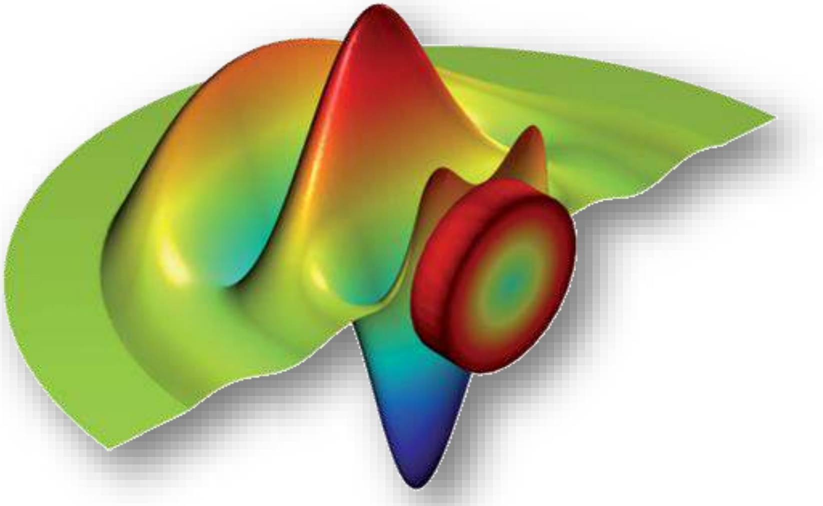
Piezoelectric Simulations

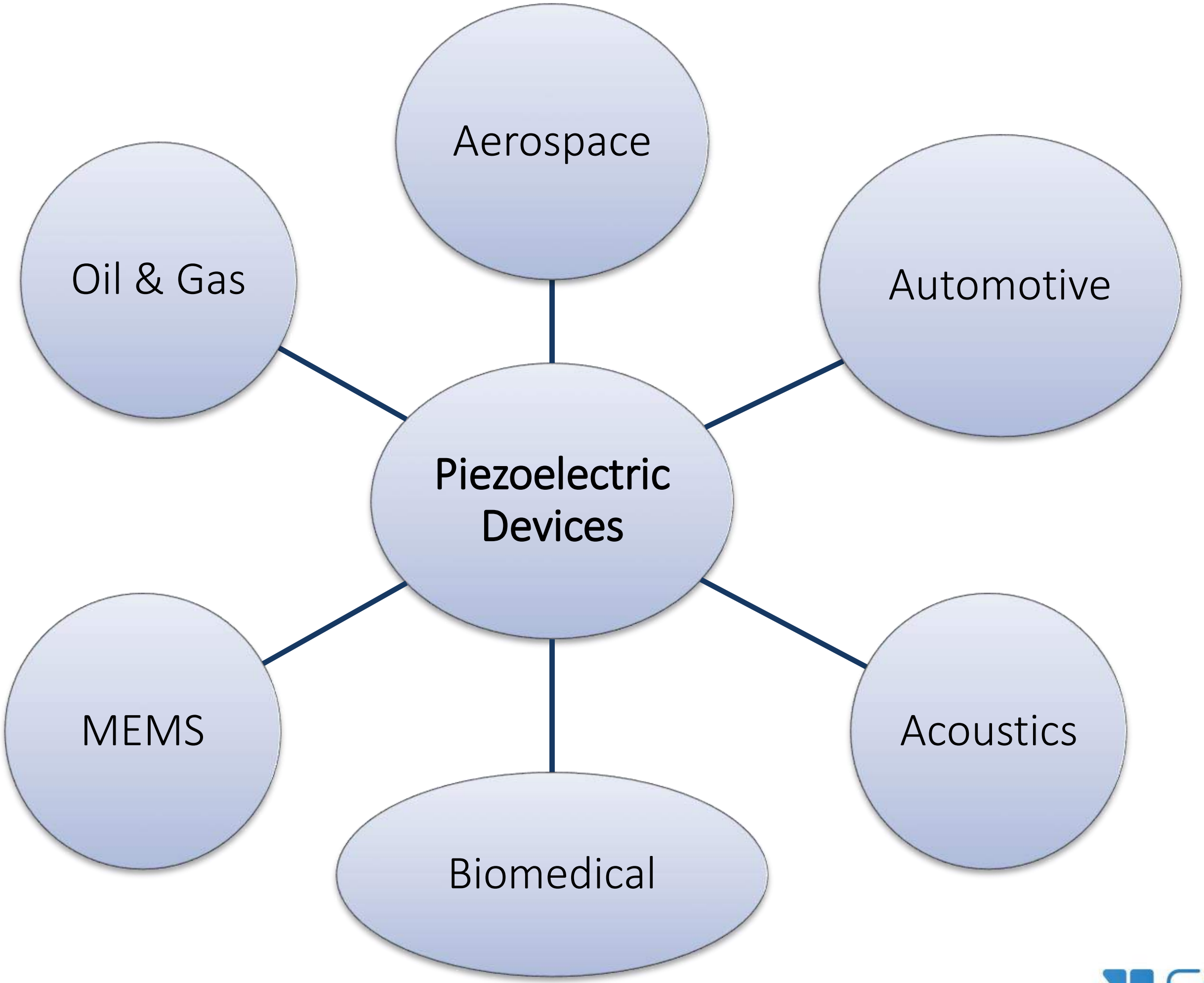


Outline

- Overview
- Examples
- Relevant Products
- Useful Features

Overview

Industries Using Piezoelectric Devices



Piezoelectric Devices

- Aerospace
- Automotive
- Acoustics
- Biomedical
- MEMS
- Oil & Gas

Piezoelectric Devices

Actuators and Sensors

- Linear and Rotary Motors
- Position Controller
- Accelerometer
- Gyroscope
- Load Cell
- Pressure Sensor
- Energy Harvester

