C_s\right)(V_2 - V_1)$$

In Time Dependent studies:

$$\mathbf{n} \cdot \mathbf{J}_1 = \frac{1}{d_s} \left( \sigma(V_1 - V_2) + \varepsilon_0 \varepsilon_r \frac{\partial}{\partial t} (V_1 - V_2) \right)$$

$$\mathbf{n} \cdot \mathbf{J}_2 = \frac{1}{d_s} \left( \sigma(V_2 - V_1) + \varepsilon_0 \varepsilon_r \frac{\partial}{\partial t} (V_2 - V_1) \right)$$

$$\mathbf{n} \cdot \mathbf{J}_1 = \left( \frac{1}{\rho_s} (V_1 - V_2) + C_s \frac{\partial}{\partial t} (V_1 - V_2) \right)$$

$$\mathbf{n} \cdot \mathbf{J}_2 = \left( \frac{1}{\rho_s} (V_2 - V_1) + C_s \frac{\partial}{\partial t} (V_2 - V_1) \right)$$

## CONTACT IMPEDANCE

Select a potentially complex-valued **Layer specification** — **Thin layer** (the default) or **Surface impedance**.

- For **Thin layer**, enter values or expressions for the:
  - **Surface thickness**  $d_s$  (SI unit: m). The default is  $5 \cdot 10^{-3}$  m (5 mm).
  - **Electrical conductivity**  $\sigma$  (SI unit: S/m) and **Relative permittivity**  $\varepsilon_r$  (dimensionless). The defaults take values **From material**. For **User defined**, enter different values or expressions. The default electrical conductivity is  $1 \cdot 10^{-2}$  S/m and the default relative permittivity is 1.
- For **Surface impedance**, enter values or expressions for the **Surface resistance**  $\rho_s$  (SI unit:  $\Omega \cdot \text{m}^2$ ) and the **Surface capacitance**  $C_s$  (SI unit: F/m<sup>2</sup>). The default surface impedance is  $1 \cdot 10^{-8}$   $\Omega \cdot \text{m}^2$  and the default surface capacitance is 0 F/m<sup>2</sup>.



*Thin-Film Resistance*: Application Library path **COMSOL\_Multiphysics/Electromagnetics/thin\_film\_resistance**

## Sector Symmetry

Select **Sector Symmetry** at interfaces between rotating objects where sector symmetry is used. It is only available for pairs. A default subnode is added. Right-click to select

additional features from the **Fallback Features** submenu. In 2D, this feature assumes rotation around the origin.



This feature is always used in conjunction with a [Periodic Condition](#) on adjacent radial sector boundaries. Note that the same periodic condition feature cannot be used on both sides of where the sector symmetry boundaries connect with the periodic boundaries. At least two periodic condition features are required for the model to compute correctly.

**PAIR SELECTION**

When using nonconforming meshes on the source and destination of a pair, for numerical stability, a finer mesh should be applied on the destination side for any pair with a condition that imposes a coupling or a constraint across the pair. The sector symmetry feature falls into this category.

**SECTOR SETTINGS**

Enter the **Number of sectors (<50)**  $n_{\text{sect}}$ . The default is 2.

Select a **Type of periodicity** — **Continuity** (the default) or **Antiperiodicity**.

Based on space dimension, enter values or expressions in the table for the **Axis of rotation**  $\mathbf{a}_{\text{rot}}$ .

**CONSTRAINT SETTINGS**

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

*Line Current Source*

The **Line Current Source** node adds a line source to edges in 3D components and to points in 2D and 2D axisymmetric components. The line source represents electric current per unit length.

**EDGE OR POINT SELECTION**



Beware that constraining the potential on edges or points usually yields a current outflow that is mesh dependent.

## LINE CURRENT SOURCE

Enter a value or expression to apply a **Line current source**  $Q_j$  (SI unit: A/m). This source represents electric current per unit length. The default is 0 A/m.



[Line Current Source \(on Axis\)](#) for 2D axisymmetric components.

### *Line Current Source (on Axis)*

The **Line Current Source (on Axis)** node adds a line source to boundaries in 2D axisymmetric components. The line source represents electric current per unit length.

## LINE CURRENT SOURCE (ON AXIS)

Enter a value or expression to apply a **Line current source**  $Q_j$  (SI unit: A/m) to boundaries. This source represents electric current per unit length.



[Line Current Source](#)

### *Point Current Source*

The **Point Current Source** node adds a point source and represents an electric current flowing out of the point. Add point sources to 3D components from the **Points** menu. Add a contribution as a **Harmonic Perturbation** by right-clicking the parent node or clicking **Harmonic Perturbation** on the **Physics** toolbar. For more information see [Harmonic Perturbation — Exclusive and Contributing Nodes](#) in the *COMSOL Multiphysics Reference Manual*.

## POINT SELECTION



Beware that constraining the potential on points usually yields a current outflow that is mesh dependent.

## POINT CURRENT SOURCE

Enter a value or expression to apply a **Point current source**  $Q_j$  (SI unit: A) to points. This source represents an electric current flowing out of the point.



- [Line Current Source](#) for 2D components
- [Point Current Source \(on Axis\)](#) for 2D axisymmetric components

### *Point Current Source (on Axis)*

The **Point Current Source (on Axis)** node adds a point source and represents an electric current flowing out of the point in 2D axisymmetric components.

## POINT SELECTION



Beware that constraining the potential on points usually yields a current outflow that is mesh dependent.

## POINT CURRENT SOURCE

Enter a value or expression to apply a **Point current source**  $Q_j$  (SI unit: A) to points. This source represents an electric current flowing out of the point.



- [Point Current Source](#) for 3D components
- [Line Current Source](#) for 2D components

### *Electric Point Dipole*

The **Electric Point Dipole** node, available for 2D and 3D components, represents the limiting case of zero separation distance between two equally strong point current sources and current sinks of opposing signs while maintaining the product between separation distance and source strength at a fixed value ( $P$ ). The positive direction is from the current sink to the current source.

## DIPOLE SPECIFICATION

Select a **Dipole specification** — **Magnitude and direction** (the default) or **Dipole moment**.

**DIPOLE PARAMETERS**

Under **Dipole Specification**:

- For **Magnitude and direction** enter coordinates for the **Electric current dipole moment direction**  $\mathbf{n}_p$  and the **Electric current dipole moment, magnitude**  $p$  (SI unit: A·m).
- For **Dipole moment** enter the components of the **Electric current dipole moment**  $\mathbf{p}$  (SI unit: A·m).



Electric Point Dipole (on Axis)

*Electric Point Dipole (on Axis)*

The **Electric Point Dipole (on Axis)**, available for 2D axisymmetric components, represents the limiting case of zero separation distance between two equally strong point current sources and current sinks of opposing signs while maintaining the product between separation distance and source strength at a fixed value ( $P$ ). The positive direction is from the current sink to the current source.

**ELECTRIC POINT DIPOLE (ON AXIS)**

Enter the **Electric current dipole moment in z direction**  $p_z$  (SI unit: A·m).



Electric Point Dipole

*Piezoresistive Material*

The **Piezoresistive Material** is normally used together with a **Piezoresistive Effect, Domain Currents** multiphysics coupling node. The node is added by default to the **Electric Currents** interface when adding a **Piezoresistivity, Domain Currents** predefined

multiphysics coupling interface. It is also available from the context menu (right-click the **Electric Currents** interface parent node) or from the **Physics** toolbar.



When the **Piezoresistive Material** node is added to the Electric Currents interface in the absence of an active **Piezoelectric Effect, Domain Currents** multiphysics coupling node, the material behaves similarly to a **Current Conservation** node, with electric properties corresponding to the relative permittivity and electrical conductivity entered. The piezoresistive effect is *not* included in the corresponding equation system.

#### PIEZORESISTIVE MATERIAL PROPERTY

This node should be used together with an active **Piezoresistive Effect, Domain Currents** multiphysics coupling node. Select a **Constitutive model** — **Piezoresistance form** or **Elastoresistance form**. For each of the following, the default uses values **From material**. For **User defined** enter other values in the matrix or field.

- Specify a **Electrical conductivity, zero stress** (SI unit: S/m). This typically comes from the material added under the Materials node.
- For **Piezoresistance form**, select a **Piezoresistance coupling matrix**  $\Pi_l$  (SI unit:  $\text{m}^4/(\text{s}\cdot\text{A}^2)$ ; note that this is equivalent to  $\Omega\cdot\text{m}/\text{Pa}$ ).
- For a **Elastoresistance form**, select an **Elastoresistance coupling matrix**  $M_l$  (SI unit:  $\Omega\cdot\text{m}$ ).



# The Electrical Circuit Interface

The **Electrical Circuit (cir)** interface () , found under the **AC/DC** branch () when adding a physics interface, is used to model currents and voltages in circuits including voltage and current sources, resistors, capacitors, inductors, and semiconductor devices. Models created with the Electrical Circuit interface can include connections to distributed field models. The physics interface supports stationary, frequency-domain and time-domain modeling and solves Kirchhoff's conservation laws for the voltages, currents and charges associated with the circuit elements.

When this physics interface is added, it adds a default **Ground Node** feature and associates that with node zero in the electrical circuit.



Circuit nodes are nodes in the electrical circuit (electrical nodes) and should not be confused with nodes in the Model Builder tree of the COMSOL Multiphysics software. Circuit node names are not restricted to numerical values but can contain alphanumeric characters.

## SETTINGS

The **Label** is the default physics interface name.

The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the `name` string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `cir`.

## RESISTANCE IN PARALLEL TO PN JUNCTIONS

For numerical stability, a large resistance is added automatically in parallel to the pn junctions in diodes and BJT devices. Enter a default value for the **Resistance in parallel to pn junctions**  $R_j$  (SI unit:  $\Omega$ ). The default value is  $1 \cdot 10^{12} \Omega$ .

## CREATE UNIQUE NODES FOR NEW DEVICES

When this setting is selected (the default), newly added devices will be assigned unused node names. The devices will be disconnected from the rest of the circuit and the nodes should be updated to reflect the actual circuit connections. When this setting is

deselected, new devices will be connected to the lowest-numbered nodes starting from 0.

|                                                                                   |                                                                                                                                                                           |
|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <ul style="list-style-type: none"><li>• <a href="#">Theory for the Electrical Circuit Interface</a></li><li>• <a href="#">Connecting to Electrical Circuits</a></li></ul> |
|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

**ELECTRICAL CIRCUIT TOOLBAR**

The following nodes are available from the **Electrical Circuit** ribbon toolbar (Windows users), **Electrical Circuit** context menu (Mac or Linux users), or right-click to access the context menu (all users):

|                                                                                   |                                                                                                                      |
|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
|  | For step-by-step instructions and general documentation descriptions, this is the <b>Electrical Circuit</b> toolbar. |
|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|

- |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• <a href="#">Ground Node</a></li><li>• <a href="#">Voltmeter</a></li><li>• <a href="#">Ampère Meter</a></li><li>• <a href="#">Resistor</a></li><li>• <a href="#">Capacitor</a></li><li>• <a href="#">Inductor</a></li><li>• <a href="#">Voltage Source</a></li><li>• <a href="#">Current Source</a></li><li>• <a href="#">Diode</a></li><li>• <a href="#">Switch</a></li><li>• <a href="#">Voltage-Controlled Voltage Source</a><sup>1</sup></li><li>• <a href="#">Voltage-Controlled Current Source</a><sup>1</sup></li><li>• <a href="#">Current-Controlled Voltage Source</a><sup>1</sup></li><li>• <a href="#">Current-Controlled Current Source</a><sup>1</sup></li></ul> | <ul style="list-style-type: none"><li>• <a href="#">Subcircuit Definition</a></li><li>• <a href="#">Subcircuit Instance</a></li><li>• <a href="#">Mutual Inductance</a></li><li>• <a href="#">Transformer</a></li><li>• <a href="#">NPN BJT and PNP BJT</a><sup>2</sup></li><li>• <a href="#">n-Channel MOSFET and p-Channel MOSFET</a><sup>2</sup></li><li>• <a href="#">External I vs. U</a><sup>3</sup></li><li>• <a href="#">External U vs. I</a><sup>3</sup></li><li>• <a href="#">External I-Terminal</a><sup>3</sup></li><li>• <a href="#">SPICE Circuit Import</a></li><li>• <a href="#">SPICE Circuit Export</a></li></ul> |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

<sup>1</sup> Selected from the **Dependent Sources** submenu when you right-click main node.  
<sup>2</sup> Selected from the **Transistors** submenu when you right-click main node.  
<sup>3</sup> Selected from the **External Couplings** submenu when you right-click main node.

## *Ground Node*

---

The **Ground Node** () feature adds a ground node with the default node number zero to the electrical circuit. This is the default node in the Electrical Circuit interface. More ground nodes can be added but those must have unique node numbers and are by default given higher node numbers.

### **GROUND CONNECTION**

Set the **Node name** for the ground node in the circuit. The convention is to use 0 (zero) for the ground node. If adding more ground nodes, each must have a unique node name (number).

## *Voltmeter*

---

The **Voltmeter** () feature connects a voltmeter (voltage measurement device) between two nodes in the electrical circuit. A voltmeter behaves electrically as an open circuit. The voltmeter node adds a Probe sampling the voltage across it.

### **NODE CONNECTIONS**

Set the two **Node names** for the connecting nodes for the resistor.

## *Ampère Meter*

---

The **Ammeter** () feature connects an ammeter (current measurement device) between two nodes in the electrical circuit. An ammeter behaves electrically as a short circuit. The ammeter node adds a Probe sampling the current through it.

### **NODE CONNECTIONS**

Set the two **Node names** for the connecting nodes for the resistor.

### **DEVICE PARAMETERS**

Enter the **Resistance** of the resistor.

## *Resistor*

---

The **Resistor** () feature connects a resistor between two nodes in the electrical circuit.

### **NODE CONNECTIONS**

Set the two **Node names** for the connecting nodes for the resistor.

#### DEVICE PARAMETERS

Enter the **Resistance** of the resistor.

#### *Capacitor*

---

The **Capacitor** () feature connects a capacitor between two nodes in the electrical circuit.

#### NODE CONNECTIONS

Set the two **Node names** for the connecting nodes for the capacitor.

#### DEVICE PARAMETERS

Enter the **Capacitance** of the capacitor.

#### *Inductor*

---

The **Inductor** () feature connects an inductor between two nodes in the electrical circuit.

#### NODE CONNECTIONS

Set the two **Node names** for the connecting nodes for the inductor.

#### DEVICE PARAMETERS

Enter the **Inductance** of the inductor.

#### *Voltage Source*

---

The **Voltage Source** () feature connects a voltage source between two nodes in the electrical circuit.

#### NODE CONNECTIONS

Set the two **Node names** for the connecting nodes for the voltage source. The first node represents the positive reference terminal.

DEVICE PARAMETERS

Enter the **Source type** that should be adapted to the selected study type. It can be **DC-source**, **AC-source**, or a time-dependent **Sine source** or **Pulse source**. Depending on the choice of source, also specify the following parameters:

- For a DC-source, the **Voltage  $V_{src}$**  (default value: 1 V). DC-sources are active in Stationary and Time-Dependent studies.
- For an AC-source: the **Voltage  $V_{src}$**  (default value: 1 V) and the **Phase  $\Theta$**  (default value: 0 rad). AC-sources are active in Frequency Domain studies only.
- For a sine source: the **Voltage  $V_{src}$**  (default value: 1 V), the **Offset  $V_{off}$**  (default value: 0 V), the **Frequency** (default value: 1 kHz), and the **Phase  $\Theta$**  (default value: 0 rad). The sine sources are active in Time-Dependent studies and also in Stationary studies, providing that a value for  $t$  has been provided as a model parameter or global variable.
- For a pulse source: the **Voltage  $V_{src}$**  (default value: 1 V), the **Offset  $V_{off}$**  (default value: 0 V), the **Delay  $t_d$**  (default value: 0s), the **Rise time  $t_r$**  and **Fall time  $t_f$**  (default values: 0 s), the **Pulse width  $p_w$**  (default value: 1  $\mu$ s), and the **Period  $T_{per}$**  (default value: 2  $\mu$ s). The pulse sources are active in Time-Dependent studies and also in Stationary studies, providing that a value for  $t$  has been provided as a model parameter or global variable.

All values are peak values rather than RMS.



For the AC source, the frequency is a global input set by the solver. AC sources should be used in Frequency-domain studies only. Do not use the **Sine source** unless the model is time-dependent.

Current Source

The **Current Source** (  ) feature connects a current source between two nodes in the electrical circuit.

NODE CONNECTIONS

Set the two **Node names** for the connecting nodes for the current source. The first node represents the positive reference terminal from where the current flows through the source to the second node.

## DEVICE PARAMETERS

Enter the **Source type** that should be adapted to the selected study type. It can be **DC-source**, **AC-source**, or a time-dependent **Sine source** or **Pulse source**. Depending on the choice of source, also specify the following parameters:

- For a DC-source, the **Current  $i_{src}$**  (default value: 1 A). DC-sources are active in Stationary and Time-Dependent studies.
- For an AC-source: the **Current  $i_{src}$**  (default value: 1 A) and the **Phase  $\Theta$**  (default value: 0 rad). AC-sources are active in Frequency Domain studies only.
- For a sine source: the **Current  $i_{src}$**  (default value: 1 A), the **Offset  $i_{off}$**  (default value: 0 A), the **Frequency** (default value: 1 kHz), and the **Phase  $\Theta$**  (default value: 0 rad). The sine sources are active in Time-Dependent studies and also in Stationary studies, providing that a value for  $t$  has been provided as a model parameter or global variable.
- For a pulse source: the **Current  $i_{src}$**  (default value: 1 A), the **Offset  $i_{off}$**  (default value: 0 A), the **Delay  $t_d$**  (default value: 0 s), the **Rise time  $t_r$**  and **Fall time  $t_f$**  (default values: 0 s), the **Pulse width  $p_w$**  (default value: 1  $\mu$ s), and the **Period  $T_{per}$**  (default value: 2  $\mu$ s). The pulse sources are active in Time-Dependent studies and also in Stationary studies, providing that a value for  $t$  has been provided as a model parameter or global variable.

All values are peak values rather than RMS.



For the AC source, the frequency is a global input set by the solver. AC sources should be used in frequency-domain studies only. Do not use the **Sine source** unless the model is time-dependent.

## *Voltage-Controlled Voltage Source*

The **Voltage-Controlled Voltage Source** () feature connects a voltage-controlled voltage source between two nodes in the electrical circuit. A second pair of nodes define the input control voltage.

## NODE CONNECTIONS

Specify four **Node names**: the first pair for the connection nodes for the voltage source and the second pair defining the input control voltage. The first node in a pair represents the positive reference terminal.

## DEVICE PARAMETERS

There are two options to define the relationship between the control voltage and resulting voltage. The **Use gain** method defines the resulting voltage to be the control voltage multiplied by the gain. The **Custom expression** method can define the relationship with an arbitrary expression.

### *Voltage-Controlled Current Source*

---

The **Voltage-Controlled Current Source** () feature connects a voltage-controlled current source between two nodes in the electrical circuit. A second pair of nodes define the input control voltage.

## NODE CONNECTIONS

Specify four **Node names**: the first pair for the connection nodes for the current source and the second pair defining the input control voltage. The first node in a pair represents the positive voltage reference terminal or the one from where the current flows through the source to the second node.

## DEVICE PARAMETERS

There are two options to define the relationship between the control voltage and resulting current. The **Use gain** method defines the resulting current to be the control voltage multiplied by the gain (SI units: S). The **Custom expression** method can define the relationship with an arbitrary expression.

### *Current-Controlled Voltage Source*

---

The **Current-Controlled Voltage Source** () feature connects a current-controlled voltage source between two nodes in the electrical circuit. The input control current is the one flowing through a two-pin device.

## NODE CONNECTIONS

Set two **Node names** for the connection nodes for the voltage source. The first node in a pair represents the positive reference terminal.

## DEVICE PARAMETERS

There are two options to define the relationship between the control current and resulting voltage. The **Use gain** method defines the resulting voltage to be the control current multiplied by the gain (SI units:  $\Omega$ ). The **Custom expression** method can define the relationship with an arbitrary expression.

## *Current-Controlled Current Source*

---

The **Current-Controlled Current Source** () feature connects a current-controlled current source between two nodes in the electrical circuit. The input control current is the one flowing through a named device that must be a two-pin device.

### **NODE CONNECTIONS**

Specify two **Node names** for the connection nodes for the current source. The first node in a pair represents the positive reference terminal from where the current flows through the source to the second node.

### **DEVICE PARAMETERS**

There are two options to define the relationship between the control current and resulting current. The **Use gain** method defines the resulting current to be the control current multiplied by the gain. The **Custom expression** method can define the relationship with an arbitrary expression.

## *Switch*

---

The **Switch** () feature is used to connect or disconnect the conducting path in a circuit under specific conditions.

### **NODE CONNECTIONS**

Specify two **Node names** for the connection nodes for the current source. The first node in a pair represents the positive reference terminal from where the current flows through the source to the second node.

### **SWITCH CONDITIONS**

There are three types of conditions, **Voltage controlled**, **Current controlled**, and **Custom expressions**. For each type of condition there are two conditions, one for turn on and one for turn off. The on condition is true if the **On condition** expression is larger than zero, while the off condition is true if the **Off condition** is less than zero.

The **Initial state** list has three options, **Use on condition**, **Use off condition**, and **Boolean expression**. The two former options mean that the switch will have an initial state matching to the on or off condition. The third option makes the switch's initial state match a custom Boolean expression. Separating on, off, and initial states makes the switch more flexible and can support Schmitt-trigger style switches and various latches.



For the **Voltage controlled** switch, it is necessary to specify two nodes that defines the voltage `sens.v` that the switch state depends on. The conditions must be written as a function of this variable. Similarly, for the **Current controlled** switch it is necessary to specify a two-pin device that defines the current `sens.i` that the switch state depends on.

## SWITCH PARAMETERS

When the switch is in the on state it has a non-zero resistance specified by the **On resistance** expression. For the off state no current flows through the switch (infinite resistance). There is also a transition time for the switch to turn on and off set by the **Switching time** expression. The switch triggers an implicit event that updates a discrete state variable (with suffix `_state`).

## *Subcircuit Definition*

---

The **Subcircuit Definition** () feature is used to define subcircuits, which can be inserted as devices into the main circuit using **Subcircuit Instance** nodes. Create the subcircuit by adding subnodes to the **Subcircuit Definition** node, either by using the **Physics** toolbar, or by right-clicking the **Subcircuit Definition**.

## SUBCIRCUIT PINS

Define the **Pin names** at which the subcircuit connects to the main circuit or to other subcircuits when referenced by a **Subcircuit Instance** node. The **Pin names** refer to circuit nodes in the subcircuit. The order in which the **Pin names** are defined is the order in which they are referenced by a Subcircuit Instance node. The devices constituting the subcircuit should be connected only to the subcircuit's pins and to themselves.

## INPUT PARAMETERS

To display this section, click the **Show More Options** button () and select **Advanced Physics Options**. Specify input parameters to a subcircuit that can be changed from a subcircuit instance. These input parameters can be used in all expression-style edit fields that affect the parameters of a device, for example, resistance, capacitance, and current gain. In this way, a subcircuit can represent a parameterized custom device model.

## Subcircuit Instance

---

The **Subcircuit Instance** () feature represents an instance of a subcircuits defined by a [Subcircuit Definition](#) feature.

### NODE CONNECTIONS

Select the **Name of subcircuit link** from the list of defined subcircuits in the circuit model and the circuit **Node names** at which the subcircuit instance connects to the main circuit or to another subcircuit if used therein.

### INPUT PARAMETERS

To display this section, click the **Show More Options** button () and select **Advanced Physics Options**. Specify input parameters to a subcircuit that can be changed from a subcircuit instance. These input parameters can be used in all expression-style edit fields that affect the parameters of a device, for example, resistance, capacitance, and current gain. In this way, a subcircuit can represent a parameterized custom device model.

## NPN BJT and PNP BJT

---

The **NPN BJT** () and the **PNP BJT** () device models are large-signal models for bipolar junction transistors (BJT). It is an advanced device model and no thorough description and motivation of the many input parameters are attempted here. Many device manufacturers provide model input parameters for this BJT model. For any particular make of BJT, the device manufacturer should be the primary source of information.

### NODE CONNECTIONS

Specify three **Node names** for the connection nodes for the **BJT** device. These represent the *collector*, *base*, and *emitter* nodes for the **NPN** transistor, and the *emitter*, *base*, and *collector* nodes for the **PNP** transistor.

MODEL PARAMETERS

Specify the **Model Parameters**. Reasonable defaults are provided but for any particular BJT, the device manufacturer should be the primary source of information.



The interested reader is referred to [Ref. 2](#) for more details on semiconductor modeling within circuits.

For an explanation of the **Model Parameters** see [Bipolar Transistors](#).

*n-Channel MOSFET and p-Channel MOSFET*

The **n-Channel MOSFET** () and the **p-Channel MOSFET** () device models are large-signal models for, respectively, an n-Channel MOS field-effect transistor (MOSFET) and p-Channel MOSFET. These are advanced device models and no thorough description and motivation of the many input parameters are attempted here. Many device manufacturers provide model parameters for the MOSFET models. For any particular make of MOSFET, the device manufacturer should be the primary source of information.

NODE CONNECTIONS

Specify four **Node names** for the connection nodes for the **n-Channel MOSFET** or **p-Channel MOSFET** device. These represent the *drain*, *gate*, *source*, and *bulk* nodes, respectively.

MODEL PARAMETERS

Specify the **Model Parameters**. Reasonable defaults are provided but for any particular MOSFET, the device manufacturer should be the primary source of information.



The interested reader is referred to [Ref. 2](#) for more details on semiconductor modeling within circuits.

For an explanation of the **Model Parameters** see [MOSFET Transistors](#).

*Mutual Inductance*

The **Mutual Inductance** allows specifying a coupling between two existing [Inductor](#) features in the circuit. The mutual inductance of the coupling is

$$M = k\sqrt{L_1 L_2}$$

where  $k$  is the coupling factor and  $L_1$  and  $L_2$  are the inductances of the inductors.

#### DEVICE PARAMETERS

Enter values or expressions for the:

- **Coupling factor**  $k$  (dimensionless). The value must be between 0 and 1, and the default is 0.98.
- **First inductance**  $L_1$  (SI unit: H) and **Second inductance**  $L_2$  (SI unit: H). These must be set to two different [Inductor](#) features in the circuit.

### *Transformer*

---

The **Transformer** feature represents either a combination of two [Inductor](#) and a [Mutual Inductance](#) features, or an ideal transformer.

#### NODE CONNECTIONS

Enter or edit the table in the **Node names** column for the **primary** and **secondary** node connections.

#### DEVICE PARAMETERS

Choose a **Transformer model** — **Specify inductors** (the default) or **Ideal transformer**.

For **Specify inductors** enter values or expressions for the:

- **Coupling factor**  $k$  (dimensionless). The default is 0.98.
- **First inductance**  $L_1$  (SI unit: H). The default is 1 mH.
- **Second inductance**  $L_2$  (SI unit: H). The default is 1 mH.

For **Ideal transformer** enter values or expressions for the **Winding ratio**  $N_1/N_2$  (dimensionless). The default is 10.

### *Diode*

---

The **Diode** device model () is a large-signal model for a diode. It is an advanced device model and no thorough description and motivation of the many input parameters are attempted here. The interested reader is referred to [Ref. 2](#) for more details on semiconductor modeling within circuits. Many device manufacturers

provide model parameters for this diode model. For any particular make of diode, the device manufacturer should be the primary source of information.

#### NODE CONNECTIONS

Specify two **Node names** for the positive and negative nodes for the **Diode** device.

#### MODEL PARAMETERS

Specify the **Model Parameters**. Reasonable defaults are provided but for any particular diode, the device manufacturer should be the primary source of information.



For an explanation of the **Model Parameters** see [Diode](#).

---

### *External I vs. U*

The **External I vs. U** () feature connects an arbitrary voltage measurement (for example, a circuit terminal or circuit port boundary or a coil domain from another physics interface) as a voltage source between two nodes in the electrical circuit. The resulting circuit current from the first node to the second node is typically coupled back as a prescribed current source in the context of the voltage measurement.

#### NODE CONNECTIONS

Specify the two **Node names** for the connecting nodes for the voltage source. The first node represents the positive reference terminal.

#### EXTERNAL DEVICE

Enter the source of the **Voltage**. If circuit or current excited terminals or circuit ports are defined on boundaries or domains or a multiturn coil domains is defined in other physics interfaces, these display as options in the **Voltage** list. Also select the **User defined** option and enter your own voltage variable, for example, using a suitable coupling operator. For inductive or electromagnetic wave propagation models, the voltage measurement must be performed as an integral of the electric field because the electric

potential only does not capture induced EMF. Also the integration must be performed over a distance that is short compared to the local wavelength.



Except when coupling to a circuit terminal, circuit port, or coil, the current flow variable must be manually coupled back in the electrical circuit to the context of the voltage measurement. This applies also when coupling to a current excited terminal. The name of this current variable follows the convention `cirn.IvsUm_i`, where `cirn` is the tag of the Electrical Circuit interface node and `IvsUm` is the tag of the **External I vs. U** node. The tags are typically displayed within curly brackets `{}` in the Model Builder.



[Nonlocal Couplings and Coupling Operators](#) in the *COMSOL Multiphysics Reference Manual*

### *External U vs. I*

The **External U vs. I** () feature connects an arbitrary current measurement (for example, a coil domain from another physics interface) as a current source between two nodes in the electrical circuit. The resulting circuit voltage between the first node and the second node is typically coupled back as a prescribed voltage source in the context of the current measurement.

#### **NODE CONNECTIONS**

Specify the two **Node names** for the connecting nodes for the current source. The current flows from the first node to the second node.

#### **EXTERNAL DEVICE**

Enter the source of the **Current**. Voltage excited terminals or lumped ports defined on boundaries in other physics interfaces are natural candidates but do not appear as options in the **Voltage** list because those do not have an accurate built-in current

measurement variable. A **User defined** option must be selected and a current variable entered, for example, using a suitable coupling operator.



The voltage variable must be manually coupled back in the electrical circuit to the context of the current measurement. This applies also when coupling to a voltage excited terminal or lumped port. The name of this voltage variable follows the convention `cirn.UvsIm_v`, where `cirn` is the tag of the Electrical Circuit interface node and `UvsIm` is the tag of the **External U vs. I** node. The tags are typically displayed within curly brackets `{ }` in the Model Builder.



[Nonlocal Couplings and Coupling Operators](#) in the *COMSOL Multiphysics Reference Manual*

### *External I-Terminal*

The **External I-Terminal** () feature connects an arbitrary voltage-to-ground measurement (for example, a circuit terminal from another physics interface) as a voltage-to-ground assignment to a node in the electrical circuit. The resulting circuit current from the node is typically coupled back as a prescribed current source in the context of the voltage measurement. This node does not apply when coupling to inductive or electromagnetic wave propagation models because then voltage must be defined as a line integral between two points rather than a single point measurement of electric potential. For such couplings, use the [External I vs. U](#) node instead.

#### **NODE CONNECTIONS**

Set the **Node name** for the connecting node for the voltage assignment.

#### **EXTERNAL TERMINAL**

Enter the source of the **Voltage**. If circuit- or current-excited terminals are defined on boundaries in other physics interfaces, these display as options in the **Voltage** list. Also

select the **User defined** option and enter a voltage variable, for example, using a suitable coupling operator.

|                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | Except when coupling to a circuit terminal, the current flow variable must be manually coupled back in the electrical circuit to the context of the voltage measurement. This applies also when coupling to a current excited terminal. The name of this current variable follows the convention <code>cirn.termIm_i</code> , where <code>cirn</code> is the tag of the Electrical Circuit interface node and <code>termIm</code> is the tag of the <b>External I-Terminal</b> node. The tags are typically displayed within curly brackets <code>{ }</code> in the Model Builder. |
|  | <a href="#">Nonlocal Couplings and Coupling Operators</a> in the <i>COMSOL Multiphysics Reference Manual</i> .                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |

### SPICE Circuit Import

Right-click the **Electrical Circuit** () feature node to import an existing SPICE netlist (select **Import Spice Netlist**). A window opens — enter a file location or browse your directories to find one. The default file extension for a SPICE netlist is `.cir`. The SPICE circuit import translates the imported netlist into Electrical Circuit interface nodes so these define the subset of SPICE features that can be imported.

|                                                                                     |                                                                                 |
|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
|  | See <a href="#">SPICE Import and Export</a> about the supported SPICE commands. |
|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|

### SPICE Circuit Export

Right-click the **Electrical Circuit** () feature node to export the current circuit to the SPICE netlist file format (select **Export Spice Netlist** ). A window opens — enter a file location or browse your directories to find one. The default file extension for a SPICE netlist is `.cir`. The compatible circuit nodes are exported as SPICE devices

|                                                                                     |                                                                        |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------|
|  | See <a href="#">for more details on the supported SPICE commands</a> . |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------|





# Theory for the Electrostatics Interface

The [Electrostatics Interface](#) is available for 3D, 2D in-plane, and 2D axisymmetric components. Applications with electrostatic equations include high-voltage apparatus, electronic devices, and capacitors. The term “statics” is not to be interpreted literally — it is the observation time, or time scale at which the applied excitation changes, that is short compared to the charge relaxation time; also, the electromagnetic wavelength and skin depth are very large compared to the size of the domain of interest.

If you do not know whether to use the Electric Currents or the Electrostatics interface, which both solve for the scalar electric potential  $V$ , consider using an explicit charge transport model. See [Charge Relaxation Theory](#).

## *Charge Relaxation Theory*

---

COMSOL Multiphysics includes physics interfaces for the modeling of static electric fields and currents. Deciding what specific physics interface and study type to select for a particular modeling situation requires a basic understanding of the charge dynamics in conductors.

The different physics interfaces involving only the scalar electric potential can be interpreted in terms of the charge relaxation process. The fundamental equations involved are *Ohm's law* for the conduction current density

$$\mathbf{J}_c = \sigma \mathbf{E}$$

the *equation of continuity*

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{J}_c = 0$$

and *Gauss' law*

$$\nabla \cdot (\epsilon \mathbf{E}) = \rho$$

By combining these, one can deduce the following differential equation for the space charge density in a homogeneous medium

$$\frac{\partial \rho}{\partial t} + \frac{\sigma}{\epsilon} \rho = 0$$

This equation has the solution

$$\rho(t) = \rho_0 e^{-t/\tau}$$

where

$$\tau = \frac{\epsilon}{\sigma}$$

is called the charge relaxation time. For a good conductor like copper,  $\tau$  is of the order of  $10^{-19}$  s, whereas for a good insulator like silica glass, it is of the order of  $10^3$  s. For a pure insulator, it becomes infinite.

When modeling real-world devices, there is not only the *intrinsic time scale* of the charge relaxation time but also an *external time scale*  $t$  at which a device is energized or the observation time. It is the relation between the external time scale and the charge relaxation time that determines what physics interface and study type to use. The results are summarized in [Table 3-3](#) below,

TABLE 3-3: SUITABLE PHYSICS INTERFACE AND STUDY TYPE FOR DIFFERENT TIME-SCALE REGIMES.

| CASE          | PHYSICS INTERFACE | STUDY TYPE                         |
|---------------|-------------------|------------------------------------|
| $\tau \gg t$  | Electrostatics    | Stationary                         |
| $\tau \ll t$  | Electric Currents | Stationary                         |
| $\tau \sim t$ | Electric Currents | Time Dependent or Frequency Domain |

#### FIRST CASE: $\tau \gg t$

If the external time scale is short compared to the charge relaxation time, the charges do not have time to redistribute to any significant degree. Thus the charge distribution can be considered as a given model input. The best approach is to solve the Electrostatics formulation using the electric potential  $V$ .

By combining the definition of the potential with Gauss' law, you can derive the classical Poisson's equation. Under static conditions, the electric potential  $V$  is defined by the equivalence  $\mathbf{E} = -\nabla V$ . Using this together with the constitutive relation  $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$  between  $\mathbf{D}$  and  $\mathbf{E}$ , you can rewrite Gauss' law as a variant of Poisson's equation

$$-\nabla \cdot (\epsilon_0 \nabla V - \mathbf{P}) = \rho$$

This equation is used in the Electrostatics interface. It is worth noting that Gauss' law does not require the charge distribution to be static. Thus, provided dynamics are slow enough that induced electric fields can be neglected and hence a scalar electric potential is justified, the formulation can be used also in the Time Dependent study type. That typically involves either prescribing the charge dynamics or coupling a separate formulation for this.



Such separate charge transport formulations can be found in the Plasma Module, the Semiconductor Module, and the Chemical Reaction Engineering Module.

#### **SECOND CASE: $\tau < T$**

If the external time scale is long compared to the charge relaxation time, the stationary solution to the equation of continuity has been reached. In a stationary coordinate system, a slightly more general form of Ohm's law than above states that

$$\mathbf{J}_c = \sigma \mathbf{E} + \mathbf{J}_e$$

where  $\mathbf{J}_e$  is an externally generated current density. The static form of the equation of continuity then reads

$$\nabla \cdot \mathbf{J}_c = -\nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = 0$$

To handle current sources, the equation can be generalized to

$$-\nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = Q_j$$

This equation is used in the static study type for the Electric Currents interface.

#### **GENERAL CASE: CHARGE DYNAMICS**

If the charge relaxation time is comparable to the external time scale, the Time Dependent or Frequency Domain study types for the Electric Currents interface must be used.

Combining the time-harmonic equation of continuity

$$\nabla \cdot \mathbf{J}_c = \nabla \cdot (\sigma \mathbf{E} + \mathbf{J}_e) = -j\omega \rho$$

with the equation  $(\nabla \cdot \mathbf{D} = \rho)$  yields the following equation for the frequency domain study type:

$$-\nabla \cdot ((\sigma + j\omega\epsilon_0)\nabla V - (\mathbf{J}_e + j\omega\mathbf{P})) = 0$$

For the Time Dependent study type, use the transient equation of continuity

$$\nabla \cdot \mathbf{J}_e = \nabla \cdot (\sigma \mathbf{E} + \mathbf{J}_e) = -\frac{\partial \rho}{\partial t}$$

and the resulting equation becomes

$$-\nabla \cdot \frac{\partial}{\partial t}(\epsilon_0 \nabla V + \mathbf{P}) - \nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = 0$$

These dynamic formulations are valid as long as induced electric fields can be ignored and hence the electric field is essentially curl free. This condition is fulfilled provided that skin effect and wave propagation effects can be ignored. The skin depth must be much larger than the geometrical dimensions of the modeled device and so must the wavelength. Note also that these formulations can be used to model dielectric regions of capacitive/resistive devices even though the interior of electrodes sometimes does not meet the large skin depth condition. In that case, the electrodes must only be represented as boundary conditions (fixed or floating potential). The interior, metallic domains are not included in the analysis. Obviously, this is only a valid approach for devices where metallic electrodes do not entirely bypass (short circuit) the capacitive/resistive layers. If metallic electrodes short circuit the capacitive/resistive layers, the time evolution of the current is determined by inductive and resistive effects with very little influence from the capacitive layers. Then the Magnetic Fields interface is the appropriate modeling tool.

### *Electrostatics Equations*

---

Under static conditions, the electric potential,  $V$ , is defined by the relationship:

$$\mathbf{E} = -\nabla V$$

Combining this equation with the constitutive relationship  $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$  between the electric displacement  $\mathbf{D}$  and the electric field  $\mathbf{E}$ , it is possible to represent Gauss' law as the following equation:

$$-\nabla \cdot (\epsilon_0 \nabla V - \mathbf{P}) = \rho$$

In this equation, the physical constant,  $\epsilon_0$  (SI unit: F/m) is the permittivity of vacuum,  $\mathbf{P}$  (SI unit: C/m<sup>2</sup>) is the electric polarization vector, and  $\rho$  (SI unit: C/m<sup>3</sup>) is a space charge density. This equation describes the electrostatic field in dielectric materials.

For in-plane 2D modeling, the Electrostatics interface assumes a symmetry where the electric potential varies only in the  $x$  and  $y$  directions and is constant in the  $z$  direction. This implies that the electric field,  $\mathbf{E}$ , is tangential to the  $xy$ -plane. With this symmetry, the same equation is solved as in the 3D case. The physics interface solves the following equation where  $d$  is the thickness in the  $z$  direction:

$$-\nabla \cdot d(\epsilon_0 \nabla V - \mathbf{P}) = \rho$$

The axisymmetric version of the physics interface considers the situation where the fields and geometry are axially symmetric. In this case, the electric potential is constant in the  $\phi$  direction, which implies that the electric field is tangential to the  $rz$ -plane.

### *The Electrostatics Interface in Time Dependent or Frequency Domain Studies*

The [Electrostatics Interface](#) can also be solved in a dynamic study (Time Dependent or Frequency Domain). The equation system solved, however, is typically always the one presented in the previous section for the stationary case, in which no transient electromagnetic effects are taken into account. The difference is that the sources of the problem (charge densities, electric potential) are assumed to be time-varying (in a Time Dependent study) or time-harmonic (in a Frequency Domain study).



Users that have a license supporting the piezoelectric material model can also include conduction losses in the frequency domain.

The support for dynamic studies simplifies the coupling of the Electrostatics interface with other physics interfaces. Using the physics interface in a dynamic study is a valid approximation only if the time-scale (or the frequency) of the study is so slow that transient electromagnetic effects can be neglected; for example, in acoustic or structural problems.

Most of the features in the Electrostatics interface have the same behavior in all study types, with the important exception of the Terminal node.

The Electrostatics interface also supports the small-signal analysis study sequence, which can be used when a time-harmonic perturbation is superposed on a static bias charge or voltage.

The ferroelectricity phenomenon is related to phase transitions in materials. In its ferroelectric phase, the material exhibits spontaneous polarization, so that it is constituted of domains with nonzero polarization even at zero applied field. This is similar to permanent magnetism in ferromagnetics, which explains the name used for such materials. Application of an electric field can rearrange the domains resulting into the net polarization in the material. At very large electric fields, the polarization saturates, as all ferroelectric domains in the material are aligned along the direction of the applied field. Domain wall interactions can also lead to a significant hysteresis in the polarization.

All domains are assumed to have polarization of the same magnitude  $P_s$ , but the polarization can have different orientations. The applied magnetic field changes the domain orientation, and the resulting net polarization in the ferroelectric material is found from the following nonlinear implicit relation:

$$\mathbf{P} = P_s L(|\mathbf{E}_{\text{eff}}|) \frac{\mathbf{E}_{\text{eff}}}{|\mathbf{E}_{\text{eff}}|} \quad (3-1)$$

The effective field in the material is given by

$$\mathbf{E}_{\text{eff}} = \mathbf{E} + \alpha \mathbf{P}$$

where the matrix  $\alpha$  characterizes the inter-domain coupling.

The polarization shape is characterized by the function  $L$  with the following properties:

For weak effective fields, the polarization is nearly linear

$$\mathbf{P} \approx \chi_0 \mathbf{E}_{\text{eff}}$$

and can be characterized by the initial electric susceptibility matrix  $\chi_0$ .

For strong fields, the polarization magnitude approaches the saturation value

$$\mathbf{P} \approx P_s \frac{\mathbf{E}_{\text{eff}}}{|\mathbf{E}_{\text{eff}}|}$$

Two possible choices are the Langevin function

$$L = \coth\left(\frac{3\chi_0|\mathbf{E}_{\text{eff}}|}{P_s}\right) - \frac{P_s}{3\chi_0|\mathbf{E}_{\text{eff}}|}$$

and a hyperbolic tangent:

$$L = \tanh\left(\frac{\chi_0|\mathbf{H}_{\text{eff}}|}{P_s}\right)$$

### HYSTERSIS MODELING

The Jiles–Atherton hysteresis model for ferroelectric materials is available COMSOL Multiphysics. The model assumes that the total polarization can be represented as a sum of reversible and irreversible parts

$$\mathbf{P} = \mathbf{P}_{\text{rev}} + \mathbf{P}_{\text{irr}}$$

The polarization change can be computed from the following incremental equation:

$$d\mathbf{P} = \mathbf{c}_r d\mathbf{P}_{\text{an}} + (\mathbf{I} - \mathbf{c}_r) d\mathbf{P}_{\text{irr}}$$

where the reversibility is characterized by the matrix  $\mathbf{c}_r$ , and the anhysteretic polarization is found from a relation similar to [Equation 3-1](#):

$$\mathbf{P}_{\text{an}} = P_s L(|\mathbf{E}_{\text{eff}}|) \frac{\mathbf{E}_{\text{eff}}}{|\mathbf{E}_{\text{eff}}|}$$

The change of the irreversible polarization can be computed from

$$d\mathbf{P}_{\text{irr}} = \max(\zeta \cdot d\mathbf{E}_{\text{eff}}, 0) \frac{\zeta}{|\zeta|}$$

$$\zeta = \mathbf{k}_p^{-1}(\mathbf{P}_{\text{an}} - \mathbf{P}_{\text{irr}})$$

where the pinning loss is characterized by the matrix  $\mathbf{k}_p$ .

### REFERENCE

1. R.C. Smith and C.L. Hom, “A Domain Wall Model for Ferroelectric Hysteresis,” *Journal of Intelligent Material Systems and Structures*, vol. 10, no. 3, pp. 195–213, 1999.



# Theory for the Electric Currents Interface

The [Electric Currents Interface](#) solves a current conservation problem for the scalar electric potential  $V$  and is available for 3D, 2D in-plane, and 2D axisymmetric components. Electrolysis and the computation of resistances of grounding plates are examples that involve conductive media with electrical conductivities and electric currents. If you are uncertain of whether to use the Electric Currents or the Electrostatics interface, which both solve for the scalar electric potential  $V$ , refer to the section on [Charge Relaxation Theory](#).

In this section:

- [Electric Currents Equations in Steady State](#)
- [Dynamic Electric Currents Equations](#)

## *Electric Currents Equations in Steady State*

---

When handling stationary electric currents in conductive media you must consider the stationary equation of continuity. In a stationary coordinate system, the point form of *Ohm's law* states that:

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$

where  $\sigma$  is the electrical conductivity (SI unit: S/m), and  $\mathbf{J}_e$  is an externally generated current density (SI unit: A/m<sup>2</sup>). The static form of the equation of continuity then states:

$$\nabla \cdot \mathbf{J} = -\nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = 0$$

To handle current sources, you can generalize the equation to:

$$-\nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = Q_j$$

In planar 2D the Electric Currents interface assumes that the model has a symmetry where the electric potential varies only in the  $x$  and  $y$  directions and is constant in the  $z$  direction. This implies that the electric field,  $\mathbf{E}$ , is tangential to the  $xy$ -plane. The Electric Currents interface then solves the following equation, where  $d$  is the thickness in the  $z$  direction:

$$-\nabla \cdot d(\sigma \nabla V - \mathbf{J}_e) = dQ_j \quad (3-2)$$

In 2D axisymmetry, the Electric Currents interface considers the situation where the fields and geometry are axially symmetric. In this case, the electric potential is constant in the  $\phi$  direction, which implies that the electric field is tangential to the  $rz$ -plane.

### *Dynamic Electric Currents Equations*

---

In the Frequency Domain and Time Dependent study types dynamic formulations accounting for both conduction currents and displacement currents are used.

Combining the time-harmonic equation of continuity

$$\nabla \cdot (\sigma \mathbf{E} + \mathbf{J}_e) + j\omega \rho = 0$$

with the equation

$$\nabla \cdot \mathbf{D} = \rho$$

and generalized to handle current sources yields the following equation:

$$-\nabla \cdot ((\sigma + j\omega\epsilon_0)\nabla V - (\mathbf{J}_e + j\omega\mathbf{P})) = Q_j$$

For the transient case, using the transient equation of continuity

$$\nabla \cdot (\sigma \mathbf{E} + \mathbf{J}_e) + \frac{\partial \rho}{\partial t} = 0$$

and generalized to handle current sources the resulting equation becomes:

$$-\nabla \cdot \frac{\partial}{\partial t}(\epsilon_0 \nabla V - \mathbf{P}) - \nabla \cdot (\sigma \nabla V - \mathbf{J}_e) = Q_j \quad (3-3)$$

In planar 2D the dynamic formulations also involves the thickness  $d$  in the  $z$  direction:

$$-\nabla \cdot d((\sigma + j\omega\epsilon_0)\nabla V - (\mathbf{J}_e + j\omega\mathbf{P})) = dQ_j$$

$$-\nabla \cdot d\frac{\partial}{\partial t}(\epsilon_0 \nabla V - \mathbf{P}) - \nabla \cdot d(\sigma \nabla V - \mathbf{J}_e) = dQ_j$$

# Theory for the Electrical Circuit Interface

The [Electrical Circuit Interface](#) theory is discussed in this section:

- [Electric Circuit Modeling and the Semiconductor Device Models](#)
- [Bipolar Transistors](#)
- [MOSFET Transistors](#)
- [Diode](#)
- [Reference for the Electrical Circuit Interface](#)



## Connecting to Electrical Circuits

---

### *Electric Circuit Modeling and the Semiconductor Device Models*

---

Electrical circuit modeling capabilities are useful when simulating all sorts of electrical and electromechanical devices ranging from heaters and motors to advanced plasma reactors in the semiconductor industry. There are two fundamental ways that an electrical circuit model relates to a physical field model.

- The field model is used to get a better, more accurate description of a single device in the electrical circuit model.
- The electrical circuit is used to drive or terminate the device in the field model in such a way that it makes more sense to simulate both as a tightly coupled system.

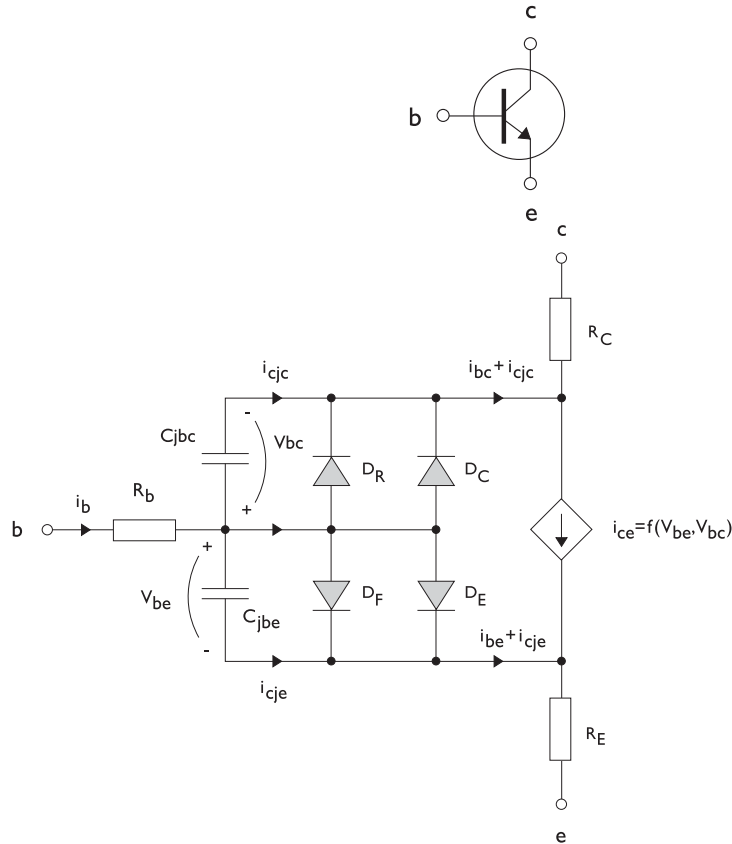
The Electrical Circuit interface makes it possible to add nodes representing circuit elements directly to the Model Builder tree in a COMSOL Multiphysics model. The circuit variables can then be connected to a physical device model to perform co-simulations of circuits and multiphysics. The model acts as a device connected to the circuit so that its behavior is analyzed in larger systems.

The fundamental equations solved by the Electrical Circuit interface are Kirchhoff's circuit laws, which in turn can be deduced from Maxwell's equations. The supported study types are Stationary, Frequency Domain, and Time Dependent.

There are three more advanced large-signal semiconductor device features available in the Electrical Circuit interface. The equivalent circuits and the equations defining their non-ideal circuit elements are described in this section. For a more complete treatise on semiconductor device modeling see [Ref. 2](#).

### Bipolar Transistors

[Figure 3-1](#) illustrates the equivalent circuit for the npn bipolar junction transistor.



*Figure 3-1: A circuit for the bipolar transistor.*

The pnp transistor model is similar in all regards to the npn transistor, with the difference that the polarities of the currents and voltages involved are reversed. The following equations are used to compute the relations between currents and voltages in the circuit.

$$\begin{aligned}
v_{rb} &= \frac{1}{A} \left( R_{BM} - \frac{R_B - R_{BM}}{f_{bq}} \right) i_b \\
f_{bq} &= \frac{1}{2 \left( 1 - \frac{v_{bc}}{V_{AF}} - \frac{v_{be}}{V_{AR}} \right)} \left( 1 + \sqrt{1 + 4 I_S \left( e^{\frac{v_{be}}{N_F V_T}} - 1 + e^{\frac{v_{bc}}{N_R V_T}} - 1 \right)} \right) \\
i_{be} &= A \left( \frac{I_S}{B_F} \left( e^{\frac{v_{be}}{N_F V_T}} - 1 \right) + I_{SE} \left( e^{\frac{v_{be}}{N_E V_T}} - 1 \right) \right) \\
i_{bc} &= A \left( \frac{I_S}{B_R} \left( e^{\frac{v_{bc}}{N_R V_T}} - 1 \right) + I_{SC} \left( e^{\frac{v_{bc}}{N_C V_T}} - 1 \right) \right) \\
i_{ce} &= A \left( \frac{I_S}{f_{bq}} \left( e^{\frac{v_{be}}{N_F V_T}} + e^{\frac{v_{bc}}{N_C V_T}} \right) \right) \\
V_T &= \frac{k_B T_{NOM}}{q}
\end{aligned}$$

There are also two capacitances that use the same formula as the junction capacitance of the diode model. In the parameter names below, replace  $x$  with  $C$  for the base-collector capacitance and  $E$  for the base-emitter capacitance.

$$C_{jbx} = AC_{Jx} \times \begin{cases} \left( 1 - \frac{v_{bx}}{V_{Jx}} \right)^{-M_{Jx}} & v_{bx} < F_C V_{Jx} \\ (1 - F_C)^{-1 - M_{Jx}} \left( 1 - F_C (1 + M_{Jx}) + M_{Jx} \frac{v_{bx}}{V_{Jx}} \right) & v_{bx} \geq F_C V_{Jx} \end{cases}$$

The model parameters are listed in the table below.

TABLE 3-1: BIPOLAR TRANSISTOR MODEL PARAMETERS

| PARAMETER | DEFAULT                 | DESCRIPTION                                    |
|-----------|-------------------------|------------------------------------------------|
| $B_F$     | 100                     | Ideal forward current gain                     |
| $B_R$     | 1                       | Ideal reverse current gain                     |
| $C_{JC}$  | 0 F/m <sup>2</sup>      | Base-collector zero-bias depletion capacitance |
| $C_{JE}$  | 0 F/m <sup>2</sup>      | Base-emitter zero-bias depletion capacitance   |
| $F_C$     | 0.5                     | Breakdown current                              |
| $I_{KF}$  | Inf (A/m <sup>2</sup> ) | Corner for forward high-current roll-off       |

TABLE 3-1: BIPOLAR TRANSISTOR MODEL PARAMETERS

| PARAMETER | DEFAULT         | DESCRIPTION                               |
|-----------|-----------------|-------------------------------------------|
| $I_{KR}$  | Inf ( $A/m^2$ ) | Corner for reverse high-current roll-off  |
| $I_S$     | $1e-15 A/m^2$   | Saturation current                        |
| $I_{SC}$  | $0 A/m^2$       | Base-collector leakage saturation current |
| $I_{SE}$  | $0 A/m^2$       | Base-emitter leakage saturation current   |
| $M_{JC}$  | 1/3             | Base-collector grading coefficient        |
| $M_{JE}$  | 1/3             | Base-emitter grading coefficient          |
| $N_C$     | 2               | Base-collector ideality factor            |
| $N_E$     | 1.4             | Base-emitter ideality factor              |
| $N_F$     | 1               | Forward ideality factor                   |
| $N_R$     | 1               | Reverse ideality factor                   |
| $R_B$     | $0 \Omega m^2$  | Base resistance                           |
| $R_{BM}$  | $0 \Omega m^2$  | Minimum base resistance                   |
| $R_C$     | $0 \Omega m^2$  | Collector resistance                      |
| $R_E$     | $0 \Omega m^2$  | Emitter resistance                        |
| $T_{NOM}$ | 298.15 K        | Device temperature                        |
| $V_{AF}$  | Inf (V)         | Forward Early voltage                     |
| $V_{AR}$  | Inf (V)         | Reverse Early voltage                     |
| $V_{JC}$  | 0.71 V          | Base-collector built-in potential         |
| $V_{JE}$  | 0.71 V          | Base-emitter built-in potential           |

Figure 3-2 illustrates an equivalent circuit for the n-channel MOSFET transistor. The p-channel MOSFET transistor is treated similarly, but the polarities of the involved voltages are reversed.