RF MEMS

- RF MEMS Switch
- SAW Filter
- BAW Filter
- Tunable Cavity Filter

Acoustic Devices

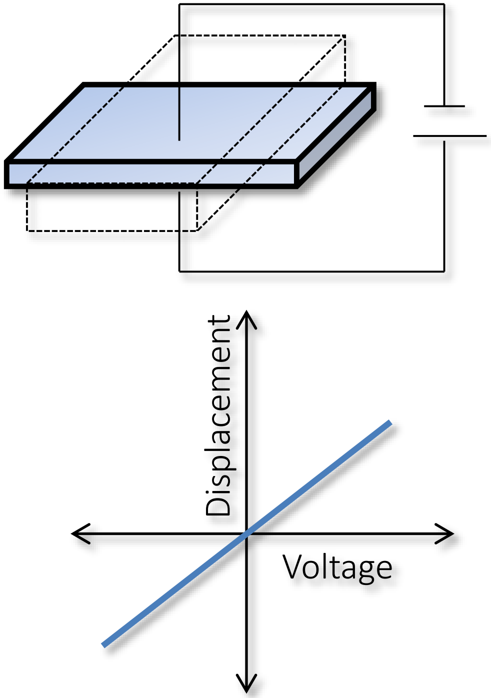
- SONAR
- Hydrophone
- Speaker
- Microphone
- Hearing Aid

Flow Control

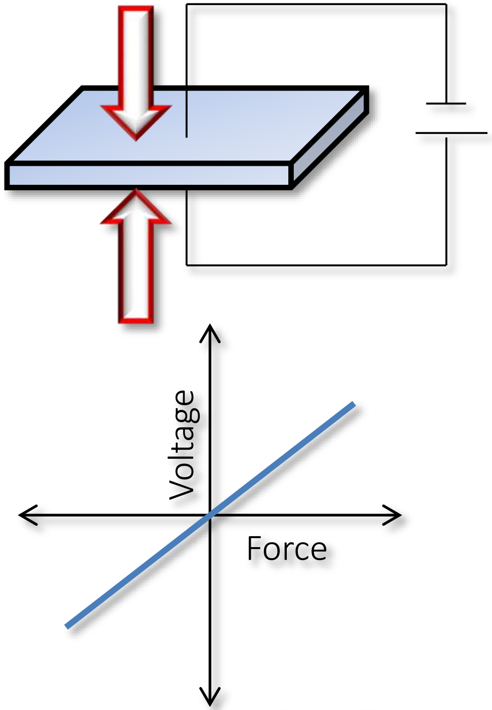
- Synthetic Jet
- Inkjet Printer
- Active Valves
- Micro Pump
- Flow Sensor

Piezoelectric Effect

Inverse effect



Direct effect



Coupled Constitutive Equations

Stress-Charge Form

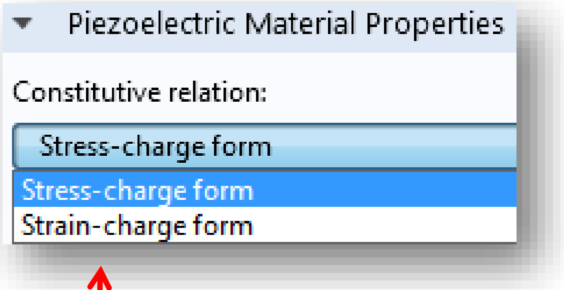
$$T = c_E S - e^T E$$

$$D = eS + \varepsilon_S E$$

Strain-Charge Form

$$S = s_E T + d^T E$$

$$D = dT + \varepsilon_T E$$



Constitutive relation: Stress-charge form

In COMSOL, you can choose any one of these equation forms based on the material data you have

T = stress; S = strain

E = electric field

D = electric displacement

c_E = elasticity matrix (rank 4 tensor c_{ijkl})

e = coupling matrix (rank 3 tensor e_{ijk})

ε_S = permittivity matrix (rank 2 tensor ε_{ij})

$$c_E = s_E^{-1}$$

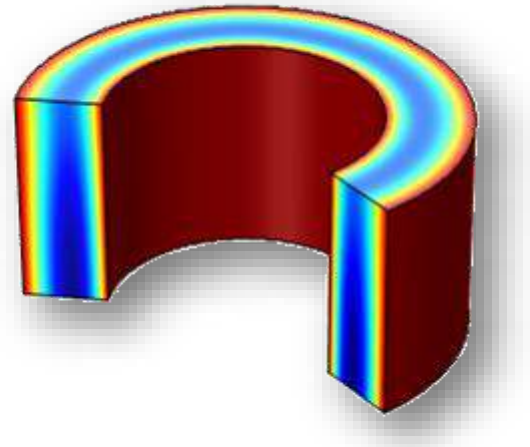
$$e = d s_E^{-1}$$

$$\varepsilon_S = \varepsilon_T - d s_E^{-1} d^T$$

Examples

A Piezoceramic Tube

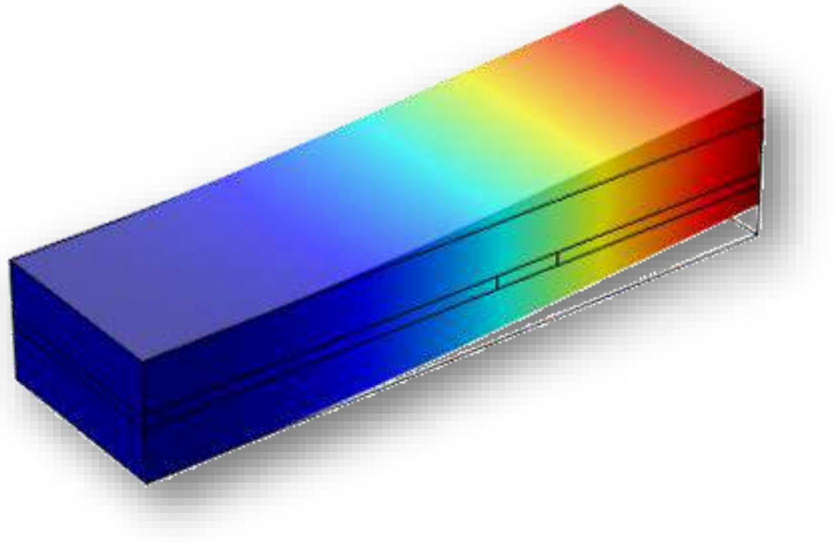
This model performs a static 2D axisymmetric analysis of a piezoelectric actuator. A radially polarized piezoelectric tube is simulated, with two sets of boundary conditions. The first case illustrates the inverse piezoelectric effect, and the second case shows the direct piezoelectric effect. The model is based on a paper by S. M. Peelamedu et al. (Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering March 1, 2000 vol. 214 no. 2 87-97).