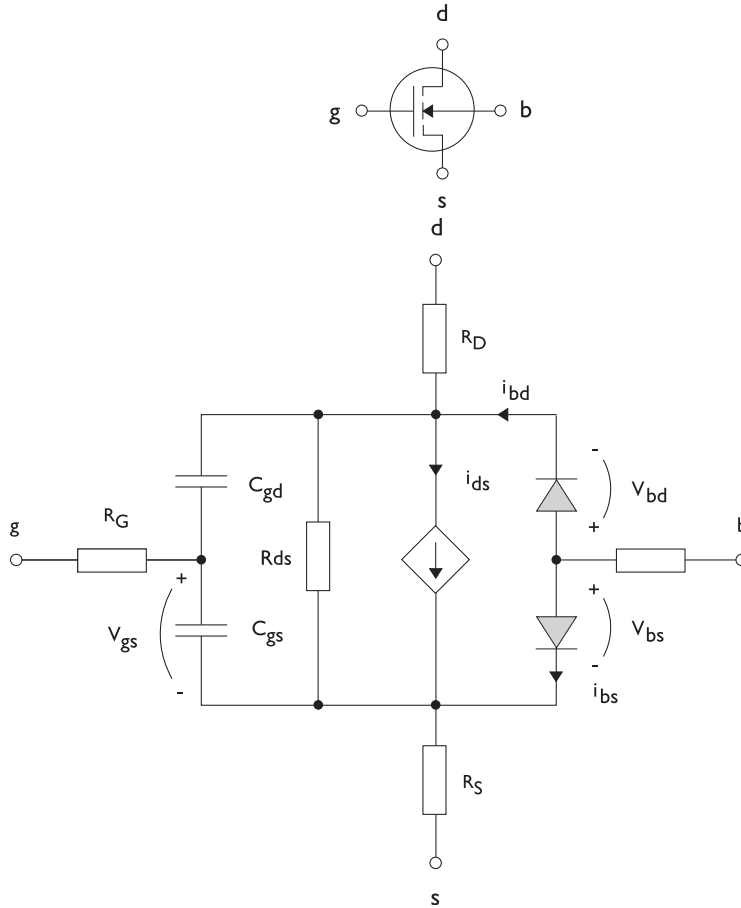


Figure 3-2: A circuit for the MOSFET transistor.

The following equations are used to compute the relations between currents and voltages in the circuit.

$$i_{ds} = \begin{cases} \frac{WK_P}{L} \frac{1}{2} (1 + \Lambda v_{ds}) v_{ds} (2v_{th} - v_{ds}) & v_{ds} < v_{th} \\ \frac{WK_P}{L} \frac{1}{2} (1 + \Lambda v_{ds}) v_{th}^2 & v_{ds} \geq v_{th} \\ 0 & v_{ds} < v_{th} \leq 0 \end{cases}$$

$$v_{th} = v_{gs} - (V_{TO} + \Gamma(\sqrt{\Phi} - v_{bs} - \sqrt{\Phi}))$$

$$i_{bd} = I_S \left( e^{\frac{v_{bd}}{NV_T}} - 1 \right)$$

$$i_{bs} = I_S \left( e^{\frac{v_{bs}}{NV_T}} - 1 \right)$$

$$V_T = \frac{k_B T_{NOM}}{q}$$

There are also several capacitances between the terminals

$$C_{gd} = C_{gd0} W$$

$$C_{gs} = C_{gs0} W$$

$$C_{jbd} = C_{BD} \times \begin{cases} \left( 1 - \frac{v_{bd}}{P_B} \right)^{-M_J} & v_{bx} < F_C P_B \\ (1 - F_C)^{-1-M_J} \left( 1 - F_C (1 + M_J) + M_J \frac{v_{bx}}{P_B} \right) & v_{bx} \geq F_C P_B \end{cases}$$

The model parameters are as follows:

TABLE 3-2: MOSFET TRANSISTOR MODEL PARAMETERS

| PARAMETER | DEFAULT               | DESCRIPTION                       |
|-----------|-----------------------|-----------------------------------|
| $C_{BD}$  | 0 F/m                 | Bulk-drain zero-bias capacitance  |
| $C_{GDO}$ | 0 F/m                 | Gate-drain overlap capacitance    |
| $C_{GSO}$ | 0 F/m                 | Gate-source overlap capacitance   |
| $F_C$     | 0.5                   | Capacitance factor                |
| $I_S$     | 1e-13 A               | Bulk junction saturation current  |
| $K_P$     | 2e-5 A/V <sup>2</sup> | Transconductance parameter        |
| $L$       | 50e-6 m               | Gate length                       |
| $M_J$     | 0.5                   | Bulk junction grading coefficient |



TABLE 3-2: MOSFET TRANSISTOR MODEL PARAMETERS

| PARAMETER          | DEFAULT            | DESCRIPTION                   |
|--------------------|--------------------|-------------------------------|
| $N$                | 1                  | Bulk junction ideality factor |
| $P_B$              | 0.75 V             | Bulk junction potential       |
| $R_B$              | 0 $\Omega$         | Bulk resistance               |
| $R_D$              | 0 $\Omega$         | Drain resistance              |
| $R_{DS}$           | Inf ( $\Omega$ )   | Drain-source resistance       |
| $R_G$              | 0 $\Omega$         | Gate resistance               |
| $R_S$              | 0 $\Omega$         | Source resistance             |
| $T_{NOM}$          | 298.15 K           | Device temperature            |
| $V_{TO}$           | 0 V                | Zero-bias threshold voltage   |
| $W$                | 50e-6 m            | Gate width                    |
| $\Gamma$ (GAMMA)   | 1 $\text{V}^{0.5}$ | Bulk threshold parameter      |
| $\Phi$ (PHI)       | 0.5 V              | Surface potential             |
| $\Lambda$ (LAMBDA) | 0 1/V              | Channel-length modulation     |

## Diode

Figure 3-3 illustrates equivalent circuit for the diode.

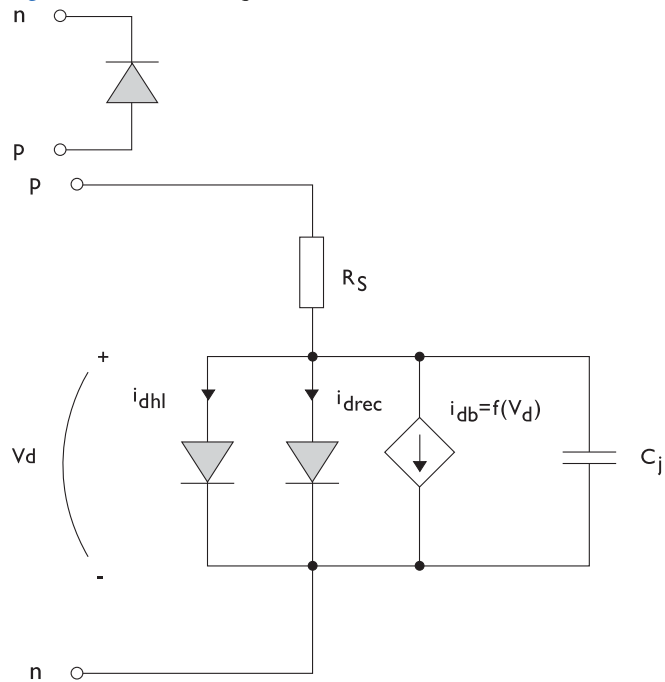


Figure 3-3: A circuit for the diode.

The following equations are used to compute the relations between currents and voltages in the circuit.

$$\begin{aligned}
i_d &= i_{dhl} + i_{drec} + i_{db} + i_c \\
i_{dhl} &= I_S \left( e^{\frac{v_d}{N V_T}} - 1 \right) \frac{1}{\sqrt{1 + \frac{I_S}{I_{KF}} \left( e^{\frac{v_d}{N V_T}} - 1 \right)}} \\
i_{drec} &= I_{SR} \left( e^{\frac{v_d}{N_R V_T}} - 1 \right) \\
i_{db} &= I_{BV} e^{\frac{v_d + B_V}{N_{BV} V_T}} \\
C_j &= C_{J0} \times \begin{cases} \left( 1 - \frac{v_d}{V_J} \right)^{-M} & v_d < F_C V_J \\ (1 - F_C)^{-1-M} \left( 1 - F_C (1 + M) + M \frac{v_d}{V_J} \right) & v_d \geq F_C V_J \end{cases} \\
V_T &= \frac{k_B T_{NOM}}{q}
\end{aligned}$$

where the following model parameters are required

TABLE 3-3: DIODE TRANSISTOR MODEL PARAMETERS

| PARAMETER | DEFAULT    | DESCRIPTION                          |
|-----------|------------|--------------------------------------|
| $B_V$     | Inf (V)    | Reverse breakdown voltage            |
| $C_{J0}$  | 0 F        | Zero-bias junction capacitance       |
| $F_C$     | 0.5        | Forward-bias capacitance coefficient |
| $I_{BV}$  | 1e-09 A    | Current at breakdown voltage         |
| $I_{KF}$  | Inf (A)    | Corner for high-current roll-off     |
| $I_S$     | 1e-13 A    | Saturation current                   |
| $M$       | 0.5        | Grading coefficient                  |
| $N$       | 1          | Ideality factor                      |
| $N_{BV}$  | 1          | Breakdown ideality factor            |
| $N_R$     | 2          | Recombination ideality factor        |
| $R_S$     | 0 $\Omega$ | Series resistance                    |
| $T_{NOM}$ | 298.15 K   | Device temperature                   |
| $V_J$     | 1.0 V      | Junction potential                   |

### *Reference for the Electrical Circuit Interface*

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2. P. Antognetti and G. Massobrio, *Semiconductor Device Modeling with Spice*, 2nd ed., McGraw-Hill, 1993.

## Fluid Flow Interfaces

This chapter describes the physics interfaces found under the **Fluid Flow** branch ()

The documentation of fluid structure interaction is found in the Structural Mechanics Module documentation, which is supplied with the MEMS Module (irrespective of whether a separate Structural Mechanics Module license is purchased). Where indicated in the list below, links to the *Structural Mechanics Module User's Guide* are included.

The list below details the documentation for the MEMS Module physics interfaces on the **Fluid Flow** branch:

- [The Thin-Film Flow Interfaces](#)
- [Theory for the Thin-Film Flow Interfaces](#)
- [The Fluid-Solid Interaction Interface](#) (in the *Structural Mechanics Module User's Guide*)
- [The Piezoelectricity Interface](#) (in the *Structural Mechanics Module User's Guide*)

See [The Single-Phase Flow, Laminar Flow Interface](#) in the *COMSOL Multiphysics Reference Manual* for other Fluid Flow interface and feature node settings.

# The Thin-Film Flow Interfaces

In this section:

- [The Thin-Film Flow, Shell Interface](#)
- [The Thin-Film Flow, Domain Interface](#)
- [The Thin-Film Flow, Edge Interface](#)
- [Domain, Boundary, Edge, Point, and Pair Nodes for the Thin-Film Flow Branch Interfaces](#)

The physics interfaces found under the **Thin-Film Flow** branch (  ) when adding a physics interface describe momentum transport. These physics interfaces can be added either singularly or in combination with other physics interfaces describing mass and energy transfer. The thin-film flow interfaces are shown in [Table 4-1](#).

TABLE 4-1: THE THIN-FILM FLOW INTERFACES DEFAULT SETTINGS

| PHYSICS INTERFACE LABEL | NAME | SPACE DIMENSION     | GEOMETRIC ENTITY LEVEL |
|-------------------------|------|---------------------|------------------------|
| Thin-Film Flow, Shell   | tffs | 3D                  | Boundaries             |
| Thin-Film Flow, Edge    | tffs | 2D, 2D axisymmetric | Boundaries             |
| Thin-Film Flow, Domain  | tff  | 2D                  | Domains                |

Each of the physics interfaces can be configured to solve either the standard **Reynolds Equation** (with a material or user-defined density specified at the absolute pressure), or to solve the **Modified Reynolds Equation**, which should be used for gas flows. The **Modified Reynolds Equation** assumes the ideal gas law and applies when gas pressure changes in the flow itself result in significant density changes.

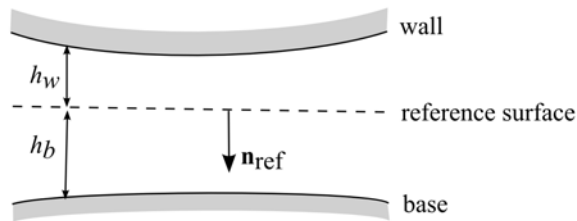
|                                                                                     |                                                          |
|-------------------------------------------------------------------------------------|----------------------------------------------------------|
|  | <a href="#">Theory for the Thin-Film Flow Interfaces</a> |
|-------------------------------------------------------------------------------------|----------------------------------------------------------|

## *The Thin-Film Flow, Shell Interface*

The **Thin-Film Flow, Shell (tffs)** interface (  ), found under the **Thin-Film Flow** branch (  ) when adding a physics interface, is used to solve the Reynolds equation or the modified Reynolds equation in a narrow channel that is represented by a surface within the geometry. It is used for lubrication, elastohydrodynamics, or gas damping simulations when the fluid channel is thin enough for the Reynolds equation or the

Modified Reynolds equation to apply. The physics interface is available for 3D geometries.

This physics interface is defined in a boundary mode, which means that the boundary level is the highest level for which this physics interface has equations and features; it does not have any features or equations on the domain level. The boundary level represents a reference surface on which the flow is solved. On one side of the boundary level there is a wall and on the other a base surface, neither of which is represented in the geometry. The wall and base surfaces are orientated with respect to the reference surface normal as shown in [Figure 4-1](#). Fluid flows in the gap between the wall and the base.



*Figure 4-1: Diagram illustrating the orientation of the wall and the base surfaces with respect to the reference surface in the Thin-Film Flow interfaces. A vector from the reference surface to the corresponding point on the wall always points in the  $-\mathbf{n}_{\text{ref}}$  direction, where  $\mathbf{n}_{\text{ref}}$  is the reference surface normal. Similarly a vector from the reference surface to the corresponding point on the base points in the  $+\mathbf{n}_{\text{ref}}$  direction. The height of the wall above the reference surface ( $h_w$ ) and the height of the base below the reference surface ( $h_b$ ) are also shown in the figure.*

Using equations on the reference surface, the physics interface computes the pressure in a narrow gap between the wall and the base. When modeling the flow, it is assumed that the total gap height,  $h = h_w + h_b$ , is much smaller than the typical lateral dimension  $L$  of the reference surface. The physics interface is used to model laminar flow in thin gaps or channels. A lubricating oil between two rotating cylinders is an example of this.

When this physics interface is added, the following default nodes are also added in the **Model Builder** — **Fluid-Film Properties**, **Border**, and **Initial Values**. Then, from the **Physics** toolbar, you can add other nodes that implement, for example, boundary conditions. You can also right-click **Thin-Film Flow, Shell** to select physics features from the context menu.

## SETTINGS

The **Label** is the default physics interface name.

The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the name string must be unique. Only letters, numbers, and underscores (\_) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `tffs`.

## PHYSICAL MODEL

Select an **Equation type** — **Reynolds equation** (the default) or **Modified Reynolds equation**.

## REFERENCE PRESSURE

Enter a **Reference pressure level**  $p_{\text{ref}}$  (SI unit: Pa). The default value is 1 [atm]. This pressure represents the ambient pressure and fluid loads are computed without accounting for this pressure.

## DEPENDENT VARIABLES

The dependent variable (field variable) is the **Pressure**  $p_f$ . The name can be changed but the names of fields and dependent variables must be unique within a component.



- [Domain, Boundary, Edge, Point, and Pair Nodes for the Thin-Film Flow Branch Interfaces](#)
- [Theory for the Thin-Film Flow Interfaces](#)

## *The Thin-Film Flow, Domain Interface*

The **Thin-Film Flow, Domain (tffs)** interface (  ), found under the **Thin-Film Flow** branch (  ) when adding a physics interface, is used to solve the Reynolds equation or the modified Reynolds equation in a narrow channel that is represented by a domain within the geometry. It is used for lubrication or gas damping simulations when the fluid channel is thin enough for the Reynolds equation or the Modified Reynolds equation to apply. The physics interface is available for 2D geometries.

When this physics interface is added, the following default nodes are also added in the **Model Builder** — **Fluid-Film Properties, Border** (the default boundary condition), and **Initial Values**. Then, from the **Physics** toolbar, add other nodes that implement, for example, boundary conditions. You can also right-click **Thin-Film Flow, Domain** to select physics features from the context menu.



SETTINGS

The **Label** is the default physics interface name.

The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the `name` string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `tff`.

The rest of the settings are the same as for [The Thin-Film Flow, Shell Interface](#).

|                                                                                   |                                                                                                                                                                                                                                                                                      |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <ul style="list-style-type: none"><li>• <a href="#">Domain, Boundary, Edge, Point, and Pair Nodes for the Thin-Film Flow Branch Interfaces</a></li><li>• <a href="#">Theory for the Thin-Film Flow Interfaces</a></li><li>• <a href="#">The Electromechanics Interface</a></li></ul> |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

*The Thin-Film Flow, Edge Interface*

The **Thin-Film Flow, Edge (tffs)** interface (  ) is used to solve the Reynolds equation or the modified Reynolds equation in a narrow channel that is represented by an edge within the geometry. It is used for lubrication, elastohydrodynamics, or gas damping simulations when the fluid channel is thin enough for the Reynolds equation or the Modified Reynolds equation to apply. The physics interface is for 2D and 2D axisymmetric components.

The rest of the settings are the same as for [The Thin-Film Flow, Shell Interface](#).

|                                                                                     |                                                                                                                                                                                                                                                                                      |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <ul style="list-style-type: none"><li>• <a href="#">Domain, Boundary, Edge, Point, and Pair Nodes for the Thin-Film Flow Branch Interfaces</a></li><li>• <a href="#">Theory for the Thin-Film Flow Interfaces</a></li><li>• <a href="#">The Electromechanics Interface</a></li></ul> |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

## Domain, Boundary, Edge, Point, and Pair Nodes for the Thin-Film Flow Branch Interfaces

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For the physics interfaces under the Thin-Film Flow branch, the following domain, boundary, edge, point, and pair nodes (listed in alphabetical order) are described in this section:

- [Border](#)
- [Fluid-Film Properties](#)
- [Initial Values](#)
- [Inlet](#)
- [Perforations](#)
- [Outlet](#)
- [Symmetry](#)
- [Wall](#)



In the *COMSOL Multiphysics Reference Manual* see [Table 2-4](#) for links to common sections and [Table 2-5](#) to common feature nodes. You can also search for information: press F1 to open the **Help** window or Ctrl+F1 to open the **Documentation** window.

## Fluid-Film Properties

---

Use the **Fluid-Film Properties** node to set the wall properties, base properties, fluid properties, and the film flow model.

### REFERENCE SURFACE PROPERTIES

In the **Thin-Film Flow, Shell (tffs)** and **Thin-Film Flow, Edge (tffs)** interfaces, the **Reference normal orientation** setting allows you to reverse the direction of the reference surface normal used by the physics interface. By default this is set to **Same direction as geometry normal**. To reverse the direction, select **Opposite direction to geometry normal**.

In the **Thin-Film Flow, Domain (tff)** interface, the **Reference surface normal orientation** setting allows you to set the direction of the reference normal so that it either points out of or into the plane of the domain. By default this is set to **Reference surface normal points out of plane**, such that the reference surface normal is given by  $\{0,0,1\}$ . Selecting **Reference surface normal points into plane** sets the reference surface normal to  $\{0,0,-1\}$ .

### WALL PROPERTIES

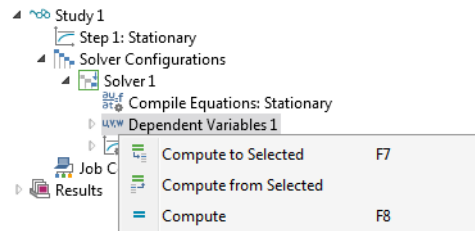
Enter a value or expression for the **Height of wall above reference plane**  $h_{w1}$  (SI unit: m). The default is 10  $\mu\text{m}$ .

By default the **Additional wall displacement** is **User defined**. Enter values or expressions for  $\mathbf{u}_w$  (SI unit: m). The defaults are 0 m. Alternatively select a feature input (defined by a separate physics interface) or **None** from the list.

When using a feature input to define an additional displacement based on the movement of a structure, refer to [Figure 4-1](#) to decide whether the additional displacement should be added to the wall or the base.

- If the reference normal points out of the structure for which the displacement is provided, the structure should be considered to be the wall, and its displacement should be added to the additional wall displacement.
- If the reference normal points into the structure for which the displacement is provided, the structure is the base and its displacement should be added to the additional base displacement.
- For the Thin-Film Flow boundary condition in the structural mechanics interfaces the displacement of the structure is automatically assigned in the correct manner.

To determine the reference normal orientation before fully solving the model, click **Show Default Solver** (  ) on the **Study** toolbar (or right-click the **Study 1** node and select **Show Default Solver**). Then expand the **Study 1>Solver Configurations>Solver 1** node, right-click the **Dependent variables** sub-node and select **Compute to Selected**.



You can then add a 2D or 3D plot group with an **Arrow Surface** plot (in 3D) (  ) or **Arrow Line** plot (in 2D) (  ), and use the **Replace Expression** (  ) button to plot the **Reference surface normal**.

Note that the orientation of the reference surface normal can be changed using the **Reference normal orientation** setting in the [Reference Surface Properties](#) section.

Select a **Wall velocity**  $\mathbf{v}_w$  (SI unit: m/s) — **None** (the default), **Calculate from wall displacement**, or **User defined**. For **User defined** enter values or expressions for the components of  $\mathbf{v}_w$  (SI unit: m/s). The defaults are 0 m/s.

## BASE PROPERTIES

See [Wall Properties](#) above for details to help you decide whether the additional displacement should be added to the wall or the base.

Enter a value or expression for the **Height of base below reference plane**  $h_{b1}$  (SI unit: m). The default is 0 m.

By default **Additional base displacement** is **User defined**. Enter values or expressions for  $\mathbf{u}_b$  (SI unit: m). The defaults are 0 m. Or select **None** from the list.

Select a **Base velocity**  $\mathbf{v}_b$  (SI unit: m/s) — **None** (the default), **Calculate from base displacement**, or **User defined**. For **User defined** enter values or expressions for the components of  $\mathbf{v}_b$  (SI unit: m/s). The defaults are 0 m/s.

## FLUID PROPERTIES

The default **Dynamic viscosity**  $\mu$  (SI unit: Pa·s) is taken **From material**. For **User defined** enter a different value or expression. The default is 0 Pa·s.

With the default options, the **Density**  $\rho$  (SI unit: kg/m<sup>3</sup>) is taken **From material**. For **User defined** enter a different value or expression. The default is 0 kg/m<sup>3</sup>. If the **Modified Reynolds Equation** is being solved, the density is determined automatically by the ideal gas law. If cavitation is enabled, the density is assumed to take the form  $\rho = \rho_c \exp(\beta p_f)$  where  $p_f$  is the fluid pressure,  $\rho_c$  is the density at the cavitation pressure, and  $\beta$  is the compressibility. (SI unit: 1/Pa). In this case enter the values for the **Density at cavitation pressure**  $\rho_c$  (SI unit: Pa) and the **Compressibility**  $\beta$  (SI unit: 1/Pa).

## FILM FLOW MODEL

Select a **Film flow model** — **No-slip walls** (the default), **Slip at walls**, **User defined-relative flow function**, or **User defined-general**. The film flow model is used to compute the mean fluid velocity as a function of the pressure gradient, the wall velocity, and the base velocity. Within the gap the fluid velocity profile is a linear combination of the Poiseuille and Couette velocity profiles.

### *No-slip Walls*

This flow model assumes no slip at both the wall and base surfaces. Thus the average fluid velocity is computed by assuming that the fluid velocity at the wall and base is equal to the wall and base velocity, respectively.

### *Slip at Walls*

Use **Slip at walls** when slip occurs at the wall and/or the base. In this case the difference between the wall or base velocity and the fluid velocity is proportional to the tangential part of the of the normal stress tensor component. The slip length divided by the fluid

viscosity is the constant of proportionality in this relationship. The mean fluid velocity is computed using this assumption, given the pressure gradient and the wall and base velocities.

Enter a **Slip length, wall**  $L_{sw}$  (SI unit: m). The default is 0.1  $\mu\text{m}$ . Select the **Use different slip length for base** check box to enter a **Slip length, base**  $L_{sb}$  (SI unit: m). The default is 0.1  $\mu\text{m}$ .

For the **Modified Reynolds Equation** it is possible to use the gas mean free path to specify the slip length. Change the **Type of Slip** setting (which defaults to **Slip Length** with the settings described above) to **Mean free path and same accommodation coefficients** or to **Mean free path and different accommodation coefficients**.

- For **Mean free path and same accommodation coefficients** enter a value for the **Wall and base accommodation coefficient**  $\alpha$  (dimensionless). The default is 0.9.
- For **Mean free path and different accommodation coefficients** enter values for the **Wall accommodation coefficient**  $\alpha_w$  (dimensionless, default 0.9) and the **Base accommodation coefficient**  $\alpha_b$  (dimensionless, default 0.9).

Select an option to define the **Mean free path** — **Compute from material properties** (the default), **User defined expression**, or **User defined with reference pressure**.

- For **User defined expression** enter an expression for the **Mean free path**  $\lambda$  (SI unit: m). The default expression is  $((70[\text{nm}]) * (1[\text{atm}])) / (\text{tf fs.ptot})$ .
- For **User defined with reference pressure** enter values for the **Mean free path at reference pressure**  $\lambda_0$  (SI unit: m; the default is 70 nm), and for the **Mean free path reference pressure**  $p_{\lambda 0}$  (SI unit: Pa; the default is 1 atm).

#### *Rarefied-Total Accommodation (Modified Reynolds Equation Only)*

The **Rarefied-total accommodation** option provides a rarefied gas model that assumes total accommodation at the wall and the base. This model is accurate to within 5% over the range  $0 < \text{Kn} < 880$  (here  $\text{Kn}$  is the Knudsen number, which is the ratio of the film thickness to the mean free path). An empirical function, fitted to stationary solutions of the Boltzmann equation, is used to define the Poiseuille component of the flow.

Select an option to define the **Mean free path** — **Compute from material properties** (the default), **User defined expression**, or **User defined with reference pressure**.

- For **User defined expression** enter an expression for the **Mean free path**  $\lambda$  (SI unit: m). The default expression is  $((70[\text{nm}]) * (1[\text{atm}])) / (\text{tfss.ptot})$ .
- For **User defined with reference pressure** enter values for the **Mean free path at reference pressure**  $\lambda_0$  (SI unit: m; the default is 70 nm) and for the **Mean free path reference pressure**  $p_{\lambda 0}$  (SI unit: Pa; the default is 1 atm).

Select a **Force model**. Select:

- **Normal-pressure forces only** (the default) to include only the normal pressure forces in the model.
- **Couette (slide film) forces only** to include only the shear forces generated from an empirical model of the rarefied flow developed for pure Couette flows.
- **Shear and normal forces** to include both the shear and pressure forces, combining the other two force models.

#### *Rarefied-General Accommodation (Modified Reynolds Equation Only)*

The **Rarefied-general accommodation** option provides a rarefied gas model that assumes the same accommodation coefficient,  $\alpha$ , at the wall and the base. This model is accurate to within 1% over the ranges  $0.7 < \alpha < 1$  and  $0.01 < \text{Kn} < 100$  (here  $\text{Kn}$  is the Knudsen number, which is the ratio of the film thickness to the mean free path). An empirical function, fitted to stationary solutions of the Boltzmann equation, is used to define the Poiseuille component of the flow.

Select an option to define the **Mean free path** — **Compute from material properties** (the default), **User defined expression**, or **User defined with reference pressure**.

- For **User defined expression** enter an expression for the **Mean free path**  $\lambda$  (SI unit: m). The default expression is  $70[\text{nm}] * 1[\text{atm}] / \text{tfss.ptot}$ .
- For **User defined with reference pressure** enter values for the **Mean free path at reference pressure**  $\lambda_0$  (SI unit: m, the default is 70 nm) and for the **Mean free path reference pressure**  $p_{\lambda 0}$  (SI unit: Pa, the default is 1 atm).

Select a **Force model**. Select:

- **Normal-pressure forces only** (the default) to include only the normal pressure forces in the model.

- **Couette (slide film) forces only** to include only the shear forces generated from an empirical model of the rarefied flow developed for pure Couette flows.
- **Shear and normal forces** to include both the shear and pressure forces, combining the other two force models.

#### *User Defined-relative Flow Function*

The **User defined-relative flow function** option enables user-defined models in which an effective fluid viscosity is employed. The fluid viscosity is divided by an additional factor  $Q_{ch}$ , which can be defined as an arbitrary expression in the GUI. It is also possible to define the expressions for the fluid forces on the wall and on the base (these are included as feature inputs in other physics interfaces).

Enter values or expressions for:

- **Relative flow rate function**  $Q_{ch}$  (dimensionless). The default is 0.
- **Fluid load on wall**  $f_w$  (SI unit:  $N/m^2$ ). The defaults are 0  $N/m^2$ .
- **Fluid load on base**  $f_b$  (SI unit:  $N/m^2$ ). The defaults are 0  $N/m^2$ .

#### *User Defined - General*

The **User defined-general** option allows for arbitrary flow models to be defined. Both the Poiseuille and Couette terms in the mean velocity can be defined arbitrarily. It is also possible to define the expressions for the fluid forces on the wall and on the base, (these are included as feature inputs in other physics interfaces).

Enter values or expressions for:

- **Poiseuille mean fluid velocity coefficient**  $v_{ave,P}$  (SI unit:  $m^3 \cdot s/kg$ ). The default is 0  $m^3 \cdot s/kg$ .
- **Couette mean fluid velocity component**  $v_{ave,C}$  (SI unit:  $m/s$ ). The defaults are 0  $m/s$ .
- **Fluid load on wall**  $f_w$  (SI unit:  $N/m^2$ ). The defaults are 0  $N/m^2$ .
- **Fluid load on base**  $f_b$  (SI unit:  $N/m^2$ ). The defaults are 0  $N/m^2$ .



[Arrow Line](#) and [Arrow Surface](#) in the *COMSOL Multiphysics Reference Manual*

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#### *Border*

Use the **Border** node to set a pressure condition at the border and the border flow type.

The **Border flow** condition is used to account for the pressure drop caused by the flow converging into the gap, outside the thin layer. The acoustic elongation options does this by adding additional thickness to the thin layer beyond the edge of the geometry (assuming a pressure gradient in this layer equal to that at the boundary). The Out-of-plane motion calculates the pressure gradient due to circulation of the fluid caused by motion of the wall or base surfaces using a predefined model. Alternatively the pressure gradient at the boundary can be specified using an arbitrary expression, which allows for more sophisticated, user-defined models.

## BORDER SETTINGS

Select a **Border condition** — **Zero pressure** (the default), **Pressure**, or **Border flow**.

For **Pressure** enter a **Pressure**  $p_{f0}$  (SI unit: Pa) to define  $p_f = p_{f0}$  on the boundary, edge, or point. The default is 0 Pa. If the reference pressure  $p_{ref}$ , defined at the physics interface level is 0,  $p_{f0}$  is the absolute pressure. Otherwise,  $p_{f0}$  is the relative pressure.

For **Border flow** select a **Border flow type** — **Acoustic boundary condition-absolute elongation**, **Acoustic boundary condition-relative elongation**, **Out-of-plane motion**, or **User defined**.

- For **Acoustic Boundary condition-absolute elongation** enter a **Border elongation**  $\Delta L$  (SI unit: m). The default is 0.1  $\mu\text{m}$ .
- For **Acoustic boundary condition-relative elongation** enter a **Relative border elongation**  $\Delta L_r$  (dimensionless). The default is 0.7.
- For **Out-of-plane motion** enter the **Model coefficients**  $\eta$ ,  $\zeta$ ,  $\chi$  with defaults 0, 0, 1, respectively. Also enter the **Slip length**,  $A$  (SI unit: m). The default slip length uses an **if** condition to set the slip length equal to that defined in the **Fluid-Film Properties** node if a suitable **Film flow model** is selected. If the Slip length is not defined in the [Fluid-Film Properties](#) node, it defaults to 0.1  $\mu\text{m}$ .

Note that the coefficients can be specified according to the results given in the paper by Gallis and Torczynski (M. A. Gallis and J. R. Torczynski, “An Improved Reynolds-Equation Model for Gas Damping of Microbeam Motion”, Journal of Microelectromechanical Systems, vol. 13, pp. 653–659, 2004). The following values are recommended:



$$\chi = \frac{1 + 8.834\left(\frac{\Lambda}{h}\right)}{1 + 5.118\left(\frac{\Lambda}{h}\right)}$$

$$\eta = \frac{0.634 + 1.572\left(\frac{\Lambda}{h}\right)}{1 + 0.537\left(\frac{\Lambda}{h}\right)}$$

$$\zeta = \frac{0.445 + 11.20\left(\frac{\Lambda}{h}\right)}{1 + 5.510\left(\frac{\Lambda}{h}\right)}$$

where  $h$  is the gap height. The above equations are valid in the range  $0 \leq \Lambda/h \leq 1$ .

- For **User defined** enter a **Normal pressure gradient** (SI unit:  $\text{N}/\text{m}^3$ ). The default is  $p_f/(0.1 \mu\text{m}) \text{ N}/\text{m}^3$ .

### *Perforations*

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Use the **Perforations** node for applications in MEMS devices, where the phenomenon of squeeze-film damping is important. A free-hanging thin plate or the substrate often has an array of etch holes that allow the gas in between to escape. The perforations feature acts as a sink for gas that is proportional to both the ambient pressure and to the pressure difference with respect to the ambient on the other side of the perforated surface. The constant of proportionality is known as the admittance,  $Y$ , and can either be defined directly or determined from the model due to Bao (M. Bao and H. Yang “Squeeze film air damping in MEMS”, Sensors and Actuators A: Physical, vol. 136, no. 1, pp. 3–27, 2014). The ambient pressure (defined at the level of the parent physics interface or Thin-Film Damping feature) is assumed to be the reference pressure specified at the physics interface level.

Note that this feature applies only when the walls do not have tangential movement.

#### **PERFORATIONS**

Select a **Perforation admittance** — **User defined** (the default) or **Bao model**.

For **User defined**, enter a value or expression for  $Y$  (SI unit:  $\text{m}^2 \cdot \text{s}/\text{kg}$ ).

For **Bao model**, choose a **Perforation shape** — **Square** (the default) or **Circular**. Then enter the following as applicable:

- **Side length**  $s_h$  (SI unit: m).
- **Hole radius**  $r_h$  (SI unit: m).
- **Hole length**  $l_h$  (SI unit: m).
- **Hole density**  $n_h$  (SI unit:  $1/\text{m}^2$ ).

### *Initial Values*

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The **Initial Values** node adds an initial value for the pressure that can serve as an initial condition for a transient simulation or as an initial guess for a nonlinear solver. If more than one set of initial values is required, add additional **Initial Values** nodes from the **Physics** toolbar.

#### **INITIAL VALUES**

Enter a value or an expression for the initial value of the **Pressure**  $p_f$  (SI unit: Pa).

### *Inlet*

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Use the **Inlet** node to define an edge or point where fluid enters the gap.

#### **INLET SETTINGS**

Select an **Inlet condition** — **Zero pressure** (the default), **Pressure**, or **Normal inflow velocity**.

- For **Zero pressure**  $p_f = 0$  applies on the boundary, edge, or point.
- For **Pressure** enter a **Pressure**  $p_{f0}$  (SI unit: Pa) to impose  $p_f = p_{f0}$  on the boundary, edge, or point. The default is 0 Pa. If the reference pressure  $p_{\text{ref}}$ , defined at the physics interface level is 0,  $p_{f0}$  is the absolute pressure. Otherwise,  $p_{f0}$  is the relative pressure.
- For **Normal inflow velocity** enter a **Normal inflow velocity**  $U_0$  (SI unit: m/s). The default is 0 m/s.

### *Outlet*

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The **Outlet** node defines an edge or point where fluid leaves the gap.

## OUTLET SETTINGS

Select an **Outlet condition** — **Zero pressure** (the default), **Pressure**, **Normal outflow velocity**, or **Outflow**.

- For **Zero pressure**,  $p_f = 0$  applies on the boundary, edge, or point.
- For **Pressure**, enter a **Pressure**  $p_{f0}$  (SI unit: Pa) to impose  $p_f = p_{f0}$  on the boundary, edge, or point. The default is 0 Pa. If the reference pressure  $p_{\text{ref}}$ , defined at the physics interface level is 0,  $p_{f0}$  is the absolute pressure. Otherwise,  $p_{f0}$  is the relative pressure.
- For **Normal outflow velocity**, enter a **Normal outflow velocity**  $U_0$  (SI unit: m/s). The default is 0 m/s.
- For **Outflow**, the fluid is allowed to leave the gap without explicitly imposing a value of pressure or velocity.

## *Wall*

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The **Wall** node prevents fluid flow in the direction perpendicular to the boundary.

## *Symmetry*

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The **Symmetry** node sets the perpendicular component of the average velocity in the gap to zero.

# Theory for the Thin-Film Flow Interfaces

The theory for the different versions of the Thin-Film Flow interfaces are described in this section:

- [Thin-Film Flow](#)
- [The Reynolds Equation](#)
- [Flow Models](#)
- [The Modified Reynolds Equation — Gas Flows](#)
- [Flow Models for Rarefied Gases](#)
- [Frequency-Domain Formulation](#)
- [Boundary Conditions](#)
- [References for the Thin-Film Flow Interfaces](#)

## *Thin-Film Flow*

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[Figure 4-2](#) shows a typical configuration for the flow of fluid in a thin layer. The upper boundary is referred to as the wall, and the lower boundary is referred to as the base. Damping or lubrication forces operate on both surfaces.

In many cases the gap is sufficiently small for the flow in the thin film to be isothermal. Usually the gap thickness,  $h$ , is much smaller than the lateral dimensions of the geometry,  $L$ . If this is the case it is possible to neglect inertial effects in the fluid in comparison to viscous effects (for MEMS devices this assumption is reasonable below MHz frequencies). Additionally, the curvature of the reference surface can be ignored when  $h/L \ll 1$ . Under these assumptions the *Reynolds equation* applies. For gas flows under the same conditions it is possible to derive a modified form of the Reynolds Equation, which uses the ideal gas law to eliminate the density from the equation system. Such a *modified Reynolds equation* can even be adapted to model the flow of rarefied gases.

Different terminology is used for thin-film flow in different fields of physics. In tribology the term *lubrication* is frequently used, especially when the fluid is a liquid. In resonant MEMS devices, flow in the thin layer of gas separating a device from the substrate on which it is fabricated often provides significant *damping*. In this case

there is usually a distinction between *squeeze-film damping*, when the direction of motion of the structure is predominantly perpendicular to the reference plane, and *slide-film damping* for motion predominantly parallel to the reference plane.

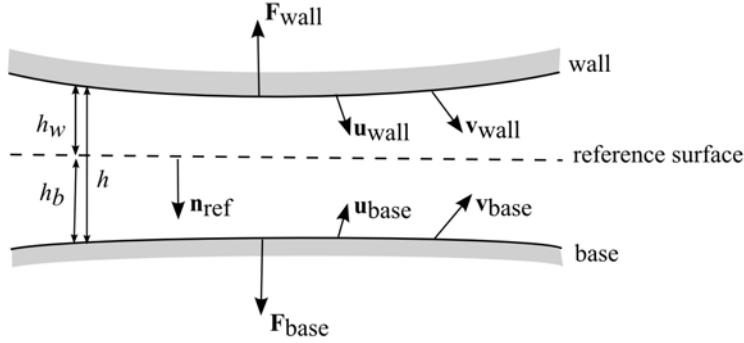


Figure 4-2: An example illustrating a typical configuration for thin-film flow. A reference surface with normal  $\mathbf{n}_{\text{ref}}$  sits in a narrow gap between a wall and base. In COMSOL Multiphysics, the vector  $\mathbf{n}_{\text{ref}}$  points into the base and out of the wall. The wall moves with a displacement  $\mathbf{u}_{\text{wall}}$  and velocity  $\mathbf{v}_{\text{wall}}$  from its initial position. Similarly the base moves from its initial position with displacement  $\mathbf{u}_{\text{base}}$  and velocity  $\mathbf{v}_{\text{base}}$ . The compression of the fluid results in an excess pressure,  $p_f$ , above the reference pressure,  $p_{\text{ref}}$ , and a fluid velocity in the gap. At a point on the reference surface the average value of the fluid velocity along a line perpendicular to the surface is given by the in plane vector  $\mathbf{v}_{\text{ave}}$ . The motion of the fluid results in forces on the wall ( $\mathbf{F}_{\text{wall}}$ ) and on the base ( $\mathbf{F}_{\text{base}}$ ). The distance to the wall above the reference surface is  $h_w$  while the base resides a distance  $h_b$  below the reference surface. The total size of the gap is  $h = h_w + h_b$ . At a given time  $h_w = h_{w1} - \mathbf{n}_{\text{ref}} \cdot \mathbf{u}_{\text{wall}}$  and  $h_b = h_{b1} - \mathbf{n}_{\text{ref}} \cdot \mathbf{u}_{\text{wall}}$  where  $h_{w1}$  and  $h_{b1}$  are the initial distances to the wall and base, respectively.

### The Reynolds Equation

The equations of fluid flow in thin films are usually formulated on a reference surface in the Eulerian frame. Consider a cylinder, fixed with respect to a stationary reference surface, as shown in Figure 4-3.

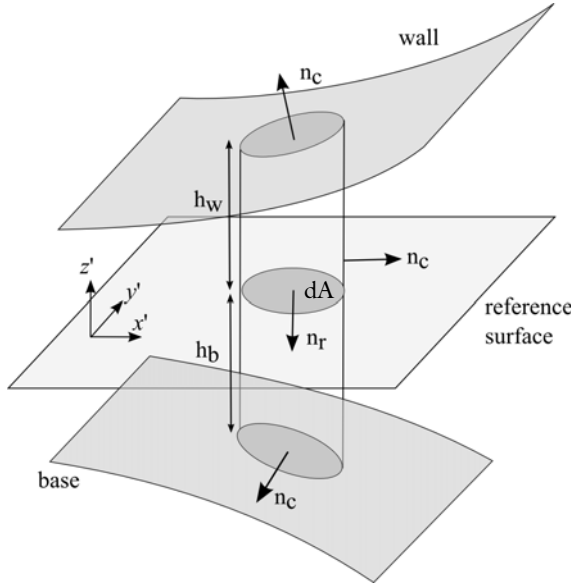


Figure 4-3: Reference cylinder, fixed with respect to the stationary reference surface, in a small gap between two surfaces (the wall and the base). The cylinder has outward normal,  $\mathbf{n}_c$ . Its area, projected onto the reference surface, is  $dA$ .

The cylinder is fixed with respect to the reference surface, but its height can change due to changes in the position of the base and the wall. Considering the flow in the reference plane, the rate at which mass accumulates within the reference cylinder is determined by the divergence of the mass flow field in the reference plane:

$$\frac{d}{dt}(\rho h) = -\nabla_t \cdot (\rho h \mathbf{v}_{av}) \quad (4-1)$$

where  $h = h_w + h_b$  and the tangential velocity,  $\mathbf{v}_{av}$  represents the mean velocity of the flow in the reference plane. Particular care must be taken with respect to the definition of  $h$ . The above equation applies if  $h$  is measured with respect to a fixed point on the reference surface as a function of time. The reference surface itself must be fixed in space and obviously cannot deform as time progresses. Equations represented on the reference surface are described as Eulerian, that is they are defined in a frame that is fixed with respect to the motion of the fluid or of the body. Fluid flow problems are usually formulated in the Eulerian frame, and COMSOL Multiphysics adopts this convention in most of its fluid flow interfaces. It is useful to note that the Eulerian

frame is usually called the spatial frame within the COMSOL Multiphysics interface. When a structure deforms in COMSOL Multiphysics, the spatial frame changes shape.

The wall and the base can, and often do, move with respect to the reference surface. The wall and base are usually the surfaces of mechanical components which are deforming as a result of the pressure building up within the region of fluid flow. When describing the physics of a deforming solid, it is often convenient to work in the Lagrangian frame, which is fixed with respect to a small control volume of the solid. As the solid deforms, the Lagrangian frame moves along with the material contained within the control volume. Using the Lagrangian frame for describing structural deformation means that changes in the local density and material orientation as a result of the distortion of the control volume do not need to be accounted for by complicated transformations. In COMSOL Multiphysics, the Lagrangian frame, usually referred to as the material frame, is used for describing structural deformations. When a structure deforms in COMSOL Multiphysics, the material frame remains in the original configuration of the structure, and the deformation is accounted for by the underlying equations.

Because of the mixed Eulerian-Lagrangian approach adopted within COMSOL Multiphysics, particular care must be taken with the formulation of the Reynolds equations. Typically it is not desirable to represent the geometry of the thin film itself directly, because it is often much smaller than the other components in the model. The equations apply on a single surface in the model, the reference surface. Since we do not want the reference surface to deform, the equations are added in the material frame (even though this frame is normally used in a Lagrangian approach) and manual transformations are added to the system to account for the fact that the structural equations also exist in the material frame, and employ a truly Lagrangian approach.

The situation encountered when both the wall and the base undergo a displacement is depicted in [Figure 4-4](#). The Eulerian wall height changes from an initial value  $h_{w1}$  to a final value  $h_w$ . Similarly the base height changes from an initial value  $h_{b1}$  to  $h_b$ .

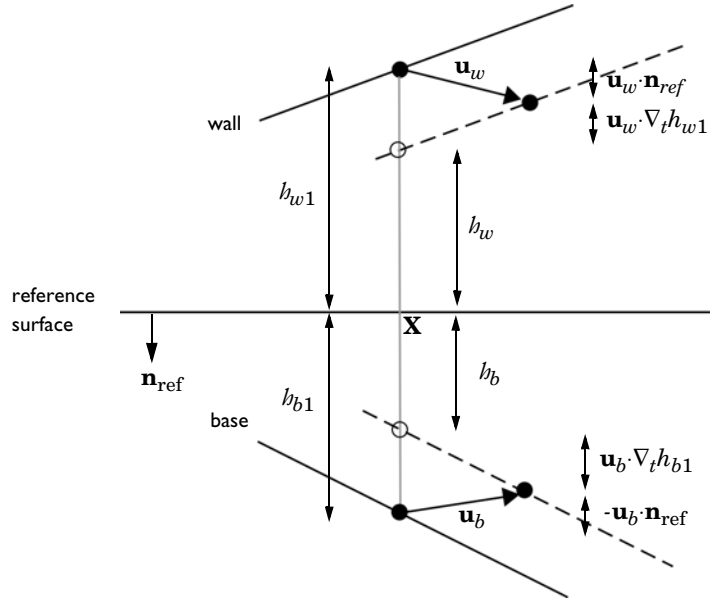


Figure 4-4: Diagram showing the displacement of the wall and the base with respect to the reference surface, and the corresponding change in the height of the channel.

From the figure it is clear that:

$$\begin{aligned}
 h_w &= h_{w1} - \mathbf{u}_w \cdot \mathbf{n}_{ref} - \mathbf{u}_w \cdot \nabla_t h_{w1} \\
 h_b &= h_{b1} + \mathbf{u}_b \cdot \mathbf{n}_{ref} - \mathbf{u}_b \cdot \nabla_t h_{b1} \\
 h &= h_w + h_b
 \end{aligned} \tag{4-2}$$

It should be noted that similar corrections should be applied to the velocity of the wall, if it is computed from the structural displacement. That is the velocity should be modified by a term proportional to its spatial gradient. This correction term, is however, a second order term, and consequently it is usually negligible in practical circumstances. It is neglected in the thin film flow interface.

Consequently, provided that the definitions of the wall and base height from Equation 4-2 are used, the Reynolds equation takes the form:

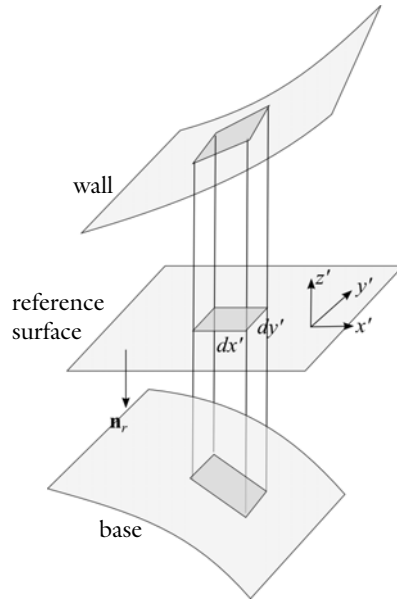
$$\frac{\partial}{\partial t}(\rho h) + \nabla_t \cdot (h \rho \mathbf{v}_{av}) = 0 \tag{4-3}$$



The definition of the average flow velocity,  $\mathbf{v}_{av}$ , together with the forces that act on the structure, remain to be specified.

### Flow Models

The Navier-Stokes equations can be nondimensionalized for a domain whose width ( $h_0$ ) is much smaller than its lateral dimension(s) ( $l_0$ ) (see [Ref. 1](#) for a detailed discussion). When  $\text{Re}(h_0/l_0)^2 \ll 1$ , and terms of order  $(h_0/l_0)^2$  are neglected, the Navier-Stokes equations reduce to a modified form of the Stokes equation, which must be considered in conjunction with the continuity relation.



*Figure 4-5: The coordinate system employed for the derivation of the average flow velocity.*

The equations are most conveniently expressed by considering a local coordinate system in which  $x'$  and  $y'$  are tangent to the plane of the reference surface, and  $z'$  is perpendicular to the surface, as illustrated in [Figure 4-5](#). Using this coordinate system:

$$\frac{\partial p_f}{\partial x'} = \frac{\partial}{\partial z'} \left( \mu \frac{\partial v_{x'}}{\partial z'} \right)$$

$$\frac{\partial p_f}{\partial y'} = \frac{\partial}{\partial z'} \left( \mu \frac{\partial v_{y'}}{\partial z'} \right)$$

$$\frac{\partial p}{\partial z'} = 0$$

Here  $p_f$  is the pressure resulting from the fluid flow,  $\mu$  is the fluid viscosity, and  $(v_{x'}, v_{y'})$  is the fluid velocity in the reference plane (which varies in the  $z'$  direction).

These equations can be integrated directly, yielding the in-plane velocity distributions, by making the assumption that the viscosity represents the mean viscosity through the film thickness. The following equations are derived:

$$\frac{\partial v_{x'}}{\partial z'} = \frac{z'}{\mu} \frac{\partial p_f}{\partial x'} + \frac{C_{1x'}}{\mu} \quad \frac{\partial v_{y'}}{\partial z'} = \frac{z'}{\mu} \frac{\partial p_f}{\partial y'} + \frac{C_{1y'}}{\mu} \quad (4-4)$$

$$v_{x'} = \frac{z'^2}{2\mu} \frac{\partial p_f}{\partial x'} + \frac{C_{1x'} z'}{\mu} + C_{2x'} \quad v_{y'} = \frac{z'^2}{2\mu} \frac{\partial p_f}{\partial y'} + \frac{C_{1y'} z'}{\mu} + C_{2y'} \quad (4-5)$$

The constants  $C_{1x'}$ ,  $C_{2x'}$ ,  $C_{1y'}$ , and  $C_{2y'}$  are determined by the boundary conditions. Equation 4-4 shows that the flow is a linear combination of laminar Poiseuille and Couette flows. The velocity profile is quadratic in form, as shown in Equation 4-5.

The average flow rate in the reference plane,  $\mathbf{v}_{av}$ , is given by:

$$\mathbf{v}_{av} = \begin{bmatrix} \frac{1}{h} \int_{-h_b}^{h_w} v_{x'} dz' \\ \frac{1}{h} \int_{-h_b}^{h_w} v_{y'} dz' \end{bmatrix} = \frac{1}{h} \begin{bmatrix} \frac{(h_w^2 - h_w h_b + h_b^2)}{6\mu} \frac{\partial p_f}{\partial x'} + \frac{h_w - h_b}{2\mu} C_{1x'} + C_{2x'} \\ \frac{(h_w^2 - h_w h_b + h_b^2)}{6\mu} \frac{\partial p_f}{\partial y'} + \frac{h_w - h_b}{2\mu} C_{1y'} + C_{2y'} \end{bmatrix}$$

The forces acting on the walls are determined by the normal component of the viscous stress tensor,  $\tau$ , at the walls ( $\tau \mathbf{n}$  - where  $\mathbf{n}$  is the normal that points out of the fluid domain). The viscous stress tensor takes the form:

$$\boldsymbol{\tau} = \mu(\nabla \mathbf{v} + (\nabla \mathbf{v})^T) - p \mathbf{I} = \begin{bmatrix} -p_f + 2\mu \frac{\partial v_{x'}}{\partial x'} & \mu \left( \frac{\partial v_{y'}}{\partial x'} + \frac{\partial v_{x'}}{\partial y'} \right) & \mu \left( \frac{\partial v_{z'}}{\partial x'} + \frac{\partial v_{x'}}{\partial z'} \right) \\ \mu \left( \frac{\partial v_{x'}}{\partial y'} + \frac{\partial v_{y'}}{\partial x'} \right) & -p_f + 2\mu \frac{\partial v_{y'}}{\partial y'} & \mu \left( \frac{\partial v_z}{\partial y'} + \frac{\partial v_{y'}}{\partial z'} \right) \\ \mu \left( \frac{\partial v_{x'}}{\partial z'} + \frac{\partial v_{z'}}{\partial x'} \right) & \mu \left( \frac{\partial v_{y'}}{\partial z'} + \frac{\partial v_z}{\partial y'} \right) & -p_f + 2\mu \frac{\partial v_{z'}}{\partial z'} \end{bmatrix}$$

Neglecting the gradient terms, which are of order  $h_0/l_0$ , results in the following form for the stress tensor:

$$\boldsymbol{\tau} \approx \begin{bmatrix} -p_f & 0 & \mu \frac{\partial v_{x'}}{\partial z'} \\ 0 & -p_f & \mu \frac{\partial v_{y'}}{\partial z'} \\ \mu \frac{\partial v_{x'}}{\partial z'} & \mu \frac{\partial v_{y'}}{\partial z'} & -p_f \end{bmatrix} \quad (4-6)$$

The components of the stress tensor can be expressed in terms of the velocity and pressure gradients using [Equation 4-4](#). Note that the normals to both the wall and the base are parallel to the  $z'$  direction, to zeroth order in  $h_0/l_0$ . The forces acting on the base and the wall are therefore given by:

$$f_w = \begin{bmatrix} \frac{h_w \partial p_f}{\mu \partial x'} + \frac{C_{1x'}}{\mu} \\ \frac{h_w \partial p_f}{\mu \partial y'} + \frac{C_{1y'}}{\mu} \\ p_f \end{bmatrix} \quad f_b = \begin{bmatrix} \frac{h_b \partial p_f}{\mu \partial x'} + \frac{C_{1x'}}{\mu} \\ \frac{h_b \partial p_f}{\mu \partial y'} + \frac{C_{1y'}}{\mu} \\ -p_f \end{bmatrix}$$

#### GENERAL SLIP BOUNDARY CONDITION

Assuming a slip length of  $L_{sw}$  at the wall and a slip length of  $L_{sb}$  at the base, the general slip boundary conditions are given by:

$$\begin{aligned}
v_{x'}(z' = -h_b) - v_{x'}^b &= \frac{L_{sb}}{\mu} \tau_{z'x'}(z' = -h_b) = L_{sb} \frac{\partial v_{x'}}{\partial z'}(z' = -h_b) \\
v_{y'}(z' = -h_b) - v_{y'}^b &= \frac{L_{sb}}{\mu} \tau_{z'y'}(z' = -h_b) = L_{sb} \frac{\partial v_{y'}}{\partial z'}(z' = -h_b) \\
v_{x'}(z' = h_w) - v_{x'}^w &= -\frac{L_{sw}}{\mu} \tau_{z'x'}(z' = h_w) = -L_{sw} \frac{\partial v_{x'}}{\partial z'}(z' = h_w) \\
v_{y'}(z' = h_w) - v_{y'}^w &= -\frac{L_{sw}}{\mu} \tau_{z'y'}(z' = h_w) = -L_{sw} \frac{\partial v_{y'}}{\partial z'}(z' = h_w)
\end{aligned}$$

For non-identical slip lengths the constants  $C_{1x'}$ ,  $C_{2x'}$ ,  $C_{1y'}$ , and  $C_{2y'}$  take the following values:

$$\begin{aligned}
C_{1x'} &= \frac{\mu(v_{x'}^w - v_{x'}^b)}{h + L_{sw} + L_{sb}} - \frac{h_b^2 - h_w^2 - 2L_{sw}h_w + 2L_{sb}h_b}{2(h + L_{sb} + L_{sw})} \frac{\partial p_f}{\partial x'} \\
C_{2x'} &= \frac{v_{x'}^w(h_b + L_{sb}) + v_{x'}^b(h_w + L_{sw})}{h + L_{sw} + L_{sb}} \\
&\quad - \frac{h_w^2(h_b + L_{sb}) + h_b^2(h_w + L_{sw}) + 2h_w h_b(L_{sw} + L_{sb}) + 2hL_{sw}L_{sb}}{2(h + L_{sw} + L_{sb})\mu} \frac{\partial p_f}{\partial x'} \\
C_{1y'} &= \frac{\mu(v_{y'}^w - v_{y'}^b)}{h + L_{sw} + L_{sb}} - \frac{h_b^2 - h_w^2 - 2L_{sw}h_w + 2L_{sb}h_b}{2(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial y'} \\
C_{2y'} &= \frac{v_{y'}^w(h_b + L_{sb}) + v_{y'}^b(h_w + L_{sw})}{h + L_{sw} + L_{sb}} \\
&\quad - \frac{h_w^2(h_b + L_{sb}) + h_b^2(h_w + L_{sw}) + 2h_w h_b(L_{sw} + L_{sb}) + 2hL_{sw}L_{sb}}{2(h + L_{sw} + L_{sb})\mu} \frac{\partial p_f}{\partial y'}
\end{aligned}$$

The average flow rate becomes:

$$\mathbf{v}_{av} = \begin{bmatrix} \frac{h(v_{x'}^w + v_{x'}^b) + 2(L_{sw}v_{x'}^w + L_{sb}v_{x'}^b)}{2(h + L_{sw} + L_{sb})} - \frac{h(h^2 + 4h(L_{sw} + L_{sb}) + 12L_{sb}L_{sw})}{12\mu(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial x'} \\ \frac{h(v_{y'}^w + v_{y'}^b) + 2(L_{sw}v_{y'}^w + L_{sb}v_{y'}^b)}{2(h + L_{sw} + L_{sb})} - \frac{h(h^2 + 4h(L_{sw} + L_{sb}) + 12L_{sb}L_{sw})}{12\mu(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial y'} \end{bmatrix}$$

which can be expressed in vector notation as:

$$\mathbf{v}_{av} = \frac{1}{2(h + L_{sw} + L_{sb})}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)((h + 2L_{sw})\mathbf{v}_w + (h + 2L_{sb})\mathbf{v}_b) - \frac{h(h^2 + 4h(L_{sw} + L_{sb}) + 12L_{sb}L_{sw})}{12\mu(h + L_{sw} + L_{sb})}\nabla_t p_f$$

The above equation can be written on the form:

$$\mathbf{v}_{av} = \mathbf{v}_{av,c} - v_{av,p} \nabla_t p_f \quad (4-7)$$

where  $\mathbf{v}_{av,c}$  is a term associated with Couette flow, and  $v_{av,p}$  is a coefficient associated with Poiseuille flow (see [Table 4-2](#) below).