http://www.comsol.com/model/a-piezoceramic-tube-37

Piezoelectric Shear-Actuated Beam

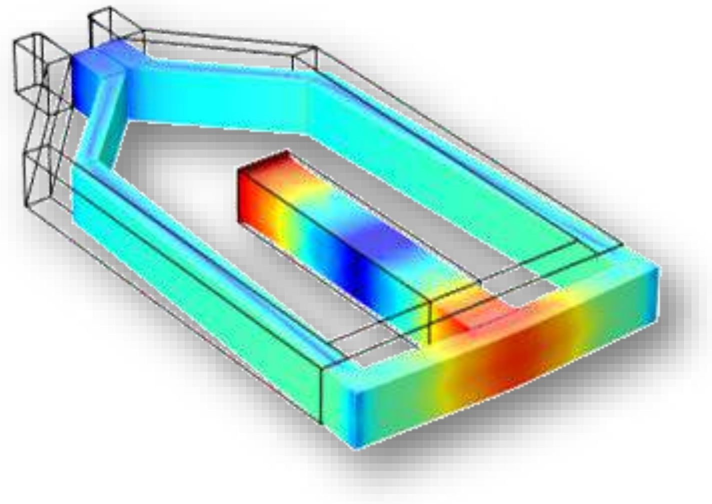
This model performs a static analysis of a composite cantilever beam equipped with a piezoceramic actuator. An electric field is applied perpendicular to the poling direction, thereby introducing a transverse deflection of the beam.



http://www.comsol.com/model/piezoelectric-shear-actuated-beam-24

Piezoelectric Actuated Microgripper

This model shows the fundamentals of how to set up a piezoelectric model with mechanical contact. The microgripper contains a stacked piezoactuator, which operates in the longitudinal mode. Simultaneous contraction in the transversal direction and elongation in the longitudinal direction closes the gripper and moves objects.



http://www.comsol.com/model/piezoelectric-actuated-microgripper-4695

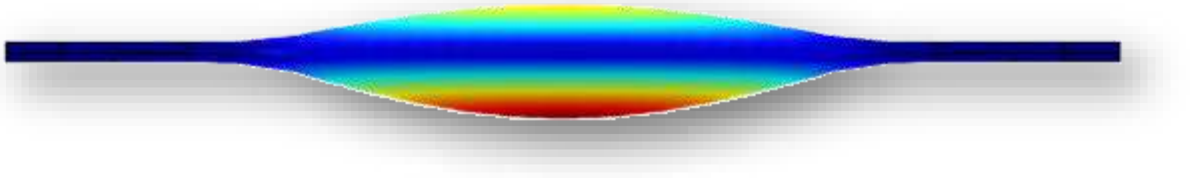
SAW Gas Sensor

This model analyzes the eigenfrequencies of a surface acoustic wave (SAW) gas sensor. In particular, the model studies how the additional mass load from an adsorbed gas lowers the resonance frequency.

http://www.comsol.com/model/saw-gas-sensor-2129

Thin Film BAW Composite Resonator

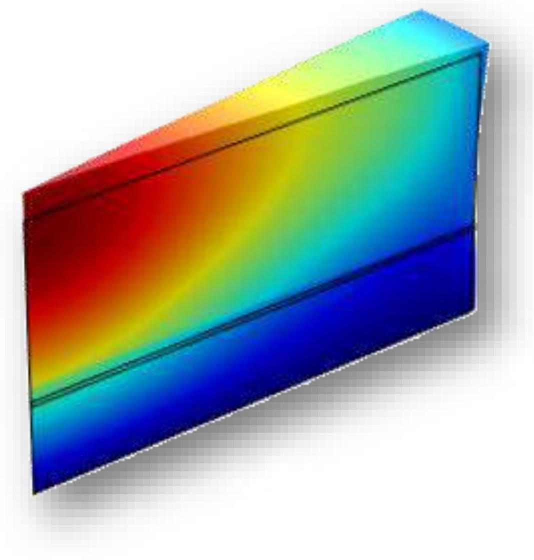
Bulk acoustic wave (BAW) resonators are useful components for many radio-frequency applications, where they can operate as narrow band filters. This example shows how you can perform eigenfrequency and frequency-response analyses of a composite thin-film BAW resonator.



http://www.comsol.com/model/thin-film-baw-composite-resonator-5784

Composite Piezoelectric Transducer

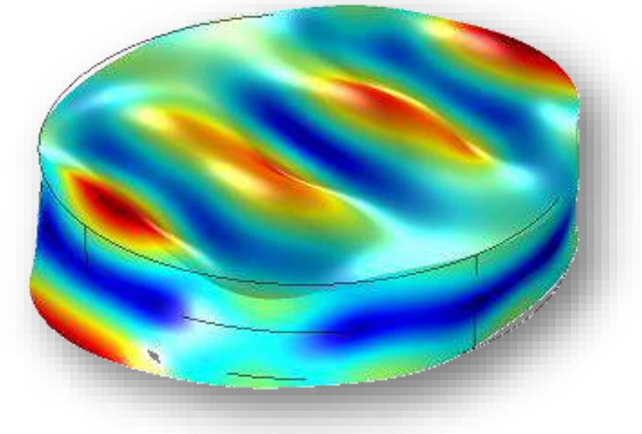
A composite piezoelectric ultrasonic transducer is analyzed. An eigenfrequency analysis is followed by a frequency response analysis to calculate the input admittance as a function of the excitation frequency.