The forces acting on the two boundaries are given by:

$$\begin{aligned} \mathbf{f}_w &= \begin{bmatrix} \frac{h(h + 2L_{sb})}{2(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial x'} + \frac{(v_{x'}^b - v_{x'}^w)\mu}{(h + L_{sw} + L_{sb})} \\ \frac{h(h + 2L_{sb})}{2(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial y'} + \frac{(v_{y'}^b - v_{y'}^w)\mu}{(h + L_{sw} + L_{sb})} \\ p_f \end{bmatrix} \\ \mathbf{f}_b &= \begin{bmatrix} \frac{h(h + 2L_{sw})}{2(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial x'} + \frac{(v_{x'}^w - v_{x'}^b)\mu}{(h + L_{sw} + L_{sb})} \\ \frac{h(h + 2L_{sw})}{2(h + L_{sw} + L_{sb})} \frac{\partial p_f}{\partial y'} + \frac{(v_{y'}^w - v_{y'}^b)\mu}{(h + L_{sw} + L_{sb})} \\ -p_f \end{bmatrix} \end{aligned} \quad (4-8)$$

Note that the  $z'$  direction corresponds to the  $-\mathbf{n}_r$  direction. The  $x'$  and  $y'$  directions correspond to the two tangent vectors in the plane. Using vector notation the forces become:

$$\begin{aligned} \mathbf{f}_w &= -\frac{h(h + 2L_{sb})}{2(h + L_{sw} + L_{sb})} \nabla_t p_f + \frac{\mu}{h + L_{sw} + L_{sb}} (\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T) (\mathbf{v}^b - \mathbf{v}^w) + p_f \mathbf{n}_w \\ \mathbf{f}_b &= -\frac{h(h + 2L_{sw})}{2(h + L_{sw} + L_{sb})} \nabla_t p_f + \frac{\mu}{h + L_{sw} + L_{sb}} (\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T) (\mathbf{v}^w - \mathbf{v}^b) + p_f \mathbf{n}_b \end{aligned}$$

In [Equation 4-8](#) it is assumed that  $\mathbf{n}_w = -\mathbf{n}_r$  and  $\mathbf{n}_b = \mathbf{n}_r$ . In COMSOL Multiphysics, the accuracy of the force terms is improved slightly over the usual approximation (which

neglects the slope of the wall and base as it is of order  $h_0/l_0$ ) by using the following equations for  $\mathbf{n}_w$  and  $\mathbf{n}_b$ :

$$\mathbf{n}_w = (-\mathbf{n}_r - \nabla_t h_w)$$

$$\mathbf{n}_b = (\mathbf{n}_r - \nabla_t h_w)$$

These definitions are derived from [Equation 4-4](#) and [Equation 4-5](#) and include the additional area that the pressure acts on as a result of the wall slope.

Once again, the force terms can be written on the form:

$$\begin{aligned}\mathbf{f}_w &= -f_{w,p} \nabla_t p_f + \mathbf{f}_{w,c} \\ \mathbf{f}_b &= -f_{b,p} \nabla_t p_f + \mathbf{f}_{b,c}\end{aligned}\tag{4-9}$$

where  $f_{w,p}$  is the Poiseuille coefficient for the force on the wall, and  $\mathbf{f}_{w,c}$  incorporates the Couette and normal forces (due to the pressure) on the wall. Similarly,  $f_{b,p}$  is the Poiseuille coefficient for the force on the base, and  $\mathbf{f}_{b,c}$  incorporates the Couette and normal forces (due to the pressure) on the base.

The cases of identical slip length and non-slip are limiting cases of the formulas derived above. The main results are summarized in [Table 4-2](#), where the constants defined in [Equation 4-7](#) and [Equation 4-9](#) are used.

TABLE 4-2: EQUATION VARIABLES FOR VARIOUS FLOW MODELS

| VARIABLE                                       | DEFINITION                                                                                                                          |
|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| <b>General Slip Flow Model</b>                 |                                                                                                                                     |
| $\mathbf{v}_{av,c}$                            | $\frac{1}{2(h + L_{sw} + L_{sb})}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)((h + 2L_{sb})\mathbf{v}_w + (h + 2L_{sw})\mathbf{v}_b)$ |
| $v_{av,p}$                                     | $\frac{h(h^2 + 4h(L_{sw} + L_{sb}) + 12L_{sb}L_{sw})}{12\mu(h + L_{sw} + L_{sb})}$                                                  |
| $\mathbf{f}_{w,c}$                             | $\frac{\mu}{h + L_{sw} + L_{sb}}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^b - \mathbf{v}^w) + p_f \mathbf{n}_w$         |
| $f_{w,p}$                                      | $\frac{h(h + 2L_{sb})}{2(h + L_{sw} + L_{sb})}$                                                                                     |
| $\mathbf{f}_{b,c}$                             | $\frac{\mu}{h + L_{sw} + L_{sb}}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^w - \mathbf{v}^b) + p_f \mathbf{n}_b$         |
| $f_{b,p}$                                      | $\frac{h(h + 2L_{sw})}{2(h + L_{sw} + L_{sb})}$                                                                                     |
| <b>Equal Slip Lengths Flow Model Lsw=Lsb=L</b> |                                                                                                                                     |
| $\mathbf{v}_{av,c}$                            | $\frac{1}{2}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}_w + \mathbf{v}_b)$                                                |
| $v_{av,p}$                                     | $(h^2 + 6L_s h)/(12\mu)$                                                                                                            |
| $\mathbf{f}_{w,c}$                             | $\frac{\mu}{h + 2L_s}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^b - \mathbf{v}^w) + p_f \mathbf{n}_w$                    |
| $f_{w,p}$                                      | $h/2$                                                                                                                               |
| $\mathbf{f}_{b,c}$                             | $\frac{\mu}{h + 2L_s}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^w - \mathbf{v}^b) + p_f \mathbf{n}_b$                    |
| $f_{b,p}$                                      | $h/2$                                                                                                                               |

TABLE 4-2: EQUATION VARIABLES FOR VARIOUS FLOW MODELS

| VARIABLE                              | DEFINITION                                                                                                |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Non-Slip Flow Model $L_{sw}=L_{sb}=0$ |                                                                                                           |
| $\mathbf{v}_{av,c}$                   | $\frac{1}{2}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}_w + \mathbf{v}_b)$                      |
| $v_{av,p}$                            | $h^2/(12\mu)$                                                                                             |
| $\mathbf{f}_{w,c}$                    | $\frac{\mu}{h}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^b - \mathbf{v}^w) + p_f \mathbf{n}_w$ |
| $f_{w,p}$                             | $h/2$                                                                                                     |
| $\mathbf{f}_{b,c}$                    | $\frac{\mu}{h}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^w - \mathbf{v}^b) + p_f \mathbf{n}_b$ |
| $f_{b,p}$                             | $h/2$                                                                                                     |

### *The Modified Reynolds Equation — Gas Flows*

Thin-film gas flows are often isothermal, and in many cases the ideal gas law can be assumed. Under these circumstances, the ideal gas law can be written on the form:

$$p_A = \frac{RT_0}{M_n} \rho$$

where  $T_0$  is the (constant) temperature of the gas,  $M_n$  is the molar mass of the gas, and  $R$  is the universal gas constant. Here the total gas pressure,  $p_A = p_{ref} + p_f$ , where  $p_A$  is the absolute pressure and  $p_f$  is the pressure developed as a result of the flow. Substituting this relation into Equation 4-3 and dividing through by the constant  $M_n / RT_0$  results in a modified form of the Reynolds equation:

$$\frac{\partial}{\partial t}(p_A h) + \nabla_t \cdot (h p_A \mathbf{v}_{av}) = 0 \quad (4-10)$$

This equation can be used to model isothermal flows of ideal gases. The average flow rate and the forces acting on the bearings are computed in the same manner as for the standard Reynolds equation.

### **SLIP BOUNDARY CONDITIONS FOR GASES**

For a gas, the slip length is often expressed using the mean free path,  $\lambda$ , and a tangential momentum accommodation coefficient,  $\alpha$ . For compatibility with the existing



literature on thin-film gas flow the following definition of the mean free path is used by COMSOL Multiphysics in the Thin-Film Flow interfaces:

$$\lambda = \frac{\mu}{p} \left( \frac{2RT}{M_n} \right)^{\frac{1}{2}}$$

The slip length is then defined as:

$$L_s = \frac{\sqrt{\pi}}{2} \lambda \left( \frac{2-\alpha}{\alpha} \right)$$

Values for the tangential-momentum-accommodation coefficients for various gas surface combinations are given in [Ref. 2](#).

### *Flow Models for Rarefied Gases*

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For gases at low pressure, the ratio of the gas mean free path,  $\lambda$ , to the gap size (known as the Knudsen number:  $\text{Kn} = \lambda/h$ ) grows. For Knudsen numbers greater than 0.1, the gas cannot be treated using the continuum Navier-Stokes equations and the Boltzmann equation must be solved instead.

At steady state, the solutions to the linearized Boltzmann equation for isothermal flow in a narrow gap between parallel plates can be expressed as a combination of Poiseuille and Couette flows. This is analogous to the solutions of the Navier-Stokes equations in the limit of small  $h_0/l_0$ . Provided that the surfaces of the wall and base are identical (which is normally the case in many practical applications), the Couette contribution to the bulk fluid velocity is unchanged (it remains the mean of the wall and base velocities for identical surfaces). The Poiseuille contribution to the flow is more complicated for a rarefied gas. A practical approach, pioneered by Fukui and Kaneko ([Ref. 3](#)) is to solve the linearized Boltzmann BGK equation over a range of Knudsen numbers and to provide an empirical fit to the flow. This results in the following form for the average velocity of the flow:

$$\mathbf{v}_{\text{av}} = \frac{1}{2}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}_w + \mathbf{v}_b) - \frac{h^2}{12\mu_{\text{eff}}} \nabla_t p$$

$$\mu_{\text{eff}} = \frac{\mu}{Q(\text{Kn}, \alpha_w, \alpha_b)}$$
(4-11)

where  $Q(\text{Kn}, \alpha_w, \alpha_b)$  is a nondimensional function of the Knudsen number ( $\text{Kn}$ ) and the tangential momentum accommodation coefficient at the wall ( $\alpha_w$ ) and base ( $\alpha_b$ ).

$Q(\text{Kn}, \alpha_w, \alpha_b)$  is obtained by solving the linearized Boltzmann BGK equation for steady Poiseuille flow with a range of Knudsen numbers and slip coefficients. This approach assumes that stationary solutions of the Boltzmann equation apply inside the gap, that is, that the flow can be treated as quasi static.

Fukui and Kaneko provided data on  $Q(\text{Kn}, \alpha_w, \alpha_b)$  for the case where  $\alpha_w = \alpha_b$  (Ref. 4), which was subsequently fitted to different empirical formulas by Veijola and others (Ref. 5). Note also that additional, more accurate, data is available in Ref. 6. Veijola provided two empirical formulas, which apply under different circumstances with various degrees of accuracy:

- $\alpha_w = \alpha_b = 1$  (available as the option Rarefied-Total Accommodation in COMSOL Multiphysics):

$$Q(Kn, 1, 1) = 1 + 9.638Kn^{1.159}$$

(accurate to within 5% in the range  $0 < Kn < 880$ )

- $\alpha_w = \alpha_b = \alpha$  (available as the option Rarefied-General Accommodation in COMSOL Multiphysics):

$$Q(\text{Kn}, \alpha, \alpha) = \frac{\tilde{Q}(D, \alpha)}{D} \quad D = \frac{\sqrt{\pi}}{2\text{Kn}}$$

$$\tilde{Q}(D, \alpha) = \frac{D}{6} + \frac{1}{\alpha^{1.34} \sqrt{\pi}} \ln\left(\frac{1}{D} + 4.1\right) + \frac{\alpha}{6.4D} + \frac{1.3(1-\alpha)}{D + 0.08D^{1.83}} + \frac{0.64\alpha D^{0.17}}{1 + 1.12D^{0.72}}$$

(accurate to within 1% in the ranges  $D > 0.01$ ,  $0.7 < \alpha < 1$  and  $0.01 < \text{Kn} < 100$ ).

Both of these empirical models are available as flow models with the options listed. Additionally, a user-defined relative flow rate function can be defined (which could, for example, be based on an interpolation function derived from the original data in Ref. 6). Data on the tangential momentum accommodation coefficients for various gas-surface combinations is available in Ref. 2.



Various definitions of the mean free path are used in the literature, frequently without explanation. For compatibility with the existing literature on thin-film flow, COMSOL Multiphysics uses the same mean free path definition as Veijola and others.

In this definition the mean free path and Knudsen number are defined as:

$$\lambda = \frac{\mu}{p} \left( \frac{2RT}{M_n} \right)^{\frac{1}{2}} \quad \text{Kn} = \frac{\mu}{ph} \left( \frac{2RT}{M_n} \right)^{\frac{1}{2}} \quad (4-12)$$

where  $\mu$  is the gas viscosity,  $p$  is the gas pressure,  $R$  is the molar gas constant,  $T$  is the temperature, and  $M_n$  is the molar mass of the gas. Ref. 2 also employs this definition of the mean free path.

In many applications the forces acting on the wall and base are important. The pressure in the gas can be computed correctly by solving Equations 4-10 and 4-11. However, this approach provides only the normal component of the traction acting on the wall and base. To obtain the shear forces, the approach adopted by Torczynski and Gallis (Ref. 7) is used. They produced an empirical expression for the shear force that has the correct behavior in the free molecular flow and continuum limits as well as in the limits for the accommodation coefficient. Torczynski and Gallis solve the problem of pure Couette flow and derive an empirical function for the slip length that predicts the correct forces for the flow in the gap in several limiting cases. Their empirical expression for the slip length is given by:

$$L_s = \frac{2-\alpha}{\alpha} \frac{2\lambda}{\sqrt{\pi}\mu} \left( 1 + \frac{d_1\alpha}{1 + (2d_2\text{Kn})/\sqrt{\pi}} \right) \quad (4-13)$$

where  $d_1 \approx 0.15$  and  $d_2 \approx 0.59$ . In principle  $d_1$  and  $d_2$  are variables themselves, but they were found to be constant to within the accuracy of the DSMC experiments used to derive their values.



The slip length in Equation 4-13 (which is used in COMSOL Multiphysics) differs slightly from the equivalent expression in Ref. 7 as a result of a different definition of the mean free path (Torczynski and Gallis' mean free path is different from Equation 4-12 by a factor of  $\sqrt{\pi}/2$ ).

Equation 4-7 gives the following expressions for the shear forces on the wall and base for pure Couette flow:

$$\mathbf{f}_w^{shear} = \frac{\mu}{h + 2L_s} (\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T) (\mathbf{v}^b - \mathbf{v}^w)$$

$$\mathbf{f}_b^{shear} = \frac{\mu}{h + 2L_s} (\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T) (\mathbf{v}^w - \mathbf{v}^b)$$

where  $L_s$  is taken from Equation 4-13.

A general flow incorporates both Poiseuille and Couette terms. Assuming that the Poiseuille and Couette flows can be superposed, the forces become:

$$\begin{aligned}\mathbf{f}_w &= -\frac{h}{2}\nabla_t p + \frac{\mu}{h+2L_s}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^b - \mathbf{v}^w) - p\mathbf{n}_r \\ \mathbf{f}_b &= -\frac{h}{2}\nabla_t p + \frac{\mu}{h+2L_s}(\mathbf{I} - \mathbf{n}_r \mathbf{n}_r^T)(\mathbf{v}^w - \mathbf{v}^b) + p\mathbf{n}_r\end{aligned}\quad (4-14)$$

here  $L_s$  is derived from Equation 4-13 and  $p$  is obtained by solving Equation 4-10 with Equation 4-11. Strictly speaking, Torczynski and Gallis' result applies for Couette flow only and was derived for a more general variable-soft-sphere gas rather than for the linearized BGK equations, using numerical simulations. From a practical perspective, it seems likely that solutions of the linearized BGK equations would also be fitted by these expressions, and in that case it should be possible to combine the forces using superposition. In the absence of a detailed proof Equation 4-14 is not the default option for the force model, but is available as an additional option.



Both Veijola and others (Ref. 5) and Cercignani and others (Ref. 5) provided data for the relative flow rate  $Q(\text{Kn}, \sigma_{sw}, \sigma_{sb})$  in specific cases where the wall and base have different accommodation coefficients. Since no details on how to compute the forces acting on the walls for highly rarefied gases were published, these models are not currently supported in COMSOL Multiphysics.

### Frequency-Domain Formulation

In the frequency domain it is necessary to make additional simplifications to the equation system to produce a fully linearized equation set. In the general case, the physical quantities in the Reynolds and flow equations take the form:

$$\begin{aligned}h_w &= h_{w1} + \tilde{h}_w & h_b &= h_{b1} + \tilde{h}_b & h &= h_{w1} + h_{b1} + \tilde{h}_w + \tilde{h}_b = h_1 + \tilde{h} \\ p_f &= \tilde{p}_f & p_A &= p_{ref} + \tilde{p}_f \\ \mathbf{v}_w &= \tilde{\mathbf{v}}_w & \mathbf{v}_b &= \tilde{\mathbf{v}}_b\end{aligned}$$

Here the tilde denotes a harmonically varying component. The components marked with the subscript 1 are static offsets to the harmonic terms. In order to linearize the equation system, it is necessary to assume that the offsets are much larger than the

harmonic components. Practically speaking this means that the harmonically varying pressures induced by the flow should be significantly smaller than the ambient pressure, and the harmonic changes in the gap size due to the wall and base displacements should be significantly less than the gap height itself. Given these assumptions, the average fluid velocity can also be written on the form:

$$\mathbf{v}_{av} = \tilde{\mathbf{v}}_{av}$$

since in general both the Couette and Poiseuille terms vary harmonically to first-order accuracy.

Substituting these terms into the Reynolds equation gives:

$$\frac{\partial}{\partial t}(\rho(h_1 + \tilde{h})) + \nabla_t \cdot (\rho(h_1 + \tilde{h})\tilde{\mathbf{v}}_{av}) = 0$$

In the frequency domain, the total absolute pressure  $p_A$  is set to the reference pressure  $p_{ref}$  because the deviation from the reference pressure  $p_f$  in this case represents an oscillating component and cannot be added to the pressure in a straightforward manner.  $\rho$  is defined as a function of  $p_A$  and so contains no small harmonic component. The products of small harmonic terms result in second-order effects (at double the frequency of interest) and can be neglected provided the harmonic terms are much smaller than the static terms. The Reynolds equation therefore reduces to:

$$\rho \frac{\partial}{\partial t}(\tilde{h}) + \nabla_t \cdot (\rho h_1 \tilde{\mathbf{v}}_{av}) = 0$$

Note that:

$$\frac{\partial}{\partial t}(\tilde{h}) = \tilde{\mathbf{v}}_b \cdot \mathbf{n}_{ref} - \tilde{\mathbf{v}}_w \cdot \mathbf{n}_{ref} - \tilde{\mathbf{v}}_b \cdot \nabla_t h_{b1} - \tilde{\mathbf{v}}_w \cdot \nabla_t h_{w1} \quad (4-15)$$

So the following result holds:

$$\rho(\tilde{\mathbf{v}}_b \cdot \mathbf{n}_{ref} - \tilde{\mathbf{v}}_w \cdot \mathbf{n}_{ref} - \tilde{\mathbf{v}}_b \cdot \nabla_t h_{b1} - \tilde{\mathbf{v}}_w \cdot \nabla_t h_{w1}) + \nabla_t \cdot (\rho h_1 \tilde{\mathbf{v}}_{av}) = 0 \quad (4-16)$$

Dropping the tildes leads to the form of the equation shown in the equation display:

$$\rho(\mathbf{v}_b \cdot \mathbf{n}_{ref} - \mathbf{v}_w \cdot \mathbf{n}_{ref} - \mathbf{v}_w \cdot \nabla_t h_{w1} - \mathbf{v}_b \cdot \nabla_t h_{b1}) + \nabla_t \cdot (\rho h_1 \mathbf{v}_{av}) = 0$$

The modified Reynolds Equation takes the following form:

$$\frac{\partial}{\partial t}((p_{ref} + \tilde{p}_f)(h_1 + \tilde{h})) + \nabla_t \cdot ((p_{ref} + \tilde{p}_f)(h_1 + \tilde{h})\tilde{\mathbf{v}}_{av}) = 0 \quad (4-17)$$

Linearizing Equation 4-17 gives:

$$p_{ref} \frac{\partial \tilde{h}}{\partial t} + h_1 \frac{\partial \tilde{p}_f}{\partial t} + \nabla_t \cdot (p_{ref} h_1 \tilde{\mathbf{v}}_{av}) = 0$$

Equation 4-15 can be used to substitute for the time derivative of the harmonic component of  $h$  in the above equation, yielding:

$$\begin{aligned} p_{ref} (\tilde{\mathbf{v}}_b \cdot \mathbf{n}_{ref} - \tilde{\mathbf{v}}_w \cdot \mathbf{n}_{ref} - \tilde{\mathbf{v}}_b \cdot \nabla_t h_{b1} - \tilde{\mathbf{v}}_w \cdot \nabla_t h_{w1}) \\ + h_1 \frac{\partial \tilde{p}_f}{\partial t} + \nabla_t \cdot (p_{ref} h_1 \tilde{\mathbf{v}}_{av}) = 0 \end{aligned} \quad (4-18)$$

Dropping the tildes and using complex notation to express the time derivative of  $p_f$  gives:

$$\begin{aligned} p_{ref} (\mathbf{v}_b \cdot \mathbf{n}_{ref} - \mathbf{v}_w \cdot \mathbf{n}_{ref} - \mathbf{v}_w \cdot \nabla_t h_{w1} - \mathbf{v}_b \cdot \nabla_t h_{b1}) \\ + i\omega h_1 p_f + \nabla_t \cdot (p_{ref} h_1 \mathbf{v}_{av}) = 0 \end{aligned}$$

Equation 4-16 and Equation 4-18 are used as the basis for the frequency domain formulation in the Thin-Film Flow interfaces. It is important to note that these equations are independent of the harmonic components of the displacement, since those terms lead to second-order contributions to the frequency-domain response (that is, they produce a response proportional to the square of the harmonic term, which results in a signal at twice the driving frequency).



Since the frequency domain results do not depend on the variation in the displacement, the additional displacement setting has no effect on the solution in a frequency-domain problem (unless the velocity is computed from it by selecting **Calculate from wall displacement** or **Calculate from base displacement** in the wall and base velocity settings, respectively). This is reflected in the equations given above (and in the equation display in the physics interface) but can be nonintuitive, particularly when setting up a model that is coupled with a structural analysis. If the velocity of both the wall and the base is set to zero, then in the frequency domain there is no response.

### *Boundary Conditions*

Most of the boundary conditions either constrain the flow into the system by prescribing a fluid velocity or constrain the pressure at the boundary. The border flow

condition is slightly more complex, requiring the gradient of the pressure to be set by specifying the value of the gradient of the pressure in the anti-normal direction such that:

$$-\mathbf{n} \cdot \nabla p = \Gamma$$

The **Border flow type** selection list enables four ways that the value of  $\Gamma$  can be specified:

- The **User defined** option allows the value of  $\Gamma$  to be directly entered as an expression in a text field. This allows for arbitrary normal pressure gradients.
- The two **Acoustic elongation** options assume a linear gradient in the pressure outside the domain away from the boundary. The pressure gradient is calculated by dividing the pressure at the boundary,  $p_f$ , by an elongation length,  $\Delta L$ . The elongation length can either be specified as an absolute length or as a fraction of the domain width, such that:

$$-\mathbf{n} \cdot \nabla p = \frac{p_f}{\Delta L}$$

- The **Out-of-plane motion** option calculates the pressure gradient at the boundary using a model detailed in [Ref. 8](#). This model is suitable for including the effects of gas damping when fluid in a thin gap is subjected to out-of-plane motion of the walls or base (for example, when a microbeam is oscillating above an extended surface). When this option is selected, text fields are provided to specify the required coefficients ( $\zeta, \eta, \chi$ ) and the pressure gradient is defined according to

$$-\mathbf{n} \cdot \nabla p = \zeta \frac{12\mu U}{\eta h^2} \left(1 + \chi \frac{6\Lambda}{h}\right)^{-1} + \frac{p - p_\infty}{\eta h^2}$$

where  $U$  is the out-of-plane velocity,  $\Lambda$  is the slip length at the walls, and  $p_\infty$  is the ambient pressure far from the boundary away from the domain.

the

### *References for the Thin-Film Flow Interfaces*

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- 9.