http://www.comsol.com/model/composite-piezoelectric-transducer-503

Thickness Shear Mode Quartz Oscillator

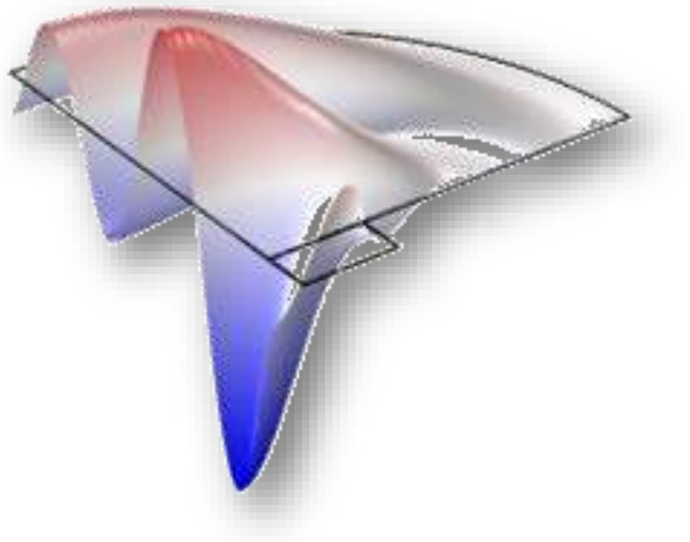
A quartz oscillator, operated in the thickness shear mode, is simulated. The model shows how to set up the co-ordinate system correctly for AT cut quartz and to model the response of a device driven at resonance. The resonant frequency of the oscillator is altered by changing the capacitance of a shunt capacitor.



http://www.comsol.com/model/thickness-shear-mode-quartz-oscillator-4707

Piezoacoustic Transducer

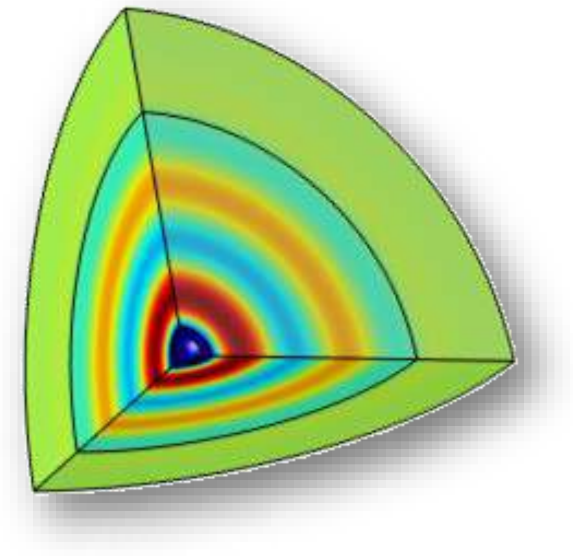
In a phased-array microphone, the piezoelectric crystal plate fits into the structure through a series of stacked layers, which are divided into rows. The space between these layers is referred to as the kerf and the rows are repeated with a periodicity, or pitch. Using functionality provided by the Acoustics Module, this model simulates a single row of such a structure, solving for the acoustic pressure generated by the transducer and the structural deformation due to the electric load.



http://www.comsol.com/model/piezoacoustic-transducer-1477

Spherical Piezoacoustic Transducer

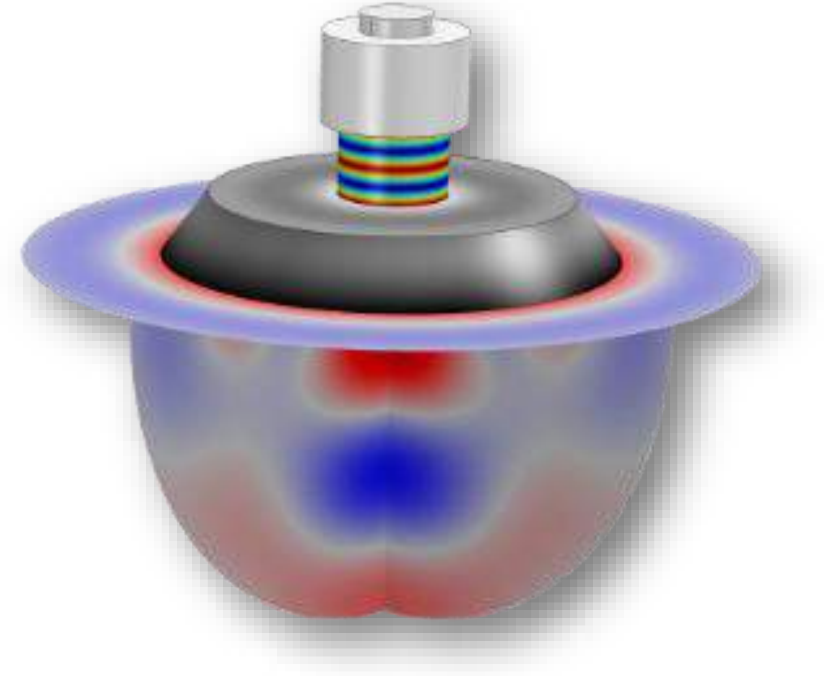
This tutorial shows how to model the acoustic waves generated in air by a hollow spherical piezoelectric material. The device is poled along the radial direction of the sphere, requiring the definition of a new local system of coordinates. Because the direction of poling imparts anisotropy to the material response, it is critical to incorporate it correctly in the simulation.