## Structural Mechanics Interfaces

The MEMS module includes many of the features found in the Solid Mechanics interface in the Structural Mechanics Module.

The documentation of shared features is found in the Structural Mechanics Module documentation. Where indicated in the list below, links to the *Structural Mechanics Module User's Guide* are included.

The list below details the documentation for the MEMS Module physics interfaces on the structural mechanics, acoustics, and fluid flow branches in the **Add Physics** dialog:

- [The Electromechanics Interface](#)
- [Theory for the Electromechanics Interface](#)
- [Theory for the Electromechanics Interface](#)
- [The Electromechanics, Boundary Elements Interface](#)
- [The Thermoelasticity Interface](#)
- [Theory for the Thermoelasticity Interface](#)
- The [Solid Mechanics](#) Interface (in the *Structural Mechanics Module User's Guide*)

- [The Elastic Waves, Time Explicit Interface](#) (in the [Elastic Waves Interfaces](#) chapter of the *Acoustics Module User's Guide*)
- [The Thermal Stress, Solid Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [The Piezoelectricity Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [The Electrostriction Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [The Ferroelectroelasticity Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [The Fluid-Solid Interaction Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [The Fluid-Solid Interaction, Fixed Geometry Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [The Fluid-Solid Interaction, Conjugate Heat Transfer Interface](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)
- [Hygroscopic Swelling Coupling](#) (in the [Multiphysics Interfaces and Couplings](#) chapter of the *Structural Mechanics Module User's Guide*)

# The Electromechanics Interface

The **Electromechanics** interface () , found under the **Electromagnetics-Structure Interaction** () branch within the **Structural Mechanics** branch () when adding a physics interface combines Solid Mechanics and Electrostatics with a moving mesh functionality to model the deformation of electrostatically actuated structures.

The **Electromechanics** interface is available for 3D, planar 2D, and axisymmetric 2D geometries.

When this multiphysics interface is added using the **Model Wizard**, a **Solid Mechanics** interface and an **Electrostatics** interfaces are added to the **Model Builder**.

In addition, the **Multiphysics Couplings** node is added, which automatically includes the multiphysics coupling feature **Electromechanical Forces**.



In previous versions of COMSOL Multiphysics (up to version 5.3), a specific physics interface called **Electromechanics** was added to the **Model Builder**. Now, a predefined multiphysics coupling approach is used, improving the flexibility and design options for your modeling. For specific details, see [The Multiphysics Branch](#) and [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

The full functionality of the Solid Mechanics and Electrostatics interfaces is accessible under the corresponding interfaces at the domain, boundary line, or point level in the geometry. The participating **Electrostatics** interface by default adds the **Charge Conservation** node with its selection set to all domains, and the material type set to Solid. This node serves to represent solid dielectric material domains. Any number of **Charge Conservation** nodes can be also added manually to the interface and configured to represent either solid or nonsolid (for example, air or free space) materials.

## Electromechanical Forces

Use **Electromechanics Forces** (  ) coupling to model electromechanical interaction between deformable solids and electric fields, particularly in case when the deformations of the structure can significantly affect the electric field distribution.



The presence of such multiphysics node in the model will enforce the **Include geometric nonlinearity** option on all applicable study nodes.

### SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the `name` string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is `eme1`.

### DOMAIN SELECTION

The domain selection is locked, so that all applicable domains are selected automatically. Such domains represent an intersection of the applicable domains under the corresponding **Electrostatics** and **Solid Mechanics** interfaces selected in the coupling feature.

In **Electrostatics** interface, the following two domains are applicable:

- **Charge Conservation**, if its material type input is set to **Solid**. Use this domain feature for solid dielectric materials.
- **Terminal**. You can use the domain terminal feature to represent conductive solid materials such as, for example, doped silicon.

In **Solid Mechanics** interface, the following domain material feature are applicable:

- **Linear Elastic Material**

- **Nonlinear Elastic Material** (with the Nonlinear Structural Materials Module)
- **Hyperelastic Material** (with the Nonlinear Structural Materials Module).



For nonsolid dielectric domains, remove them from the **Solid Mechanics** interface selection but keep them selected in the **Electrostatics** interface selection.

## ELECTROMAGNETIC STRESS

To display this section, click the **Show More Options** button (  ) and select **Advanced Physics Options** in the **Show More Options** dialog box.

Here, you can select the **Electromagnetic Stress Tensor** to be used in the coupling. The following options are available:

- **Minkowsky** (default)
- **Einstein-Laub**
- **Chu**

See [About different stress forms](#) chapter for more details.

## COUPLED INTERFACES

This section defines the physics interfaces involved in this Electromechanical Forces coupling. The **Solid mechanics** and **Electrostatics** lists include all applicable physics interfaces.

The default values depend on how the node is created.

- If it is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (Mac and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it is added automatically when the physics interface is chosen in the **Model Wizard** or **Add Physics** window, then the two participating physics interfaces are selected.

You can also select **None** from either list to uncouple the coupling from a physics interface. If the physics interface is removed from the **Model Builder**, for example **Solid**

**Mechanics** is deleted, then the **Solid mechanics** list defaults to **None** as there is nothing to couple to.



If a physics interface is deleted and then added to the model again, then in order to reestablish the coupling, you need to choose the physics interface again from the lists. This is applicable to all multiphysics coupling nodes that would normally default to the once present physics interface. See [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

### *Deforming Domain*

When **Electromechanics** multiphysics interface is added using the **Model Wizard**, a **Deforming Domain** and a **Symmetry** nodes are added automatically in **Model Builder** under the **Definitions** node. These nodes serve to represent domains and boundaries where the mesh can deform. By default, both nodes have empty selection. Under the **Deforming Domain**, you can select those domain that represent nonsolid dielectric materials such as air, fluid, and free space. However, this is only needed if the boundaries of such domains experience significant changes due to the deformation or rotation of the adjacent solid domains. Otherwise, the moving mesh computations could just introduce unnecessary overhead and nonlinearity in the model (see [Deformed Mesh Fundamentals](#)). Domains selected in the Solid Mechanics interface are not applicable.

Under the **Deforming Domain**, you can also choose the **Mesh smoothing type**, by default set to **Hyperelastic**. More information of the smoothing type can be found in the [Deforming Domain](#) chapter in the *COMSOL Multiphysics Reference Manual*.

By default, the mesh is fixed at all external boundaries of the geometry. Use the **Symmetry** node to select the external boundaries, where the mesh can slide along the boundary. You can also add other types of boundary conditions for the mesh motion, for details see [Moving Mesh Features](#) in the *COMSOL Multiphysics Reference Manual*.

# Theory for the Electromechanics Interface

The [Electromechanics Interface](#) theory is described in this section:

- [Overview of Forces in Continuum Mechanics](#)
- [The Electromagnetic Stress Tensor](#)
- [References for the Electromechanics Interface](#)

## *Overview of Forces in Continuum Mechanics*

---

The deformation of linear elastic materials subject to external loads is described by Cauchy's equation:

$$\rho \frac{d^2 \mathbf{u}}{dt^2} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f}_v$$

where  $\rho$  is the density,  $\mathbf{u}$  denotes the structural displacement vector,  $\boldsymbol{\sigma}$  is the stress tensor, and  $\mathbf{f}_v$  is an external volume force (such as gravity).

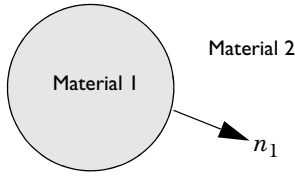
In the stationary case, there is no acceleration, and the equation representing the force balance is

$$\mathbf{0} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f}_v$$

The stress tensor must be continuous across a stationary boundary between two materials. This corresponds to the equation

$$\mathbf{n}_1(\boldsymbol{\sigma}_2 - \boldsymbol{\sigma}_1) = \mathbf{0} \quad (5-1)$$

where  $\sigma_1$  and  $\sigma_2$  represent the stress tensor in Materials 1 and 2, respectively, and  $\mathbf{n}_1$  is the normal vector pointing out from the domain containing Material 1.



For more information on the mechanical stress tensor for elastic materials, see the documentation for the physics interfaces. For example, [Structural Mechanics Interfaces](#).

### *The Electromagnetic Stress Tensor*

Within a vacuum or other medium, forces between charged bodies can be computed on the assumption that a fictitious state of stress exists within the field. Historically the consistency of this approach led 19th-century physicists to postulate the existence of the ether, a ubiquitous medium through which electromagnetic forces propagate. While these ideas have been superseded by the development of special relativity, the use of an electromagnetic stress tensor (also known as the Maxwell stress tensor) remains an accurate and convenient technique to compute electromagnetic forces.

Maxwell stresses exists in all dielectric materials, including air and even free space. However, the force magnitude is rather small, and it usually can cause significant deformations only at small dimension.

The electromagnetic stress tensor in a vacuum (in the absence of magnetic fields) is given by ([Ref. 1](#)):

$$\sigma_{EM, V} = \epsilon_0 \mathbf{E} \otimes \mathbf{E} - \frac{1}{2}(\epsilon_0 \mathbf{E} \cdot \mathbf{E})I \quad (5-2)$$

Where  $\mathbf{E}$  is the electric field,  $I$  is the identity tensor,  $\epsilon_0$  is the permittivity of free space, and

$$(\mathbf{E} \otimes \mathbf{E})_{ij} = E_i E_j$$

Within an isotropic linear dielectric under small deformations, the electric displacement vector is related to the electric field as ([Ref. 2](#)):



$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \varepsilon_0 \chi \mathbf{E}$$

where the electric susceptibility  $\chi$  can be a function of the mechanical strain in the material

$$\chi = \chi_0(I - 2\mathbf{T} + \text{tr}(\mathbf{T})\mathbf{I})$$

where the small strain tensor is given by

$$\mathbf{T} = \frac{1}{2}(\nabla \mathbf{u} + \nabla \mathbf{u}^T)$$

The corresponding electromagnetic stress tensor takes the following form:

$$\sigma_{\text{EM}} = \varepsilon_0 \varepsilon_r \mathbf{E} \otimes \mathbf{E} - \frac{1}{2} \varepsilon_0 \varepsilon_r (\mathbf{E} \cdot \mathbf{E}) \mathbf{I} \quad (5-3)$$

where the relative permittivity of the material with the absence of deformation is introduced as  $\varepsilon_r = 1 + \chi_0$ . It can be written equivalently as

$$\sigma_{\text{EM}} = \sigma_{\text{EM}, \text{V}} + \varepsilon_0 \chi_0 \left[ \mathbf{E} \otimes \mathbf{E} - \frac{1}{2} (\mathbf{E} \cdot \mathbf{E}) \mathbf{I} \right]$$

where the two terms represent, respectively, the contributions from: the underlying free space and the material polarization.



The [Electromechanical Forces](#) coupling feature applies the free space contribution to the stress as a body load and adds the material contributions to the stress tensor variable defined by the corresponding Solid Mechanics interface.

## LARGE DEFORMATIONS

For finite deformations, the expressions for the electromagnetic stress and material polarization can be derived using the following thermodynamic potential called electric enthalpy:

$$H_{\text{eme}} = W_s(C) - \frac{1}{2} [\varepsilon_0 \varepsilon_r J C^{-1}] : (\mathbf{E}_m \otimes \mathbf{E}_m)$$

where the subscript m indicates that the vector components must be taken on the material frame, and the right Cauchy-Green deformation tensor is

$$C = F^T F$$

with  $F = \nabla \mathbf{u} + I$ , and  $J = \det(F)$ . The mechanical energy function  $W_s(C)$  depends on the solid model used.

The total second Piola-Kirchhoff stress tensor is given by

$$S = 2 \frac{\partial H_{\text{eme}}}{\partial C}$$

and the electric displacement can be calculated as

$$\mathbf{D}_m = - \frac{\partial H_{\text{eme}}}{\partial \mathbf{E}_m}$$



COMSOL Multiphysics only includes the functionality to apply the electromechanical forces to an isotropic material.

The electromagnetic stress tensor can be used to compute the forces acting on a dielectric body. From [Equation 5-1](#) the balance of forces at the surface of a dielectric body (material 1) in vacuum or air (material 2) implies:

$$\mathbf{n}_1(\sigma_2 - \sigma_1) = \mathbf{0}$$

where the total stress tensors in media 1 and 2 are, respectively:

$$\sigma_1 = \sigma_{EM} + \sigma_m$$

$$\sigma_2 = \sigma_{EM, V} + p$$

where  $\sigma_m$  is a mechanical component of the total stress and the pressure  $p$  due to air (if present). Using [Equation 5-2](#):

$$\mathbf{n}_1 \sigma_2 = -p \mathbf{n}_1 - \left( \frac{1}{2} \epsilon_0 \mathbf{E} \cdot \mathbf{E} \right) \mathbf{n}_1 + \epsilon_0 (\mathbf{n}_1 \cdot \mathbf{E}) \mathbf{E}.$$



The [Electromechanical Forces](#) coupling feature applies the above defined traction as a boundary load on the boundaries which are external for the coupling feature selection but internal for the corresponding Electrostatics interface.

COMSOL Multiphysics does not explicitly include the pressure definition on the Electromechanical Forces coupling feature. However, it is possible to add an additional surface force to the corresponding Solid Mechanics interface if the pressure is known or computed by another physics interface.

#### ABOUT DIFFERENT STRESS FORMS

There exists a long-lasting controversy in scientific literature about the definition of electromagnetic forces acting on solids. An extensive review can be found in [Ref. 3](#). Many classic textbooks (for example, [Ref. 1](#) and [Ref. 2](#)) operate with the so-called Minkowski stress tensor that is usually written as:

$$\sigma_{\text{EM}} = \mathbf{D} \otimes \mathbf{E} - \frac{1}{2} (\mathbf{D} \cdot \mathbf{E}) \mathbf{I}$$

The corresponding electromagnetic body force can be written as

$$\mathbf{f} = \nabla \cdot \sigma_{\text{EM}} = \rho_e \mathbf{E} - \frac{1}{2} (\mathbf{E} \otimes \mathbf{E}) : \nabla \chi$$

which sometimes is referred to as the Korteweg-Helmholtz force. For homogeneous materials without deformation, one has  $\nabla \chi = 0$ . Hence, in the absence of free charges ( $\rho_e = 0$ ), the body force becomes zero. Thus, the whole electromechanical load on the solid is due to the Maxwell stress jumps at the boundaries between domains with different material properties.

There exists two most often used alternatives. The first one is called Einstein-Laub stress tensor:

$$\sigma_{\text{EM}} = \mathbf{D} \otimes \mathbf{E} - \frac{1}{2} (\epsilon_0 \mathbf{E} \cdot \mathbf{E}) \mathbf{I}$$

This form is widely accepted in modern electroelasticity and material science, see [Ref. 4](#). The corresponding body force can be written as:

$$\mathbf{f} = \nabla \cdot \boldsymbol{\sigma}_{\text{EM}} = \rho_e \mathbf{E} + (\mathbf{P} \cdot \nabla) \mathbf{E}$$

which is also called Kelvin force. Note that it is nonzero as soon as there are electric field variation and polarization within the material:

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

The other alternative is Chu stress tensor:

$$\boldsymbol{\sigma}_{\text{EM}} = \varepsilon_0 \mathbf{E} \otimes \mathbf{E} - \frac{1}{2}(\varepsilon_0 \mathbf{E} \cdot \mathbf{E}) \mathbf{I} \quad (5-4)$$

and the corresponding electromagnetic body force is given by

$$\mathbf{f} = \nabla \cdot \boldsymbol{\sigma}_{\text{EM}} = \rho_e \mathbf{E} - (\nabla \cdot \mathbf{P}) \mathbf{E}$$

Note that in contrast to the above equation, the expression for the stress tensor itself ([Equation 5-4](#)) seems to ignore the material polarization properties. However, if the frame difference is important because of the deformations, one has

$$\mathbf{D}_m = \varepsilon_0 J C^{-1} \mathbf{E}_m + \varepsilon_0 \chi_m \mathbf{E}_m \quad (5-5)$$

The electric enthalpy can be written as

$$H_{\text{eme}} = W_s(C) - \frac{1}{2} \mathbf{D}_m \cdot \mathbf{E}_m$$

Then,

$$\mathbf{D}_m = - \frac{\partial H_{\text{eme}}}{\partial \mathbf{E}_m}$$

and the electromechanical second Piola-Kirchhoff stress tensor is given by

$$\mathbf{S}_{\text{EM}} = 2 \frac{\partial H_{\text{eme}}}{\partial \mathbf{C}} = J \mathbf{F}^{-1} \boldsymbol{\sigma}_{\text{EM}} \mathbf{F}^{-T} \quad (5-6)$$

where  $\sigma_{\text{EM}}$  is given by Equation 5-4, which shows the consistency of the theory. The key assumption behind the derivation of Equation 5-6 is that the material components of the electric susceptibility  $\chi_m$  are independent of deformations.



COMSOL Multiphysics provides a choice of the electromagnetic stress model, which is available in the [Electromechanical Forces](#) coupling feature. Any of the above presented three options can be selected; the default choice is the Minkowski stress tensor.

### *References for the Electromechanics Interface*

1. J.A. Stratton, *Electromagnetic Theory*, Cambridge, MA, 1941.
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3. D.J. Griffiths, “Resource Letter EM-1: Electromagnetic Momentum,” *Am. J. Phys.*, vol. 80, pp. 7–18, 2012.
4. L. Dorfmann, R.W. Ogden, *Mechanics and Electrodynamics of Electroelastic and Magnetoelastic Interactions*, Springer, 2014.

# The Electromechanics, Boundary Elements Interface

The **Electromechanics, Boundary Elements** interface () , found under the **Electromagnetics-Structure Interaction** () branch within the **Structural Mechanics** branch () when adding a physics interface combines Solid Mechanics and Electrostatics, Boundary Elements to model the deformation of electrostatically actuated structures.

The **Electromechanics, Boundary Elements** interface is available for 3D and planar 2D geometries.

When this multiphysics interface is added using the **Model Wizard**, a **Solid Mechanics** interface and an **Electrostatics, Boundary Elements** interface are added to the **Model Builder**.

In addition, the **Multiphysics Couplings** node is added, which automatically includes the multiphysics coupling feature **Electromechanical Interface**.

## *Electromechanical Interface*

Use **Electromechanical Interface** () to model electromechanical interaction between deformable solid domains and nonsolid voids, where the electric field is computed using the boundary element method. The backward coupling to Electrostatics is due to the deformations of the boundaries.



The presence of such multiphysics node in the model will enforce the **Include geometric nonlinearity** option on all applicable study nodes.

## SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern <name>.<variable\_name>. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the name string must be unique. Only letters, numbers, and underscores (\_) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is `eme1`.

**BOUNDARY SELECTION**

Applicable boundaries are those that are both external boundaries to the domains selected under the **Solid Mechanics** interface and boundaries to the domains selected under the **Electrostatics, Boundary Elements** interface. In particular, all boundaries external to **Solid Mechanics** selection are applicable if the selection of the **Electrostatics, Boundary Elements** contains **Infinite void**.



For nonsolid dielectric domains, remove them from the **Solid Mechanics** interface selection but keep them selected in the **Electrostatics, Boundary Elements** interface selection.

The coupling is a boundary load on a structure caused by the Maxwell Stress at the selected boundaries. The backward coupling to Electrostatics is due to the change of the spatial position of the boundaries caused by the deformation of the structure.



Only electrically linear and isotropic materials can be modeled using **Electrostatics, Boundary Elements**. For more details, see [The Electromechanics, Boundary Elements Interface](#) chapter of the *AC/DC Module User's Guide*.

**COUPLED INTERFACES**

This section defines the physics interfaces involved in this Electromechanical Forces coupling. The **Solid mechanics** and **Electrostatics, Boundary Elements** lists include all applicable physics interfaces.

The default values depend on how the node is created.

- If it is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (Mac and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it is added automatically when the physics interface is chosen in the **Model Wizard** or **Add Physics** window, then the two participating physics interfaces are selected.

You can also select **None** from either list to uncouple the coupling from a physics interface. If the physics interface is removed from the **Model Builder**, for example **Solid Mechanics** is deleted, then the **Solid mechanics** list defaults to **None** as there is nothing to couple to.



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If a physics interface is deleted and then added to the model again, then in order to reestablish the coupling, you need to choose the physics interface again from the lists. This is applicable to all multiphysics coupling nodes that would normally default to the once present physics interface. See [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

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# The Thermoelasticity Interface

The **Thermoelasticity** multiphysics interface () can be found under the **Thermal-Structure Interaction** () branch within the **Structural Mechanics** branch () when adding a physics interface using the Model Wizard or the Add Physics window. The thermoelastic effect results in local cooling of material under tension and heating of material that is compressed. Irreversible heat transfer occurs between the warm and cool regions of the solid, producing mechanical losses, which can be important, particularly for small structures.

When this multiphysics interface is added, the Model Builder tree structure is populated with two physics interfaces (**Solid Mechanics** and **Heat Transfer in Solids**), and the **Thermal Expansion** multiphysics coupling.

In the Settings window for the Solid Mechanics interface, the **Structural Transient Behavior** is set to **Include inertial terms** by default. In the Settings window for Thermal Expansion, under the section **Heat Sources**, the check box for **Thermoelastic damping** is enabled by default.

## *On the Study Types for Thermoelasticity*

Since this multiphysics interface is aimed at computing the thermoelastic damping of MEMS structures under vibration, it only makes sense to analyze the model in the time or frequency domain. Furthermore, for the frequency-domain study types, it is necessary to first include a stationary study step in order to establish the baseline temperature (the linearization point for the temperature field). Therefore, only the following three study types are recommended for the Thermoelasticity multiphysics interface: **Time Dependent**; **Thermal Perturbation**, **Eigenfrequency**; and **Thermal Perturbation**, **Frequency Domain**.

## *On the Temperature Variable for Thermoelasticity*

As mentioned above, for the frequency domain study types, there are two components of the temperature variable: the baseline temperature and the harmonic temperature (which varies around the baseline). To specify the baseline temperature at a boundary, use the **Temperature** boundary condition. To specify the harmonic temperature at the

boundary, right-click the **Temperature** node and select the **Harmonic Perturbation** subnode.



*Thermoelastic Damping in a MEMS Resonator*: Application Library  
path **MEMS\_Module/Actuators/thermoelastic\_damping\_3d**

#### *On the Constituent Physics Interfaces*

The Solid Mechanics interface is intended for general structural analysis of 3D, 2D, or axisymmetric bodies. In 2D, plane stress or plane strain assumptions can be used. The Solid Mechanics interface is based on solving Navier's equations, and results such as displacements, stresses, and strains are computed.

The Heat Transfer in Solids interface provides features for modeling heat transfer by conduction, convection, and radiation. A Solid model is active by default on all domains. All functionality for including other domain types, such as a fluid domain, is also available. The temperature equation defined in solid domains corresponds to the differential form of the Fourier's law that may contain additional contributions like heat sources.

#### *On the Couplings*

The coupling occurs on the domain level, where two physical effects occur:

- The temperature from the Heat Transfer interface acts as a thermal load for the Solid Mechanics interface, causing thermal expansion.
- The tension and compression from the Solid Mechanics interface acts as a heat source for the Heat Transfer interface, causing local cooling and heating.

These effects are implemented by the combination of the multiphysics coupling mentioned above, and the use of the temperature from the default model inputs.

#### **COUPLING FEATURES**

When physics interfaces are added from the Model Wizard or using the Add Physics window then the appropriate coupling feature is automatically added to the physics interface. However, the physics interfaces can be added one at a time, followed by the coupling features.

For example, if single **Solid Mechanics** and **Heat Transfer in Solids** interfaces are added, then COMSOL Multiphysics adds an empty **Multiphysics** node. You can then choose the **Thermal Expansion** coupling feature.



Coupling features are available from the context menu (right-click the **Multiphysics** node) or from the **Physics** toolbar, **Multiphysics Couplings** menu.

**PHYSICS INTERFACES AND COUPLING FEATURES**



Use the online help in COMSOL Multiphysics to locate and search all the documentation. All these links also work directly in COMSOL Multiphysics when using the Help system.

*Coupling Feature*

The [Fluid-Solid Interaction Interface](#) node is described in the section [The Thermal Stress, Solid Interface](#) in the *Structural Mechanics User's Guide*.



*Thermoelastic Damping in a MEMS Resonator*: Application Library path **MEMS\_Module/Actuators/thermoelastic\_damping\_3d**

# Theory for the Thermoelasticity Interface

The [Thermoelasticity Interface](#) theory is described in this section:

- [Background Thermoelasticity Theory](#)
- [References for the Thermoelasticity Interface](#)

## *Background Thermoelasticity Theory*

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When an elastic rod is stretched reversibly and adiabatically its temperature drops. The drop in temperature compensates for the increase in entropy caused by the stress in the rod (since the process is reversible the entropy remains constant). The equations of thermoelasticity incorporate this phenomenon, together with the irreversible processes that occur in a vibrating rod (which result in net entropy increases). When a structure vibrates in a mode with both local compression and expansion there are always some losses associated with the irreversible heat conduction between the expanding areas that cool and the contracting areas that heat. These losses result in thermoelastic damping, which can be important, particularly in small vibrating structures, such as resonant MEMS devices.



References 1 to 5 in the section [References for the Thermoelasticity Interface](#) provide useful background information.

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The equations of thermoelasticity are derived from the first law of thermodynamics, which can be stated as follows:

$$dU = dQ' + dW' \quad (5-7)$$

where  $dU$  is the change in internal energy,  $dQ'$  is the heat flow into the system (the prime indicates an inexact differential in this case) and  $dW'$  is the work done on the system. For a small part of a solid (sufficiently small that the stresses and strains are uniform), with an initial reference density,  $\rho_0$ , the first law can be rewritten in the following form (assuming that the differential changes occur between equilibrium states):

$$du = T_a ds + \frac{1}{\rho_0} \sigma : d\epsilon \quad (5-8)$$

where  $T_a$  is the absolute temperature,  $s$  is the entropy per unit mass,  $\sigma$  is the elastic part of the second Piola-Kirchhoff stress (in general a rank 2 tensor),  $\epsilon$  is the material strain (also a tensor). In general the second Piola-Kirchhoff stress tensor,  $\mathbf{p}$ , must be split into elastic ( $\sigma$ ) and inelastic ( $\tau$ ) parts such that:

$$\mathbf{p} = \sigma + \tau$$

The elastic part of the stress tensor,  $\sigma$ , does work  $\sigma : d\epsilon$  during a change in the strain. The inelastic part of the stress tensor,  $\tau$ , generates heat at a rate  $\tau : (d\epsilon/dt)$  when the strain is changing and is identified with internal or material damping. These internal damping mechanisms are associated with microscopic phenomena such as dislocation movement.

From Equation 5-8 it is possible to make the following identifications for  $T_a$  and  $\sigma$ :

$$T_a = \left( \frac{\partial u}{\partial s} \right)_\epsilon \quad \sigma = \rho_0 \left( \frac{\partial u}{\partial \epsilon} \right)_s$$

Next the *entropy balance equation* must be derived. Since thermoelasticity involves irreversible processes, the assumption of equilibrium required to derive Equation 5-8 is no longer valid. Instead an assumption of “local” equilibrium is made. It is assumed that although the system is not in equilibrium, there exists within small elements a state of local equilibrium, for which the local entropy per unit mass,  $s$ , is the same function of the internal energy, strain, and particle number as it was in equilibrium. This assumption is commonly employed in the modeling of transport phenomena and is justified only by the validity of conclusions derived from it and by results obtained from specific microscopic models, for near-equilibrium situations. For a small volume element in the material frame Equation 5-8 can then be written as:

$$\rho_0 ds = \frac{1}{T_a} \rho_0 du - \frac{1}{T_a} \sigma : d\epsilon$$

The rate of change of entropy can then be written as:

$$\rho_0 \frac{ds}{dt} = \rho_0 \frac{1}{T_a} \frac{du}{dt} - \frac{1}{T_a} \sigma : \frac{d\epsilon}{dt} \quad (5-9)$$

From the first law (Equation 5-7) the rate of change of internal energy is given by:

$$\rho_0 \frac{du}{dt} = \frac{dq}{dt} + \frac{dw}{dt}$$

where  $w$  is the work done per unit volume and  $q$  is the heat accumulated per unit volume. The heat accumulated can be written as the sum of the heat sources and the divergence in the material frame heat flux:

$$\frac{dq}{dt} = -(\nabla \cdot \mathbf{q}) + Q + \tau : \frac{d\epsilon}{dt}$$

where  $Q$  represents the heat source per unit volume and  $\tau$  is the inelastic part of the stress tensor. The rate of doing work (per unit reference volume) by a linear elastic material is given by the elastic part of the second Piola-Kirchhoff stress contracted with the rate of material strain. Per unit volume the following equation is obtained:

$$\frac{dw}{dt} = \sigma : \frac{d\epsilon}{dt}$$

so Equation 5-9 reduces to:

$$\rho_0 \frac{ds}{dt} = -\frac{1}{T_a} \nabla \cdot \mathbf{q} + \frac{1}{T_a} Q + \frac{1}{T_a} \tau : \frac{d\epsilon}{dt} \quad (5-10)$$

The definition of the material thermal conductivity gives:

$$\mathbf{q} = -\kappa \nabla T_a$$

where  $\kappa$  is the thermal conductivity, defined in the material frame.