http://www.comsol.com/model/radially-polarized-spherical-piezoelectric-acoustic-transducer-6210

Tonpilz Piezo Transducer

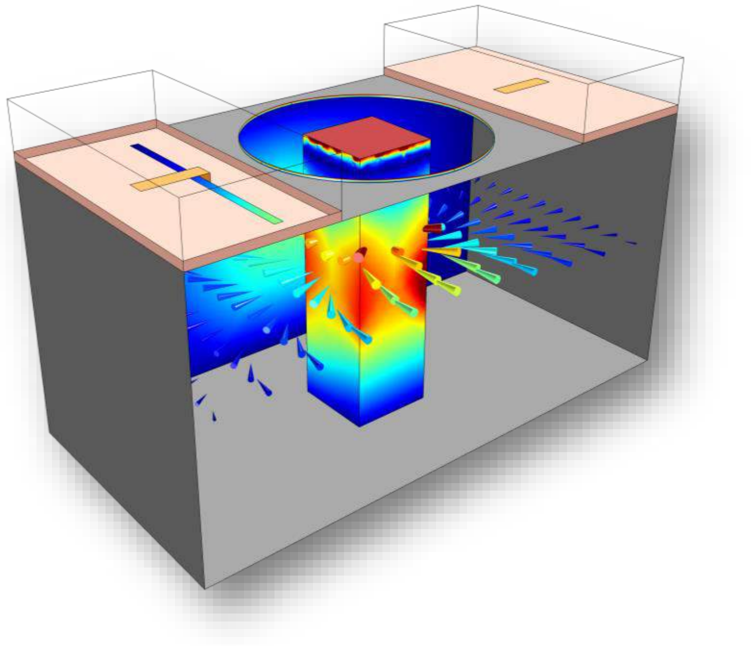
A tonpilz transducer is used for relatively low frequency, high power sound emission. It is one of the popular transducer configuration for SONAR applications. The transducer consists of piezoceramic rings stacked between a head mass and a tail mass which are connected by a central bolt. In this model the frequency response of the transducer is studied to determine structural and acoustic response of the device such as deformation, stresses, radiated pressure, sound pressure level, far-field beam pattern, the transmitting voltage response (TVR) curve, and the directivity index (DI) of the sound beam.



http://www.comsol.com/model/tonpilz-piezo-transducer-11478

Tunable Evanescent Mode Cavity Filter using a Piezoelectric Device

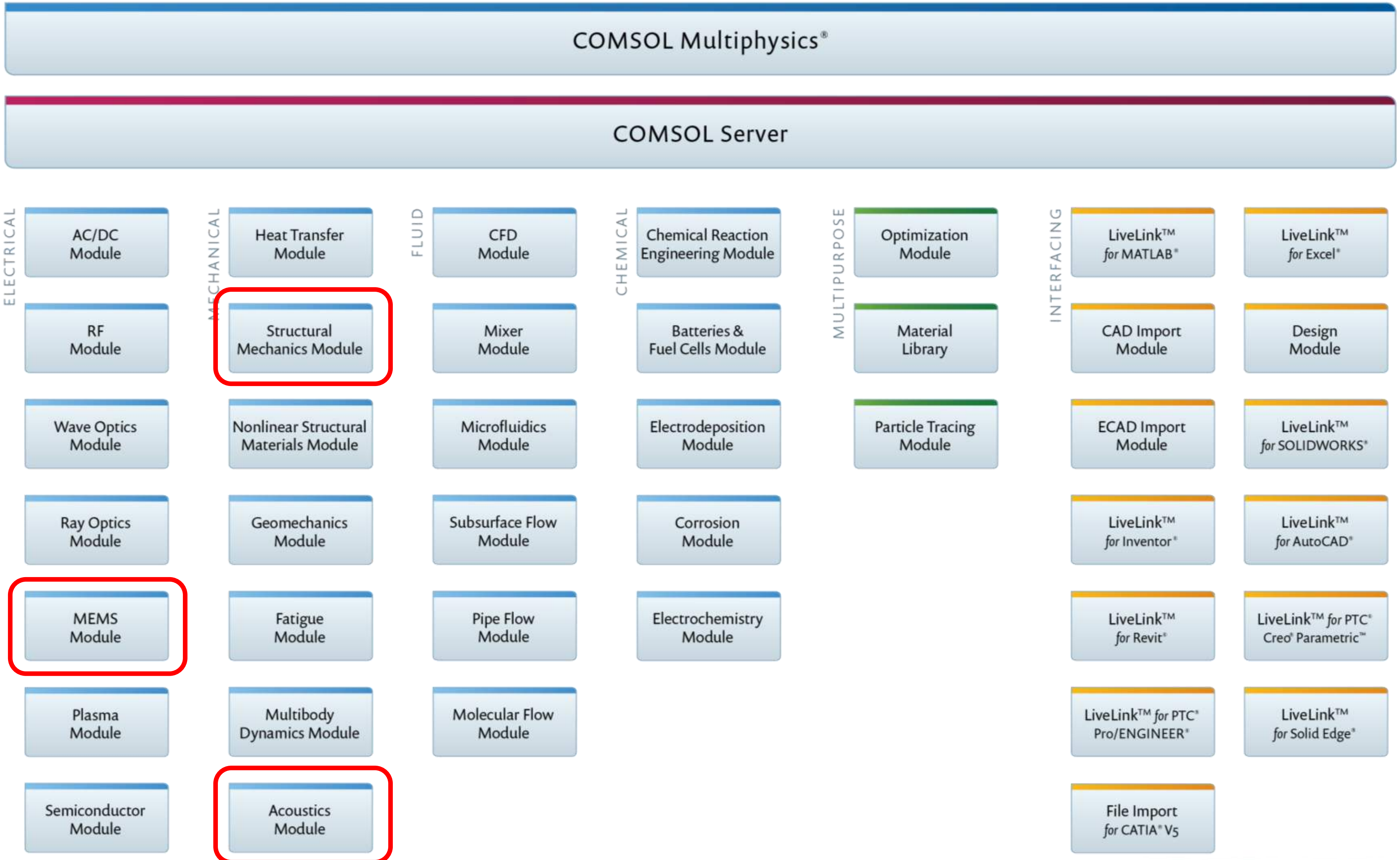
An evanescent mode cavity filter can be realized by adding a structure inside of the cavity. This structure changes the resonant frequency below that of the dominant mode of the unfilled cavity. A piezo actuator is used to control the size of a small air gap which provides the tunability of the resonant frequency.



http://www.comsol.com/model/tunable-evanescent-mode-cavity-filter-using-a-piezoelectric-device-12619

Relevant Products

COMSOL Product Line – Version 5.0



COMSOL Multiphysics®

COMSOL Server

ELECTRICAL	MECHANICAL	FLUID	CHEMICAL	MULTIPURPOSE	INTERFACING	
AC/DC Module	Heat Transfer Module	CFD Module	Chemical Reaction Engineering Module	Optimization Module	LiveLink™ *for* MATLAB®	LiveLink™ *for* Excel®
RF Module	Structural Mechanics Module	Mixer Module	Batteries & Fuel Cells Module	Material Library	CAD Import Module	Design Module
Wave Optics Module	Nonlinear Structural Materials Module	Microfluidics Module	Electrodeposition Module	Particle Tracing Module	ECAD Import Module	LiveLink™ *for* SOLIDWORKS®
Ray Optics Module	Geomechanics Module	Subsurface Flow Module	Corrosion Module		LiveLink™ *for* Inventor®	LiveLink™ *for* AutoCAD®
MEMS Module	Fatigue Module	Pipe Flow Module	Electrochemistry Module		LiveLink™ *for* Revit®	LiveLink™ *for* PTC® Creo® Parametric™
Plasma Module	Multibody Dynamics Module	Molecular Flow Module			LiveLink™ *for* PTC® Pro/ENGINEER®	LiveLink™ *for* Solid Edge®
Semiconductor Module	Acoustics Module				File Import *for* CATIA® V5	

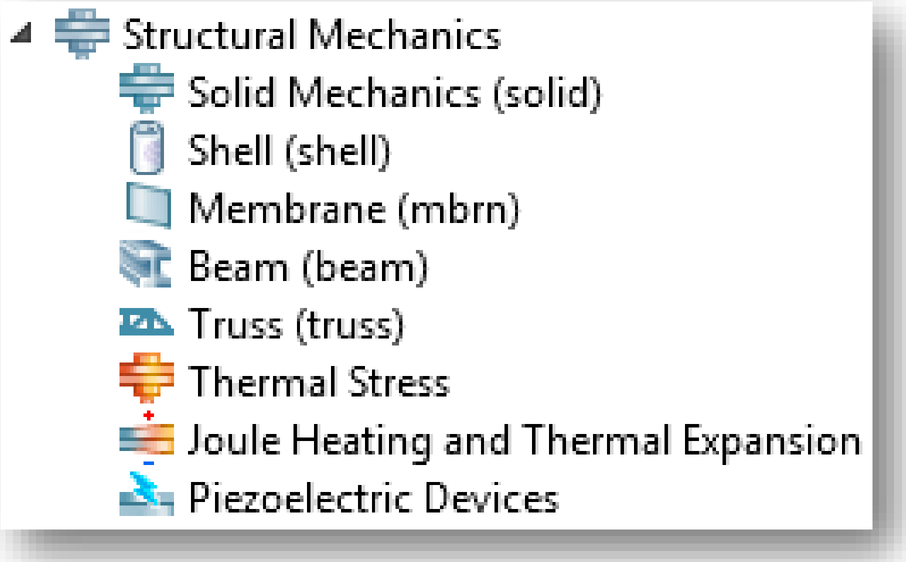
Relevant COMSOL Modules

- Identical piezo-implementation in these modules
  - Structural Mechanics Module
  - MEMS Module
  - Acoustics Module

- When do you need one or the other?

When do you need…

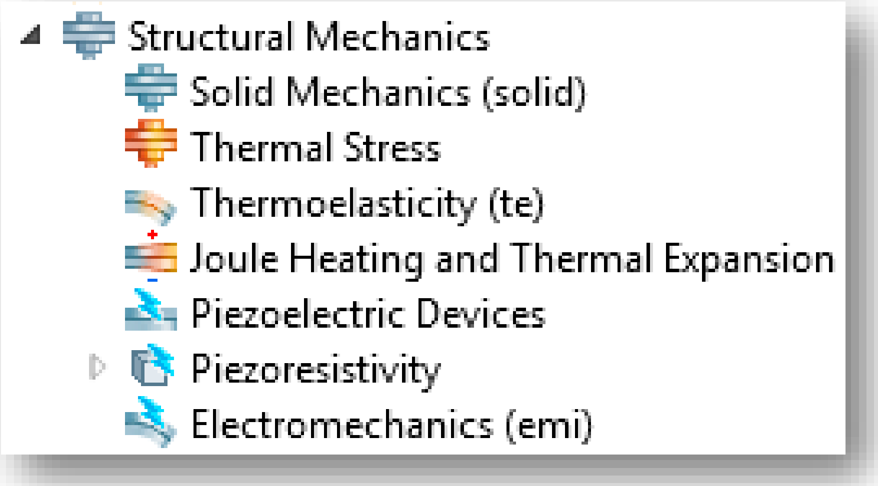
- Structural Mechanics Module:
  - Useful if you are planning to use any of the special structural elements (*beam, plate, shell, truss, membrane*)



Structural Mechanics
  - Solid Mechanics (solid)
  - Shell (shell)
  - Membrane (mbrn)
  - Beam (beam)
  - Truss (truss)
  - Thermal Stress
  - Joule Heating and Thermal Expansion
  - Piezoelectric Devices