Therefore the equation is:

$$T_a \rho_0 \frac{ds}{dt} = \nabla \cdot (\kappa \nabla T_a) + Q + \tau : \frac{d\epsilon}{dt} \quad (5-11)$$

It is now necessary to derive an expression for the rate of change of entropy with respect to time. In order to do this an assumption of local equilibrium is used once again. Using Equation 5-8 the equation is written:

$$d\left(u - T_a s - \frac{1}{\rho_0} \sigma : \epsilon\right) = -s dT_a - \frac{1}{\rho_0} \epsilon : d\sigma$$

which defines a new *thermodynamic potential*, the Gibbs free energy per unit mass, given by:

$$g = u - T_a s + \frac{1}{\rho_0} \boldsymbol{\sigma} : \boldsymbol{\varepsilon}$$

Changes in the Gibbs free energy per unit mass take the form:

$$dg = -s dT_a - \frac{1}{\rho_0} \boldsymbol{\varepsilon} : d\boldsymbol{\sigma}$$

which leads to the relations:

$$s = -\left(\frac{\partial g}{\partial T_a}\right)_{\boldsymbol{\sigma}} \quad \boldsymbol{\varepsilon} = -\rho_0 \left(\frac{\partial g}{\partial \boldsymbol{\sigma}}\right)_{T_a}$$

By differentiating each of the above equations a second time, it is possible to derive the following *Maxwell relation*:

$$\left(\frac{\partial s}{\partial \boldsymbol{\sigma}}\right)_{T_a} = \frac{1}{\rho_0} \left(\frac{\partial \boldsymbol{\varepsilon}}{\partial T_a}\right)_{\boldsymbol{\sigma}} = \frac{\partial^2 g}{\partial \boldsymbol{\sigma} \partial T_a} \quad (5-12)$$

It is now possible to derive an expression for the entropy of the solid. Assuming that the elastic stress is an invertible function of the strain, we can write  $s=s(\boldsymbol{\sigma}, T_a)$ . Thus:

$$ds = \left(\frac{\partial s}{\partial \boldsymbol{\sigma}}\right)_{T_a} : d\boldsymbol{\sigma} + \left(\frac{\partial s}{\partial T_a}\right)_{\boldsymbol{\sigma}} dT_a$$

Using the Maxwell relation in [Equation 5-12](#):

$$ds = \frac{1}{\rho_0} \left(\frac{\partial \boldsymbol{\varepsilon}}{\partial T_a}\right)_{\boldsymbol{\sigma}} : d\boldsymbol{\sigma} + \left(\frac{\partial s}{\partial T_a}\right)_{\boldsymbol{\sigma}} dT_a$$

Therefore:

$$\frac{ds}{dt} = \frac{1}{\rho_0} \left(\frac{\partial \boldsymbol{\varepsilon}}{\partial T_a}\right)_{\boldsymbol{\sigma}} : \frac{d\boldsymbol{\sigma}}{dt} + \left(\frac{\partial s}{\partial T_a}\right)_{\boldsymbol{\sigma}} \frac{dT_a}{dt}$$

By definition the heat capacity of the solid at constant stress is given by:

$$c_p = \left(\frac{\partial q}{\partial T}\right)_{\boldsymbol{\sigma}} = T_a \left(\frac{\partial s}{\partial T}\right)_{\boldsymbol{\sigma}}$$

Thus:

$$\frac{ds}{dt} = \frac{1}{\rho_0} \left( \frac{\partial \epsilon}{\partial T_a} \right)_{\sigma} : \frac{d\sigma}{dt} + \frac{c_p}{T_a} \frac{dT_a}{dt} \quad (5-13)$$

Substituting Equation 5-13 into Equation 5-11 gives the following equation for thermoelasticity:

$$\rho_0 c_p \frac{dT_a}{dt} = \nabla \cdot (\kappa \nabla T_a) + Q + \tau : \frac{d\epsilon}{dt} - T_a \left( \frac{\partial \epsilon}{\partial T_a} \right)_{\sigma} : \frac{d\sigma}{dt} \quad (5-14)$$

An additional heat source term is present in Equation 5-14, compared to the standard heat transfer equations in solids. This term couples the structural problem with the heat transfer problem. In turn the heat transfer equation couples back into the structural problem through the constitutive relationship.

In the particular case of a linear elastic material (in the absence of damping) the stress and strain are related by Duhamel-Hooke's law:

$$(\sigma - \sigma_i) = \mathbf{C} : (\epsilon - \epsilon_i - \alpha(T_a - T_{\text{ref}})) \quad (5-15)$$

where  $\mathbf{C}$  is the elasticity tensor,  $\sigma_i$  is the initial stress,  $\epsilon_i$  is the initial strain, and  $T_{\text{ref}}$  is the reference temperature at which the strain and stresses take the initial values.

This equation couples the heat transfer equation to the structural problem. Given a temperature independent thermal expansivity, and no material damping, Equation 5-14 takes the form:

$$\rho_0 c_p \frac{dT_a}{dt} = \nabla \cdot (\kappa \nabla T_a) + Q - T_a \alpha : \frac{d\sigma}{dt}$$



This is the usual form of the equation for linear thermoelasticity. In the COMSOL Multiphysics Material Library, a slightly unusual definition of the thermal expansivity is used, so that  $\alpha$  is not temperature independent. COMSOL Multiphysics therefore implements a version of Equation 5-14, which automatically includes these effects. In brief, an expression for  $\epsilon$  is obtained by solving Equation 5-15 and the expression is differentiated with respect to  $T_a$  while keeping  $\sigma$  constant.

## LINEARIZED EQUATIONS AND FREQUENCY DOMAIN FORMULATION

In the time domain it is convenient to linearize Equation 5-14, and this is necessary to solve problems in the frequency domain.



The independent variables in the system are  $T_a$  and  $\mathbf{u}$  (where  $\mathbf{u}$  is the displacement vector). Since the displacements drive the thermal equations it is natural to write the displacement vector as consisting of small deviations from its equilibrium value such that:

$$\mathbf{u} = \mathbf{u}_0 + a\mathbf{u}_1 + a^2\mathbf{u}_2 + \dots$$

where  $a$  is a constant that is subsequently set to 1 and that is used to keep track of the order of the term in the expansion.

The corresponding temperatures, stresses, and strains in the device are given by:

$$T_a = T_0 + aT_1 + a^2T_2 + \dots$$

$$\varepsilon = \varepsilon_0 + a\varepsilon_1 + a^2\varepsilon_2 + \dots$$

$$\sigma = \sigma_0 + a\sigma_1 + a^2\sigma_2 + \dots$$

$$\tau = a_1\tau_1 + a^2\tau_2 + \dots$$

where  $a$  is a constant that is subsequently set to 1.  $a$  can be used to track the order of the deviation from  $T_0$ .

Substituting these relations into [Equation 5-14](#) and keeping terms up to the second order gives:

$$\begin{aligned} a\rho_0c_p \frac{dT_1}{dt} + a^2\rho_0c_p \frac{dT_2}{dt} = & \nabla \cdot (\kappa \nabla T_0) + a \nabla \cdot (\kappa \nabla T_1) + a^2 \nabla \cdot (\kappa \nabla T_2) + Q_0 \\ & + a^2\tau_1 : \frac{d\varepsilon_1}{dt} - aT_0 \left( \frac{\partial \varepsilon}{\partial T_a} \right)_{\sigma} : \frac{d\sigma_1}{dt} \\ & - a^2T_1 \left( \frac{\partial \varepsilon}{\partial T_a} \right)_{\sigma} : \frac{d\sigma_1}{dt} - a^2T_0 \left( \frac{\partial \varepsilon}{\partial T_a} \right)_{\sigma} : \frac{d\sigma_2}{dt} \\ & - a^2T_0T_1 \frac{\partial}{\partial T_a} \left( \frac{\partial \varepsilon}{\partial T_a} \right)_{\sigma} : \frac{d\sigma_1}{dt} \end{aligned}$$

Note that the heat source term,  $Q$ , is assumed to be time independent ( $Q=Q_0$ ). The final term in the above equation results from consideration of the Taylor expansion of the strain at constant stress, which to first order can be represented by a Taylor series of the form:

$$\varepsilon(T_a) = \varepsilon(T_0 + aT_1) = \varepsilon_0 + \left(\frac{\partial \varepsilon_0}{\partial T_a}\right) aT_1 + \dots$$

Consequently:

$$\left(\frac{\partial \varepsilon}{\partial T_a}\right)_\sigma = \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma + aT_1 \frac{\partial}{\partial T_a} \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma + \dots$$

Note that for the particular case of a linear elastic material:

$$\sigma_0 - \sigma_i = \mathbf{C} : (\varepsilon_0 - \varepsilon_i - \alpha(T_0 - T_{ref}))$$

$$a\sigma_1 + a^2\sigma_2 = \mathbf{C} : (a\varepsilon_1 + a^2\varepsilon_2 - a\alpha T_1 - a^2\alpha T_2)$$

$$a\tau_1 + a^2\tau_2 = i\eta \mathbf{C} : (a\varepsilon_1 + a^2\varepsilon_2 - a\alpha T_1 - a^2\alpha T_2)$$

where the material damping has been introduced into the equation system by means of an anisotropic loss factor,  $\eta$ .

Grouping together terms of the same order in  $a$  gives the following equations:

$$-\nabla \cdot (\kappa \nabla T_0) = Q_0$$

$$a\rho_0 c_p \frac{dT_1}{dt} = a\nabla \cdot (\kappa \nabla T_1) - aT_0 \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma : \frac{d\sigma_1}{dt}$$

$$a^2\rho_0 c_p \frac{dT_2}{dt} = a^2\nabla \cdot (\kappa \nabla T_2) + a^2\tau_1 : \frac{d\varepsilon_1}{dt} - a^2T_1 \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma : \frac{d\sigma_1}{dt}$$

$$-a^2T_0T_1 \frac{\partial}{\partial T_a} \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma : \frac{d\sigma_1}{dt} - a^2T_0 \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma : \frac{d\sigma_2}{dt}$$

The linear equation can be written in the form:

$$\rho_0 c_p \frac{dT}{dt} = \nabla \cdot (\kappa \nabla T) - T_0 \left(\frac{\partial \varepsilon_0}{\partial T_a}\right)_\sigma : \frac{d\sigma}{dt} \quad (5-16)$$

Where  $a=1$  and the subscript has been dropped from the dependent variable  $T$  (previously  $T_1$ ) and the stress deviation  $\sigma$  (previously  $\sigma_1$ ). Equation 5-16 is solved by the Thermoelasticity interface. Writing the equation in the frequency domain gives:

$$i\omega\rho_0c_pT = \nabla \cdot (\kappa\nabla T) - i\omega T_0 \left( \frac{\partial \epsilon_0}{\partial T} \right)_{\sigma} : \sigma$$

This is the frequency domain form of the equations solved by COMSOL Multiphysics.

Considering the quadratic terms in [Equation 5-12](#), there are four second-order heat source terms in the equation system:

$$Q_{visc} = \tau_1 : \frac{d\epsilon_1}{dt}$$

$$Q_{TED1} = -T_1 \left( \frac{\partial \epsilon_0}{\partial T} \right)_{\sigma} : \frac{d\sigma_1}{dt}$$

$$Q_{TED2} = -T_0 T_1 \frac{\partial}{\partial T} \left( \frac{\partial \epsilon_0}{\partial T} \right)_{\sigma} : \frac{d\sigma_1}{dt}$$

$$Q_{TED3} = -T_0 \left( \frac{\partial \epsilon_0}{\partial T} \right)_{\sigma} : \frac{d\sigma_2}{dt}$$

In the frequency domain, the first three terms involve the products of small harmonic deviations with other similar terms (that is, terms that vary in time in a similar manner to  $\cos^2 \omega t$ ). The trigonometric identity  $\cos^2 \omega t = (1 + \cos 2\omega t)/2$  makes it explicit that these terms have a time-independent heating effect in addition to the heating that occurs at double the frequency of the driving signal). These second-order terms have a small effect on the time-varying solution and lead to a second harmonic term in the frequency domain. However, if the time average is nonzero, this can, over many oscillatory periods, result in a change in the background temperature. In COMSOL Multiphysics the (nonzero) time-averaged heat sources are available as variables, so that the self heating of the structure can be computed.

First note that the time average of the term  $Q_{TED3}$  must be zero, since although the second order stress term  $\sigma_2$  has a nonzero time average, its time derivative cannot. The other terms in the expression for  $Q_{TED3}$  are all time independent. Each of the remaining terms can have a nonzero time average as these involve the multiplication of two separate first-order terms (potentially with phase differences between them). The following result for the multiplication of two general oscillatory complex numbers,  $a_1 e^{i(\omega t + \phi 1)}$  and,  $a_2 e^{i(\omega t + \phi 2)}$  are useful:

$$\begin{aligned}
& \text{Re}\left\{a_1 e^{i\phi_1} e^{i\omega t}\right\} \text{Re}\left\{a_2 e^{i\phi_2} e^{i\omega t}\right\} \\
&= a_1 a_2 \frac{1}{4} (e^{i(\omega t + \phi_1)} + e^{-i(\omega t + \phi_1)}) (e^{i(\omega t + \phi_2)} + e^{-i(\omega t + \phi_2)}) \\
&= a_1 a_2 \frac{1}{4} (e^{i(\phi_1 - \phi_2)} + e^{-i(\phi_1 - \phi_2)} + e^{i(2\omega t + \phi_1 + \phi_2)} + e^{-i(2\omega t + \phi_1 + \phi_2)})
\end{aligned}$$

Taking the time average of the above expression gives:

$$\begin{aligned}
\langle \text{Re}\left\{a_1 e^{i\phi_1} e^{i\omega t}\right\} \text{Re}\left\{a_2 e^{i\phi_2} e^{i\omega t}\right\} \rangle &= a_1 a_2 \frac{1}{4} (e^{i(\phi_1 - \phi_2)} + e^{-i(\phi_1 - \phi_2)}) \\
\langle \text{Re}\left\{a_1 e^{i\phi_1} e^{i\omega t}\right\} \text{Re}\left\{a_2 e^{i\phi_2} e^{i\omega t}\right\} \rangle &= \frac{1}{2} \text{Re}\left\{a_1 e^{i\phi_1} e^{i\omega t} a_2 e^{-i\phi_2} e^{-i\omega t}\right\}
\end{aligned}$$

The time average heat sources above can be written in the following form in the frequency domain:

$$\langle Q_{visc} \rangle = \frac{1}{2} \text{Re}\{\tau:(i\omega \epsilon)^*\}$$

$$\langle Q_{TED1} \rangle = -\frac{1}{2} \text{Re}\left\{T\left(\frac{\partial \epsilon_0}{\partial T}\right)_\sigma:(i\omega \sigma)^*\right\}$$

$$\langle Q_{TED2} \rangle = -\frac{1}{2} \text{Re}\left\{T_0 T \frac{\partial}{\partial T}\left(\frac{\partial \epsilon_0}{\partial T}\right)_\sigma:(i\omega \sigma)^*\right\}$$

The derivation of the last term  $\langle Q_{TED2} \rangle$  strongly relies on the prerequisite that the temperature dependence of the thermal expansion coefficient  $\alpha$  is thermodynamically consistent. Since this prerequisite is usually not satisfied due to measurement or formulation errors, we have decided to remove the variable from the physics interface.

COMSOL Multiphysics also defines a total heat source term (`solid.Qh`) of the form:

$$\langle Q_h \rangle = \langle Q_{visc} \rangle + \langle Q_{TED1} \rangle$$

The `realdot` operator is used to evaluate these quantities in a manner that produces the correct terms in the Jacobian for sensitivity analyses. To compute the slow time dependence of the background temperature, the steady-state equation can be modified

to allow for the time dependence of the background temperature and solved together with the frequency domain equations. In such a frequency-transient formulation, the following equations are solved:

$$\rho_0 c_p \frac{dT_0}{dt} = \nabla \cdot (\kappa \nabla T_0) + \langle Q_h \rangle + Q_0$$

$$i\omega \rho_0 c_p T = \nabla \cdot (\kappa \nabla T) - i\omega T_0 \left( \frac{\partial \epsilon}{\partial T} \right)_{\sigma} : \sigma$$



With this formulation, the transient part of the problem can be solved on a time scale that is much longer than the period of the oscillations.



[Operators, Functions, and Constants](#) and [Studies and Solvers](#) in the *COMSOL Multiphysics Reference Manual*

### *References for the Thermoelasticity Interface*

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# Piezoresistivity Interfaces

This chapter describes the physics interfaces found under the **Structural Mechanics>Piezoresistivity** subbranch ()

In this chapter:

- [The Piezoresistivity, Domain Currents Interface](#)
- [The Piezoresistivity, Boundary Currents Interface](#)
- [The Piezoresistivity, Shell Interface](#)
- [Theory for the Piezoresistivity Interfaces](#)

# The Piezoresistivity, Domain Currents Interface

The **Piezoresistivity, Domain Currents** predefined multiphysics coupling interface () found under the **Structural Mechanics>Piezoresistivity** branch () when adding a physics interface, combines the **Solid Mechanics** and **Electric Currents** interfaces to simulate the piezoresistive effect. This multiphysics interface is appropriate for situations when the thicknesses of the conducting and piezoresistive layers are resolved by the mesh.

When this multiphysics interface is added using the **Model Wizard**, a **Solid Mechanics** interface and an **Electric Currents** interface are added to the **Model Builder**.

In addition, the **Multiphysics Couplings** node is added, which automatically includes the multiphysics coupling feature **Piezoresistive Effect, Domain Currents**.

The participating **Electric Currents** interface by default adds the **Piezoresistive Material** node with its selection set to all domains. This node can also be added manually to the interface similar to any other material model therein. All piezoresistivity properties are entered in this node.

The **Piezoresistive Effect, Domain Currents** multiphysics coupling node can be active only on the selection where both features **Piezoresistive Material** and **Linear Elastic Material** (or **Hyperelastic Material**) are active.



In previous versions of COMSOL Multiphysics (up to version 5.2), a specific physics interface called **Piezoresistivity, Domain Currents** was added to the **Model Builder**. Now, a predefined multiphysics coupling approach is used, improving the flexibility and design options for your modeling. For specific details, see [The Multiphysics Branch](#) and [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

## SETTINGS FOR PHYSICS INTERFACES AND COUPLING FEATURES

When physics interfaces are added using the predefined couplings, for example **Piezoresistivity, Domain Currents**, specific settings are included with the physics interfaces and the coupling features.



However, if physics interfaces are added one at a time, followed by the coupling features, these modified settings are not automatically included.

For example, if both **Solid Mechanics** and **Electric Currents** interfaces are added, COMSOL Multiphysics adds an empty **Multiphysics Couplings** node. You can choose the available coupling feature **Piezoresistive Effect, Domain Currents**, but the modified settings are not included. In this example, the **Piezoresistive Material** node needs to be added manually.



Coupling features are available from the context menu (right-click the **Multiphysics Couplings** node) or from the **Physics** toolbar, **Multiphysics** menu.

PHYSICS INTERFACES AND COUPLING FEATURES



Use the online help in COMSOL Multiphysics to locate and search all the documentation. All these links also work directly in COMSOL Multiphysics when using the Help system.

*Coordinate Systems*

When setting up a model, the coordinate systems used for the participating physics interfaces should be consistent. In particular, the selected item for the **Coordinate system** menu under the **Solid Mechanics>Linear Elastic Material>Coordinate System Selection** section should match the one for the **Coordinate system** menu under the **Electric Currents>Piezoresistive Material>Coordinate System Selection** section.

*Coupling Feature*

The following multiphysics coupling feature node is described in this section:

- [Piezoresistive Effect, Domain Currents](#)



- [Theory for the Piezoresistivity Interfaces](#)

*Piezoresistive Effect, Domain Currents*

The **Piezoresistive Effect, Domain Currents** multiphysics coupling (  ) computes the appropriate conductivity tensor according to the mechanical stress or strain from the

**Linear Elastic Material** node in the **Solid Mechanics** interface and the piezoresistivity properties from the **Piezoresistive Material** node in the **Electric Currents** interface. The computed conductivity tensor is passed to the **Current Conservation** node in the **Electric Currents** interface.

## SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern <name>.<variable\_name>. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the name string must be unique. Only letters, numbers, and underscores (\_) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is pzrd1.

## DOMAIN SELECTION

Only domains that have both **Piezoresistive Material** selected in the **Electric Currents** interface and **Linear Elastic Material** selected in the **Solid Mechanics** interface are applicable.

## COUPLED INTERFACES

This section defines the physics involved in the **Piezoresistive Effect, Domain Currents** multiphysics coupling. The **Solid mechanics** and **Electric Currents** lists include all applicable physics interfaces.

The default values depend on how the **Piezoresistive Effect, Domain Currents** node is created.

- If it is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (Mac and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it is added automatically when a **Piezoresistivity, Domain Currents** multiphysics coupling interface is selected in the **Model Wizard** or **Add Physics** window, then the participating **Solid Mechanics** and **Electric Currents** interfaces are selected.

You can also select **None** from either list to uncouple the **Piezoresistive Effect, Domain Currents** node from a physics interface. If the physics interface is removed from the

**Model Builder**, for example if **Solid Mechanics** is deleted, then the list defaults to **None** as there is nothing to couple to.



If a physics interface is deleted and then added to the model again, then in order to reestablish the coupling, you need to choose the physics interface again from the lists. This is applicable to all multiphysics coupling nodes that would normally default to the once present interface. See [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

# The Piezoresistivity, Boundary Currents Interface

The **Piezoresistivity, Boundary Currents** predefined multiphysics coupling interface () , found under the **Structural Mechanics>Piezoresistivity** branch () when adding a physics interface, combines the **Solid Mechanics** and **Electric Currents, Shell** Interfaces to simulate the piezoresistive effect. This multiphysics interface is appropriate for situations in which the thickness of the piezoresistive layer is much less than that of the structural layer.

When this multiphysics interface is added using the **Model Wizard**, a **Solid Mechanics** interface and an **Electric Currents, Shell** interface are added to the **Model Builder**.

In addition, the **Multiphysics Couplings** node is added, which automatically includes the multiphysics coupling feature **Piezoresistive Effect, Boundary Currents**.

The participating **Electric Currents, Shell** interface by default adds the **Piezoresistive Material** node with its selection set to all domains. This node can also be added manually to the interface similar to any other material model therein. All piezoresistivity properties are entered in this node.

The **Piezoresistive Effect, Boundary Currents** multiphysics coupling node can be active only on the selection where both features **Piezoresistive Material** and **Linear Elastic Material** (or **Hyperelastic Material**) are active.



In previous versions of COMSOL Multiphysics (up to version 5.2), a specific physics interface called **Piezoresistivity, Boundary Currents** was added to the **Model Builder**. Now, a predefined multiphysics coupling approach is used, improving the flexibility and design options for your modeling. For specific details, see [The Multiphysics Branch](#) and [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

## SETTINGS FOR PHYSICS INTERFACES AND COUPLING FEATURES

When physics interfaces are added using the predefined couplings, for example **Piezoresistivity, Boundary Currents**, specific settings are included with the physics interfaces and the coupling features.

However, if physics interfaces are added one at a time, followed by the coupling features, these modified settings are not automatically included.

For example, if both **Solid Mechanics** and **Electric Currents, Shell** interfaces are added, COMSOL Multiphysics adds an empty **Multiphysics Couplings** node. You can choose the available coupling feature **Piezoresistive Effect, Boundary Currents** but the modified settings are not included. In this example the **Piezoresistive Material** node needs to be added manually.

|                                                                                   |                                                                                                                                                                          |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | Coupling features are available from the context menu (right-click the <b>Multiphysics Couplings</b> node) or from the <b>Physics</b> toolbar, <b>Multiphysics</b> menu. |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

PHYSICS INTERFACES AND COUPLING FEATURES

|                                                                                   |                                                                                                                                                                              |
|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | Use the online help in COMSOL Multiphysics to locate and search all the documentation. All these links also work directly in COMSOL Multiphysics when using the Help system. |
|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Coordinate Systems

When setting up a model, the coordinate systems used for the participating physics interfaces should be consistent. In particular, the selected item for the **Coordinate system** menu under the **Solid Mechanics>Linear Elastic Material>Coordinate System Selection** section should match the one for the **Coordinate system** menu under the **Electric Currents, Shell>Piezoresistive Material>Coordinate System Selection** section.

Coupling Feature

The following multiphysics coupling feature node is described in this section:

- [Piezoresistive Effect, Boundary Currents](#)

|                                                                                     |                                                              |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------|
|  | • <a href="#">Theory for the Piezoresistivity Interfaces</a> |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------|

|                                                                                     |                                                                                                                              |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
|  | <i>Piezoresistive Pressure Sensor</i> Application Library path:<br><b>MEMS_Module/Sensors/piezoresistive_pressure_sensor</b> |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|

The **Piezoresistive Effect, Boundary Currents** multiphysics coupling node () computes the appropriate conductivity tensor according to the mechanical stress or strain from the **Linear Elastic Material** node in the **Solid Mechanics** interface and the piezoresistivity properties from the **Piezoresistive Material** node in the **Electric Currents, Shell** interface. The computed conductivity tensor is passed to the **Current Conservation** node in the **Electric Currents, Shell** interface.

#### SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern <name>.<variable\_name>. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the name string must be unique. Only letters, numbers, and underscores (\_) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is pzrb1.

#### BOUNDARY SELECTION

Only boundaries that have both **Piezoresistive Material** selected in the **Electric Currents, Shell** interface and are adjacent to domains with **Linear Elastic Material** selected in the **Solid Mechanics** interface are applicable.

#### COUPLED INTERFACES

This section defines the physics involved in the **Piezoresistive Effect, Boundary Currents** multiphysics coupling. The **Solid mechanics** and **Electric currents, shell** lists include all applicable physics interfaces.

The default values depend on how the **Piezoresistive Effect, Boundary Currents** node is created.

- If it is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (Mac and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it is added automatically when a **Piezoresistivity, Boundary Currents** multiphysics coupling interface is selected in the **Model Wizard** or **Add Physics** window, then the participating **Solid Mechanics** and **Electric Currents, Shell** interfaces are selected.

You can also select **None** from either list to uncouple the **Piezoresistive Effect, Boundary Currents** node from a physics interface. If the physics interface is removed from the **Model Builder**, for example if **Solid Mechanics** is deleted, then the list defaults to **None** as there is nothing to couple to.



If a physics interface is deleted and then added to the model again, then in order to reestablish the coupling, you need to choose the physics interface again from the lists. This is applicable to all multiphysics coupling nodes that would normally default to the once present interface. See [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

---

# The Piezoresistivity, Shell Interface



This physics interface requires a Structural Mechanics Module license. For theory and physics interface feature descriptions relating to the Shell interface, see the *Structural Mechanics Module User's Guide*.

The **Piezoresistivity, Shell** predefined multiphysics coupling interface (  ), found under the **Structural Mechanics>Piezoresistivity** branch (  ) when adding a physics interface, is used when the structural layer is thin enough to be treated by the **Shell** interface, but the conducting and piezoresistive layers are still much thinner than the structural layers.

When this multiphysics interface is added using the **Model Wizard**, a **Shell** interface and an **Electric Currents, Shell** interface are added to the **Model Builder**.

In addition, the **Multiphysics Couplings** node is added, which automatically includes the multiphysics coupling feature **Piezoresistive Effect, Shell**.

The participating **Electric Currents, Shell** interface by default adds the **Piezoresistive Material** node with its selection set to all domains. This node can also be added manually to the interface similar to any other material model therein. All piezoresistivity properties are entered in this node.