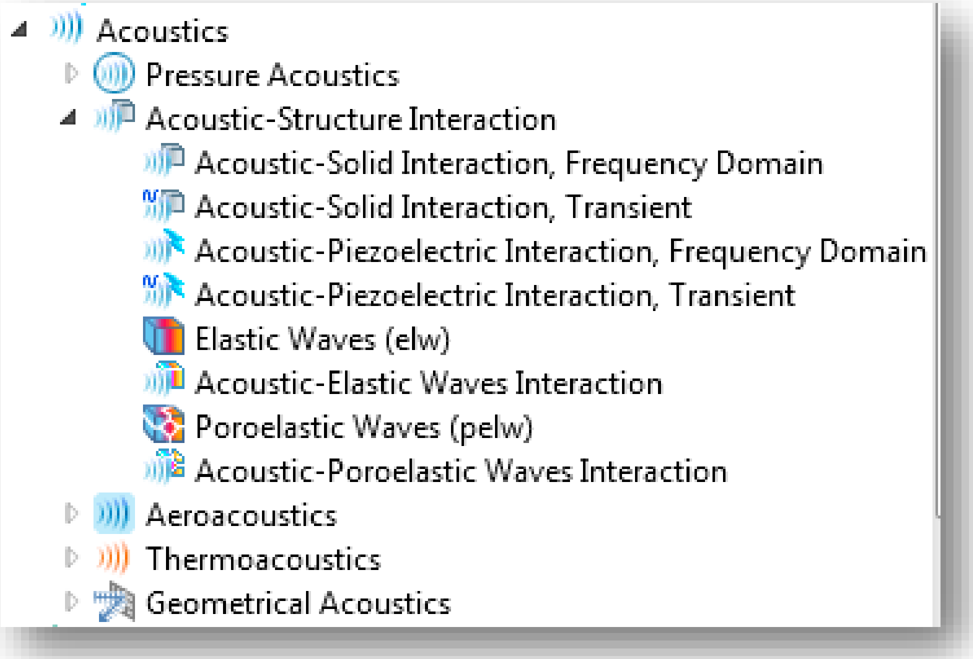
When do you need…

- MEMS Module:
  - Useful if you are planning to calculate lumped parameters (Z, Y, S)
  - Connect your FEA model to lumped electrical circuits
  - Combine with other exotic multiphysics effects (*Electromechanics, Thermoelasticity* and *Piezoresistivity*)



When do you need…

- Acoustics Module:
  - Special interfaces such as *Acoustic-Piezoelectric Interaction* in both frequency domain and time domain
  - Useful if you are planning to model acoustic transducers or acoustic-structure interaction



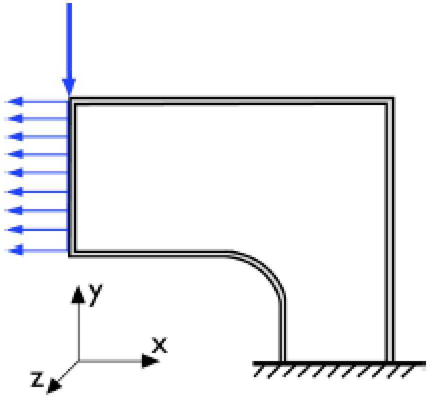
- Acoustics
  - Pressure Acoustics
  - Acoustic-Structure Interaction
    - Acoustic-Solid Interaction, Frequency Domain
    - Acoustic-Solid Interaction, Transient
    - Acoustic-Piezoelectric Interaction, Frequency Domain
    - Acoustic-Piezoelectric Interaction, Transient
    - Elastic Waves (elw)
    - Acoustic-Elastic Waves Interaction
    - Poroelastic Waves (pelw)
    - Acoustic-Poroelastic Waves Interaction
  - Aeroacoustics
  - Thermoacoustics
  - Geometrical Acoustics

Useful Features

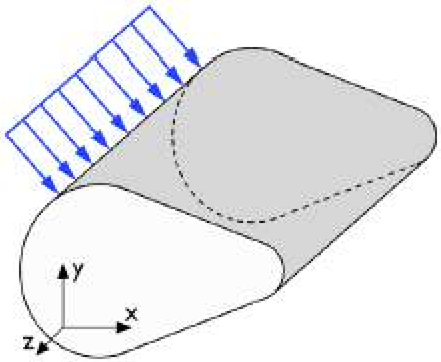
Key Steps in Modeling

- Device Geometry
- Material Properties
- Piezoelectric Physics Setup
- Coupling With More Physics
- Analysis Types