The **Piezoresistive Effect, Shell** multiphysics coupling node can be active only on the selection where both a **Piezoresistive Material** and a **Linear Elastic Material** feature are active.



In previous versions of COMSOL Multiphysics (up to version 5.2), a specific physics interface called **Piezoresistivity, Shell** was added to the **Model Builder**. Now, a predefined multiphysics coupling approach is used, improving the flexibility and design options for your modeling. For specific details, see [The Multiphysics Branch](#) and [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

## SETTINGS FOR PHYSICS INTERFACES AND COUPLING FEATURES

When physics interfaces are added using the predefined couplings (for example, **Piezoresistivity, Shell**) specific settings are included with the physics interfaces and the coupling features.



However, if physics interfaces are added one at a time, followed by the coupling features, these modified settings are not automatically included.

For example, if both **Shell** and **Electric Currents, Shell** interfaces are added, COMSOL adds an empty **Multiphysics Couplings** node. You can choose the available coupling feature **Piezoresistive Effect, Shell** but the modified settings are not included. In this example the **Piezoresistive Material** node needs to be added manually.



Coupling features are available from the context menu (right-click the **Multiphysics Couplings** node) or from the **Physics** toolbar, **Multiphysics** menu.

PHYSICS INTERFACES AND COUPLING FEATURES



Use the online help in COMSOL Multiphysics to locate and search all the documentation. All these links also work directly in COMSOL Multiphysics when using the Help system.

Coordinate Systems

When setting up a model, the coordinate systems used for the participating physics interfaces should be consistent. In particular, the selected item for the **Coordinate system** menu under the **Shell>Linear Elastic Material>Shell Local System>Coordinate System Selection** section should match the one for the **Coordinate system** menu under the **Electric Currents, Shell>Piezoresistive Material>Coordinate System Selection** section.

Coupling Feature

The following multiphysics coupling feature node is described in this section:

- [Piezoresistive Effect, Shell](#)



- [Theory for the Piezoresistivity Interfaces](#)



*Piezoresistive Pressure Sensor, Shell* Application Library path:  
**MEMS\_Module/Sensors/piezoresistive\_pressure\_sensor\_shell**

The **Piezoresistive Effect, Shell** multiphysics coupling node (  ) computes the appropriate conductivity tensor according to the mechanical stress or strain from the **Linear Elastic Material** node in the **Shell** interface and the piezoresistivity properties from the **Piezoresistive Material** node in the **Electric Currents, Shell** interface. The computed conductivity tensor is passed to the **Current Conservation** node in the **Electric Currents, Shell** interface.

### SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern <name>.<variable\_name>. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the name string must be unique. Only letters, numbers, and underscores (\_) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is pzrs1.

### BOUNDARY SELECTION

Only boundaries that have both **Piezoresistive Material** selected in the **Electric Currents, Shell** interface and **Linear Elastic Material** selected in the **Shell** interface are applicable.

### COUPLED INTERFACES

This section defines the physics involved in the **Piezoresistive Effect, Shell** multiphysics coupling. The **Shell** and **Electric currents, shell** lists include all applicable physics interfaces.

The default values depend on how the **Piezoresistive Effect, Shell** node is created.

- If it is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (Mac and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it is added automatically when a **Piezoresistivity, Shell** multiphysics coupling interface is selected in the **Model Wizard** or **Add Physics** window, then the participating **Shell** and **Electric Currents, Shell** interfaces are selected.

You can also select **None** from either list to uncouple the **Piezoresistive Effect, Shell** node from a physics interface. If the physics interface is removed from the **Model Builder**, for example if **Shell** is deleted, then the list defaults to **None** as there is nothing to couple to.



If a physics interface is deleted and then added to the model again, then in order to reestablish the coupling, you need to choose the physics interface again from the lists. This is applicable to all multiphysics coupling nodes that would normally default to the once present interface. See [Multiphysics Modeling Workflow](#) in the *COMSOL Multiphysics Reference Manual*.

# Theory for the Piezoresistivity Interfaces

In this section:

- [Piezoresistive Materials](#)
- [Electric Currents Formulation](#)
- [Tensor Versus Matrix Formulations](#)
- [Material Property Definitions](#)
- [Coordinate Systems and Material Orientation](#)
- [References for the Piezoresistivity Interfaces](#)



- [The Piezoresistivity, Domain Currents Interface](#)
- [The Piezoresistivity, Boundary Currents Interface](#)
- [The Piezoresistivity, Shell Interface](#)



The Piezoresistivity, Shell interface uses features from the Shell interface, which requires the Structural Mechanics Module. Both the theory and features are described in the *Structural Mechanics Module User's Guide*.

## *Piezoresistive Materials*

A piezoresistive material responds to an applied stress with a change in its resistivity. Normally piezoresistive materials are semiconductors, and the effect is associated with band structure changes that alter the carrier mobility and number density much more significantly than an applied stress would change, for example, the resistance of a similar metal. The equivalent elastoresistance effect relates the strain in the material to a change in resistivity. Note that the dependence between the structural mechanics and the electrical properties of the material is unidirectional, so that applied currents do not induce changes in the material stress or strain (assuming that other effects, such as heating of the material, are negligible).

Within a piezoresistive material, the relation between the electric field,  $\mathbf{E}$ , and the current,  $\mathbf{J}$ , becomes:

$$\mathbf{E} = \rho \cdot \mathbf{J} + \Delta\rho \cdot \mathbf{J} \quad (6-1)$$

where  $\rho$  is the resistivity and  $\Delta\rho$  is the induced change in the resistivity. In the general case both  $\rho$  and  $\Delta\rho$  are rank 2 tensors (matrices). The change in resistance is related to the stress,  $\sigma$  (for the piezoresistance form of the equations), or the strain,  $\epsilon$  (for the elastoresistance form of the equations), by the constitutive relationship:

$$\begin{aligned} \Delta\rho &= \Pi \cdot \sigma && \text{piezoresistance form} \\ \Delta\rho &= \mathbf{M} \cdot \epsilon && \text{elastoresistance form} \end{aligned} \quad (6-2)$$

where  $\Pi$  is the piezoresistance tensor (SI unit:  $\text{Pa}^{-1}\Omega\text{m}$ ) and  $\mathbf{M}$  is the elastoresistance tensor (SI unit:  $\Omega\text{m}$ ). Both of these quantities are material properties.  $\Pi$  and  $\mathbf{M}$  are in this case rank 4 tensors; however, they can be represented as matrices if the resistivity, stress, and strain are converted to vectors within a reduced subscript notation.



## Tensor Versus Matrix Formulations

### *Electric Currents Formulation*

The flow of electric current through a conducting medium in the quasistatic case is governed by the equation of continuity which can be written in the form:

$$\nabla \cdot \left( \mathbf{J} - \mathbf{J}_e + \frac{\partial}{\partial t} \mathbf{D} \right) = Q_j$$

where  $\mathbf{J}$  is the induced electric current,  $\mathbf{J}_e$  includes external current sources that do not result from the material conductivity (such as thermoelectric currents),  $\mathbf{D}$  is the electric displacement field, and  $Q_j$  is a current source term. Both  $Q_j$  and  $\mathbf{J}_e$  are usually zero for piezoelectric devices.

In the stationary or quasistatic case, the electric current is related to the electric field,  $\mathbf{E}$ , by the constitutive relation:

$$\mathbf{J} = \sigma_{(c)} \cdot \mathbf{E} \quad (6-3)$$

where  $\sigma_{(c)}$  is the conductivity tensor (the subscript  $c$  is used here to distinguish the conductivity from the strain).

Relating  $\mathbf{E}$  and  $\mathbf{D}$  to the electric potential ( $\mathbf{E} = -\nabla V$ ,  $\mathbf{D} = \epsilon_0 \epsilon_{(r)} \mathbf{E}$ , where  $\epsilon_0$  is the permittivity of free space and  $\epsilon_{(r)}$  is the relative permittivity tensor) gives:

$$-\nabla \cdot \left( \sigma_{(c)} \cdot \nabla V - \mathbf{J}_e + \frac{\partial}{\partial t} (\epsilon_0 \epsilon_{(r)} \cdot \nabla V) \right) = Q_j \quad (6-4)$$

If current flow is restricted to a thin layer on the surface of a material this equation takes the form:

$$-\nabla_t \cdot \left( d_s \left( \sigma_{(c)} \cdot \nabla_t V - \mathbf{J}_e + \frac{\partial}{\partial t} (\epsilon_0 \epsilon_{(r)} \cdot \nabla_t V) \right) \right) = Q_j \quad (6-5)$$

where the operator  $\nabla_t$  represents the tangential derivative along the thin layer surface. Equation 6-4 and Equation 6-5 form the basis of the Electric Currents interface.



The constitutive relationship described by Equation 6-3 uses the conductivity form rather than the resistivity form used in Equation 6-1.

Since the equations of piezoelectricity are by convention formulated in the resistivity form, Equation 6-1 must be inverted to give:

$$\mathbf{J} = (\sigma_{(c)}^{-1} + \Delta\rho)^{-1} \cdot \mathbf{E} \quad (6-6)$$

Although this expression appears cumbersome, it is required in this form for the general case where the conductivity and change in resistivity are nonsymmetric tensor quantities. For convenience, the tensor  $\sigma_{(c, \text{eff})}$  is defined in the interfaces (for example, for The Piezoresistivity, Domain Currents Interface as `pzrd.sigmaceffXX`, `pzrd.sigmaceffXY`, and so forth) in the following manner:

$$\sigma_{(c, \text{eff})} = (\sigma_{(c)}^{-1} + \Delta\rho)^{-1} \quad (6-7)$$

The Piezoresistivity, Domain Currents Interface solves a modified form of Equation 6-4 on the domain level:

$$-\nabla \cdot \left( \sigma_{(c, \text{eff})} \cdot \nabla(V) - \mathbf{J}_e + \frac{\partial}{\partial t} (\epsilon_0 \epsilon_{(r)} \cdot \nabla V) \right) = Q_j$$

while The Piezoresistivity, Boundary Currents Interface and The Piezoresistivity, Shell Interface solve a modified form of equation Equation 6-5 on the boundary level:

$$-\nabla_t \cdot \left( d_s \left( \sigma_{(c, \text{eff})} \cdot \nabla_t(V) - \mathbf{J}_e + \frac{\partial}{\partial t} (\epsilon_0 \epsilon_{(r)} \cdot \nabla_t V) \right) \right) = Q_j$$

where  $\sigma_{(c, \text{eff})}$  is computed from Equation 6-7 and from the definition of  $\Delta\rho$  given in Equation 6-2.



- The Electric Currents Interface
- Theory for the Electric Currents Interface

### Tensor Versus Matrix Formulations

The constitutive relations defined in Equation 6-2 relate the change in resistivity matrix (a rank 2 tensor) to the stress or strain matrix (also a rank 2 tensor). This means that the piezoresistivity tensor and the elastoresistance tensor are both rank 4 tensors. A formal tensor formulation of Equation 6-1 therefore takes the form:

$$\begin{aligned} (E_i = \rho_{ij} \mathcal{J}^j + \Pi_{ijkl} \mathcal{J}^j \sigma^{kl}) & \text{piezoresistance form} \\ E_i = \rho_{ij} \mathcal{J}^j + M_{ij}^{kl} \mathcal{J}^j \epsilon_{kl} & \text{elastoresistance form} \end{aligned} \quad (6-8)$$

Here the Einstein summation convention is used. Note that this equation implies that  $\Delta\rho_{ij} = \Pi_{ijkl} \sigma^{kl}$  and  $\Delta\rho_{ij} = M_{ij}^{kl} \epsilon_{kl}$ . The tensors  $\Pi$  and  $M$  have a number of symmetry properties, that result from the fact that both  $\sigma$ ,  $\epsilon$ , and  $\Delta\rho$  are symmetric and can be represented in the following form:

$$\sigma = \begin{bmatrix} \sigma^{xx} & \sigma^{xy} & \sigma^{xz} \\ \sigma^{xy} & \sigma^{yy} & \sigma^{yz} \\ \sigma^{xz} & \sigma^{yz} & \sigma^{zz} \end{bmatrix} \quad \epsilon = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{xy} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{xz} & \epsilon_{yz} & \epsilon_{zz} \end{bmatrix} \quad \Delta\rho = \begin{bmatrix} \Delta\rho_{xx} & \Delta\rho_{xy} & \Delta\rho_{xz} \\ \Delta\rho_{xy} & \Delta\rho_{yy} & \Delta\rho_{yz} \\ \Delta\rho_{xz} & \Delta\rho_{yz} & \Delta\rho_{zz} \end{bmatrix}$$

As a result of this symmetry, it is possible to represent  $\sigma$ ,  $\epsilon$ , and  $\Delta\rho$  as six component vectors. There are two conventions for ordering the components in these vectors and the Piezoresistivity interfaces all use the Voigt notation prevalent in the literature.



The Structural Mechanics branch interfaces use a distinct *standard notation* by default but does also support the Voigt notation.

Cubic materials, such as silicon, possess symmetries that mean the two notations are, in any case, equivalent when defining material properties. Within Voigt notation the vectors,  $s$ ,  $e$ , and  $\Delta r$ , which correspond to  $\sigma$ ,  $\epsilon$ , and  $\Delta\rho$  are:

$$s = \begin{bmatrix} \sigma^{xx} \\ \sigma^{yy} \\ \sigma^{zz} \\ \sigma^{yz} \\ \sigma^{xz} \\ \sigma^{xy} \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{bmatrix} \quad e = \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ 2\epsilon_{yz} \\ 2\epsilon_{xz} \\ 2\epsilon_{xy} \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \end{bmatrix} \quad \Delta r = \begin{bmatrix} \Delta \rho_{xx} \\ \Delta \rho_{yy} \\ \Delta \rho_{zz} \\ \Delta \rho_{yz} \\ \Delta \rho_{xz} \\ \Delta \rho_{xy} \end{bmatrix} = \begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \Delta r_3 \\ \Delta r_4 \\ \Delta r_5 \\ \Delta r_6 \end{bmatrix}$$

This notation is known as the reduced subscript notation, since the number of subscripts required to represent the stress, strain, or change in resistivity is reduced from two to one. The relationship between the stress or strain and the resistivity change becomes:

$$\begin{aligned} \Delta r &= \pi \cdot s && \text{piezoresistance form} \\ \Delta r &= m \cdot e && \text{elastoresistance form} \end{aligned}$$

Where  $\pi$  and  $m$  are now matrices related to the components of the corresponding  $\Pi$  and  $M$  tensors in the following manner:

$$\pi = \begin{bmatrix} \Pi_{1111} & \Pi_{1122} & \Pi_{1133} & 2\Pi_{1123} & 2\Pi_{1113} & 2\Pi_{1112} \\ \Pi_{2211} & \Pi_{2222} & \Pi_{2233} & 2\Pi_{2223} & 2\Pi_{2213} & 2\Pi_{2212} \\ \Pi_{3311} & \Pi_{3322} & \Pi_{3333} & 2\Pi_{3323} & 2\Pi_{3313} & 2\Pi_{3312} \\ \Pi_{2311} & \Pi_{2322} & \Pi_{2333} & 2\Pi_{2323} & 2\Pi_{2312} & 2\Pi_{2312} \\ \Pi_{1311} & \Pi_{1322} & \Pi_{1333} & 2\Pi_{1323} & 2\Pi_{1313} & 2\Pi_{1312} \\ \Pi_{1211} & \Pi_{1222} & \Pi_{1233} & 2\Pi_{1223} & 2\Pi_{1213} & 2\Pi_{1212} \end{bmatrix}$$

$$m = \begin{bmatrix} M_{11}^{11} & M_{11}^{22} & M_{11}^{33} & M_{11}^{23} & M_{11}^{13} & M_{11}^{12} \\ M_{22}^{11} & M_{22}^{22} & M_{22}^{33} & M_{22}^{23} & M_{22}^{13} & M_{22}^{12} \\ M_{33}^{11} & M_{33}^{22} & M_{33}^{33} & M_{33}^{23} & M_{33}^{13} & M_{33}^{12} \\ M_{23}^{11} & M_{23}^{22} & M_{23}^{33} & M_{23}^{23} & M_{23}^{13} & M_{23}^{12} \\ M_{13}^{11} & M_{13}^{22} & M_{13}^{33} & M_{13}^{23} & M_{13}^{13} & M_{13}^{12} \\ M_{12}^{11} & M_{12}^{22} & M_{12}^{33} & M_{12}^{23} & M_{12}^{13} & M_{12}^{12} \end{bmatrix}$$



Components of the  $\Pi$  and  $M$  tensors that do not appear in these matrices are always equal to one of those that does appear as a result of symmetry constraints.



For the most general triclinic crystal groups, the  $\pi$  and  $m$  matrices are not necessarily symmetric, as is the case for the elasticity matrix in structural mechanics.

This is because the rank four tensors  $\Pi$  and  $M$  lack one of the symmetry properties of the elasticity tensor ( $\Pi_{ijkl} \neq \Pi_{klij}$  and  $M_{ij}^{kl} \neq M_{kl}^{ij}$  see [Ref. 1](#) and [Ref. 2](#) for details). Finally the relationship between  $\pi$  and  $m$  is given by:

$$m = \pi \cdot D \quad (6-9)$$

where  $D$  is the elasticity matrix (s=D-c), which is defined in Voigt notation as:

$$D = \begin{bmatrix} C^{1111} & C^{1122} & C^{1133} & C^{1123} & C^{1113} & C^{1112} \\ & C^{2222} & C^{2233} & C^{2223} & C^{2213} & C^{2212} \\ & & C^{3333} & C^{3323} & C^{3313} & C^{3312} \\ & & & C^{2323} & C^{2313} & C^{2312} \\ & \text{symmetric} & & & C^{1313} & C^{1312} \\ & & & & & C^{1212} \end{bmatrix}$$

### *Material Property Definitions*

The definitions of the piezoresistance and elastoiresistance material properties implied by [Equation 6-1](#), [Equation 6-2](#), and [Equation 6-8](#) include the resistivity of the material implicitly. This approach is common in the theoretical literature (see for example [Ref. 1](#) and [Ref. 2](#)), since it is essential for a generalized description of the phenomena. However, many engineering texts (see for example [Ref. 3](#), [Ref. 4](#), and [Ref. 5](#)) describe the material properties in terms of a relative change in resistivity. In this approach the quantities  $\pi'$  and  $m'$  are defined such that:

$$\begin{aligned} \pi &= \rho_0 \pi' \\ m &= \rho_0 m' \end{aligned} \quad (6-10)$$

where  $\rho_0$  is the scalar resistivity of the undeformed material. Here  $\pi'$  has the units  $\text{Pa}^{-1}$  and  $m'$  is dimensionless. For comparison  $\pi$  has the units  $\Omega\text{mPa}^{-1}$  and  $m$  has units  $\Omega\text{m}$ .

[Equation 6-10](#) only applies when the resistivity is isotropic in the unstressed case. Cubic materials, such as silicon, have an isotropic resistivity when unstressed and so can employ this approach. It has the advantage that the piezoresistive material properties do not change with doping level for lightly doped silicon (dopant concentrations of less than approximately  $10^{16} \text{ cm}^{-3}$ ). In COMSOL Multiphysics the built-in material properties have been implemented so that the dopant number density is added in the interface as a model input and the resistivity and conductivity are computed automatically within the material. These quantities are then included as part of the definitions of  $\pi$  and  $m$ . This approach provides the maximum level of flexibility (enabling noncubic materials and nonuniform dopant densities to be straightforwardly modeled), without sacrificing the convenience of the approach usually adopted for cubic materials. When entering custom material properties for materials not present in the library, it is important to remember that the resistivity should be included in the piezoresistance or elastoresistance material properties entered in the material library.



The piezoresistive material properties for single crystal silicon included with the MEMS module are based on [Ref. 6](#) and [Ref. 7](#). Those provided for polysilicon are based on [Ref. 3](#) and [Ref. 7](#).



[About the Material Libraries for the MEMS Module](#)

### *Coordinate Systems and Material Orientation*

The material orientation is defined in COMSOL Multiphysics by means of a local coordinate system. The local coordinate system is the coordinate system that corresponds to the physical property axes of the material, that is, the orthogonal coordinate system in which the material properties are defined (see section 4.3 of [Ref. 2](#)). For materials with orthogonal crystallographic axes, the physical property axes correspond to the crystallographic axes. For other crystals a definition of the orientation of these axes should be provided with the material properties — often the standard described in [Ref. 2](#) is used. In COMSOL Multiphysics, the equations of solid mechanics are usually solved in the local coordinate system, whilst the electric currents

equations are solved in the global system. Appropriate coordinate transforms of the relevant physical quantities have been implemented in the Piezoresistivity interfaces.



Reduced subscript matrices and vectors do not obey the usual tensor transformation rules for coordinate transforms. The COMSOL Multiphysics software uses the quadratic transformation laws to transform these quantities between coordinate systems where this is necessary. See [Ref. 1](#) for further details.

The local coordinate system for a material is set within the Linear Elastic Material, Piezoresistive Material, or Conductive Material features (or their equivalents). These features default to using the global system, but alternative systems can be defined by adding one of the coordinate system nodes to the Definitions node level of the Model Builder. Often the Rotated System feature is used to specify the new coordinate system in terms of Euler angles.



Converting from Miller indices and wafer flat orientations to the appropriate Euler angles is not straightforward and a carefully drawn diagram is recommended.



[Coordinate Systems](#) in the *COMSOL Multiphysics Reference Manual*

### *References for the Piezoresistivity Interfaces*

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6. C.S. Smith, “Piezoresistance Effect in Germanium and Silicon”, *Physical Review*, vol. 94, no. 1, pp. 42–49, 1957.

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## Glossary

This [Glossary of Terms](#) contains finite-element modeling terms specific to the MEMS Module and its applications. For mathematical terms as well as geometry and CAD terms specific to the COMSOL Multiphysics® software and its documentation, see the glossary in the *COMSOL Multiphysics Reference Manual*. To find references in the documentation set where you can find more information about a given term, see the index.

# Glossary of Terms

**accelerometer** A sensor that measures acceleration or gravitational force. See also *sensor*.

**actuator** A device or mechanism that produces mechanical motion.

**ALE** See *arbitrary Lagrangian-Eulerian method*.

**arbitrary Lagrangian-Eulerian (ALE) method** A technique to formulate equations in a mixed kinematical description. An ALE referential coordinate system is typically a mix between the material (Lagrangian) and spatial (Eulerian) coordinate systems.

**aspect ratio** The ratio of the dimensions of a device in different directions, for example, the ratio of height to width. See also *lateral aspect ratio* and *vertical aspect ratio*.

**biosensor** A general term for sensor devices that either detect biological substances or use antibodies, enzymes, or other biological molecules in their operation. Biosensors are a subcategory of chemical sensors.

**bonding** A process by which one substrate is firmly attached to the surface of another.

**buckling** The sudden collapse or reduction in stiffness of a structure under a critical combination of applied loads.

**cantilever beam** A beam with one end fixed and one end free.

**capacitive sensor** A sensor that produces a signal due to a change in its capacitance.

**Cauchy stress** The most fundamental stress measure defined as force/deformed area in fixed directions not following the body.

**compliance matrix** The inverse of the elasticity matrix. See *elasticity matrix*.

**comb drive** A MEMS device consisting of interdigitated fingers similar in appearance to two interlocking combs.

**constitutive equations** The equations formulating the stress-strain relationship of a material.

**creep** Time-dependent material nonlinearity that usually occurs in metals at high temperatures in which the effect of the variation of stress and strain with time is of interest.

**damping** Dissipation of energy in a vibrating structure. A common assumption is viscous damping, where the damping is proportional to the velocity. See also *Rayleigh damping*.

**elastic deformation** A nonpermanent deformation that recovers its shape completely upon the release of an applied stress.

**elasticity matrix** The matrix  $D$  relating strain to stresses:

$$\sigma = D\varepsilon$$

**Eulerian** Model described and solved in a coordinate system that is fixed (spatial). See also *Lagrangian* and *arbitrary Lagrangian-Eulerian method*.

**frequency-response analysis** An analysis solving for the steady-state response from a harmonic excitation. Typically a frequency sweep is performed, solving for many excitation frequencies.

**Green-Lagrange strain** A measure of nonlinear strain used in large-deformation analysis. In a small-strain large rotation analysis, the *Green-Lagrange strain* corresponds to the engineering strain with the strain values interpreted in the original directions. The *Green-Lagrange strain* is a natural choice when formulating a problem in the undeformed state.

**initial strain** The strain in a stress-free structure before it is loaded. See also *strain* and *residual strain*.

**initial stress** The stress in a nondeformed structure before it is loaded. See also *stress* and *residual stress*.

**Joule heating** The increase in temperature of a medium as a result of resistance to an electric current flowing through it.

**Knudsen number** A dimensionless number that provides a measure of how rarefied a gas flow is, in other words, the average distance between the gas molecules compared to the length scale of the flow. The following equation defines the Knudsen number  $Kn$  where  $\lambda$  is the mean free path of the molecules and  $L$  is a length scale characteristic to the flow.

$$Kn = \frac{\lambda}{L}$$

**Lagrangian** Model described and solved in a coordinate system that moves with the material. See also *Eulerian* and *arbitrary Lagrangian-Eulerian method*.

**large deformation** The deformations are so large so the nonlinear effect of the change in geometry or stress stiffening need to be accounted for.

**lateral aspect ratio** The ratio of the length of a structure in the plane of a wafer to its width in that plane. See also *aspect ratio* and *vertical aspect ratio*.

**MEMS** An acronym for *microelectromechanical systems*. More generally, *MEMS* refers to systems, devices, and components with microscale size and in which the physics is not necessarily limited to electrical or mechanical phenomena.

**microsystems** See *MEMS*.

**piezoelectricity** The ability of certain crystalline materials to produce an electric voltage when subjected to mechanical stress (direct piezoelectric effect). Inversely, the material's ability to change shape when an external voltage is applied (reverse piezoelectric effect).

**plane strain** An assumption on the strain field where all out-of-plane strain components are assumed to be zero.

**plane stress** An assumption on the stress field where all out-of-plane stress components are assumed to be zero.

**principle of virtual work** States that the variation in internal strain energy is equal to the work done by external forces.

**proof mass** A predetermined test mass in a measurement device or machine that serves as the reference mass for the quantity to be measured.



**Rayleigh damping** A viscous damping model where the damping is proportional to the mass and stiffness through the mass and stiffness damping parameters.

**residual strain** Strain remaining in a structure after some operation, for example, the strain resulting from cooling a system after high-temperature bonding. It often appears as the initial strain for any consequent tasks. See also *strain* and *initial strain*.

**residual stress** Stress remaining in a structure after some operation, for example, stress resulting from cooling a system after high-temperature bonding. It often appears as the initial stress for any consequent tasks. See also *stress* and *initial stress*.

**second Piola-Kirchhoff stress** Conjugate stress to *Green-Lagrange strain* used in large deformation analysis.

**sensor** A device that measures a physical variable such as temperature or pressure and converts it (usually) to an electrical signal.

**slide-film damping** The damping effect of a fluid between two solid surfaces when the distance between them is small compared to their area and there is mostly tangential movement (lubrication). Slide-film damping is a type of *thin-film damping*.

**spin tensor** The skew-symmetric part of the velocity gradient tensor.

**squeeze-film damping** The damping effect of a fluid between two solid surfaces when the distance between them is small compared to their area and there is mostly normal movement. Squeeze-film damping is a type of *thin-film damping*.

**strain** Relative change in length, a fundamental concept in structural mechanics.

**stress** Internal forces in a material. Normal stresses are defined as forces/area normal to a plane, and shear stresses are defined as forces/area in the plane. A fundamental concept in structural mechanics.

**thermoelastic damping** When an elastic rod is stretched reversibly and adiabatically its temperature drops. The drop in temperature compensates for the increase in entropy caused by the stress in the rod (since the process is reversible the entropy remains constant). In a general deformation, the strain in a structure is nonuniform and so the temperature changes in a nonuniform manner throughout the structure. The irreversible flow of heat that accompanies these temperature changes result in energy loss and damping of the structure.

**thin-film damping** Damping that occurs in a thin channel of fluid (fluid film) between moving structures. See *squeeze-film damping* and *slide-film damping*.

**transducer** A device that converts one type of energy to another. It often refers to a device that responds to a physical parameter and converts it to an electrical signal.

**vertical aspect ratio** The ratio of the height of a structure perpendicular to a wafer's surface to its depth in the wafer's plane.

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