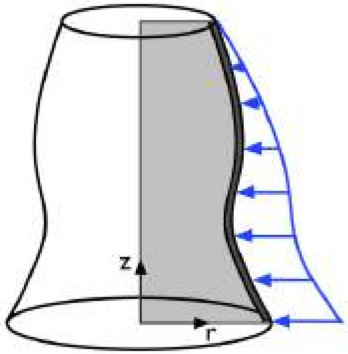
Types of Modeling Geometry



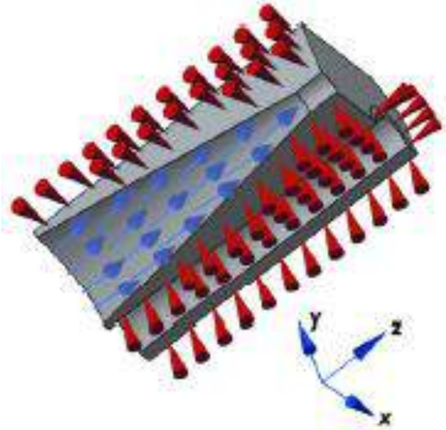
2D – Plane Stress



2D – Plane Strain

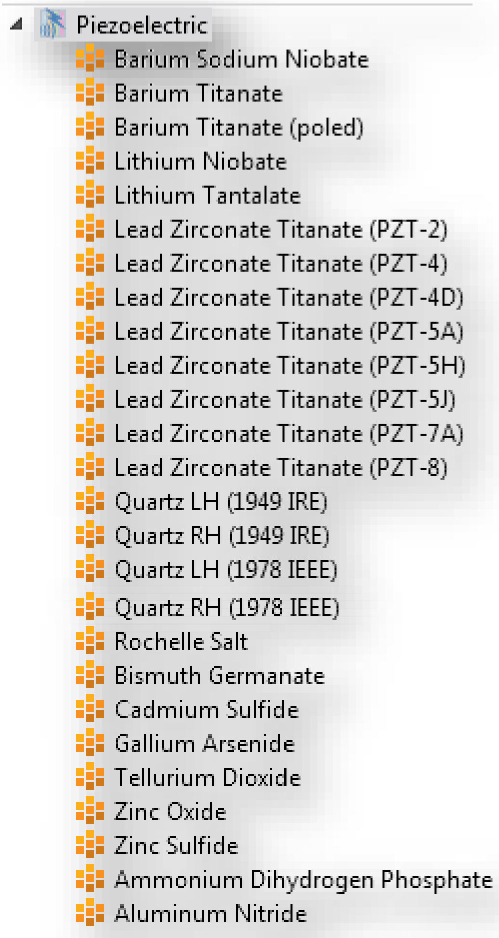


2D – Axial Symmetry



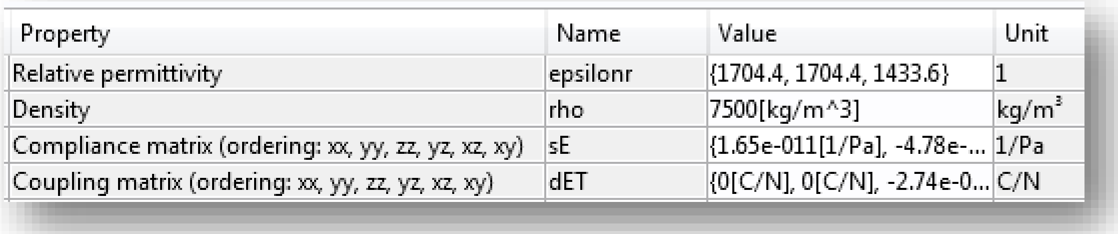
3D - Solid

Material Properties

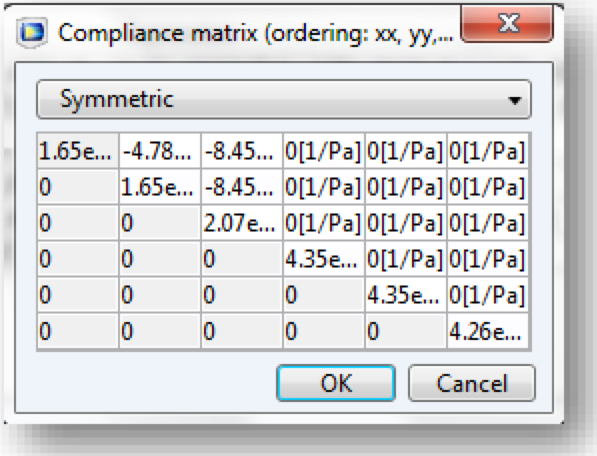


- Piezoelectric
  - Barium Sodium Niobate
  - Barium Titanate
  - Barium Titanate (poled)
  - Lithium Niobate
  - Lithium Tantalate
  - Lead Zirconate Titanate (PZT-2)
  - Lead Zirconate Titanate (PZT-4)
  - Lead Zirconate Titanate (PZT-4D)
  - Lead Zirconate Titanate (PZT-5A)
  - Lead Zirconate Titanate (PZT-5H)
  - Lead Zirconate Titanate (PZT-5J)
  - Lead Zirconate Titanate (PZT-7A)
  - Lead Zirconate Titanate (PZT-8)
  - Quartz LH (1949 IRE)
  - Quartz RH (1949 IRE)
  - Quartz LH (1978 IEEE)
  - Quartz RH (1978 IEEE)
  - Rochelle Salt
  - Bismuth Germanate
  - Cadmium Sulfide
  - Gallium Arsenide
  - Tellurium Dioxide
  - Zinc Oxide
  - Zinc Sulfide
  - Ammonium Dihydrogen Phosphate
  - Aluminum Nitride

- 23 different piezo materials
- View and edit the properties
- Add your own piezo materials



Property	Name	Value	Unit
Relative permittivity	epsilonr	{1704.4, 1704.4, 1433.6}	1
Density	rho	7500[kg/m^3]	kg/m^3
Compliance matrix (ordering: xx, yy, zz, yz, xz, xy)	sE	{1.65e-011[1/Pa], -4.78e-...	1/Pa
Coupling matrix (ordering: xx, yy, zz, yz, xz, xy)	dET	{0[C/N], 0[C/N], -2.74e-0...	C/N

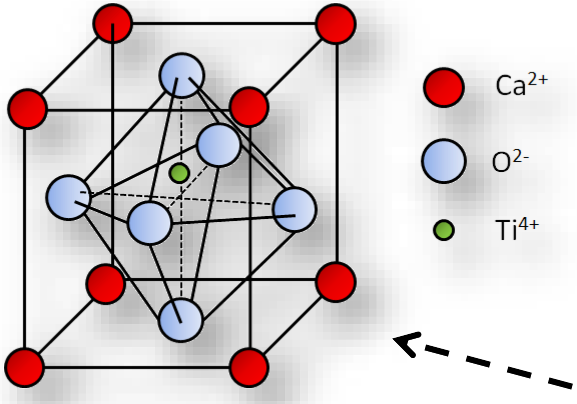


Compliance matrix (ordering: xx, yy,...

Symmetric

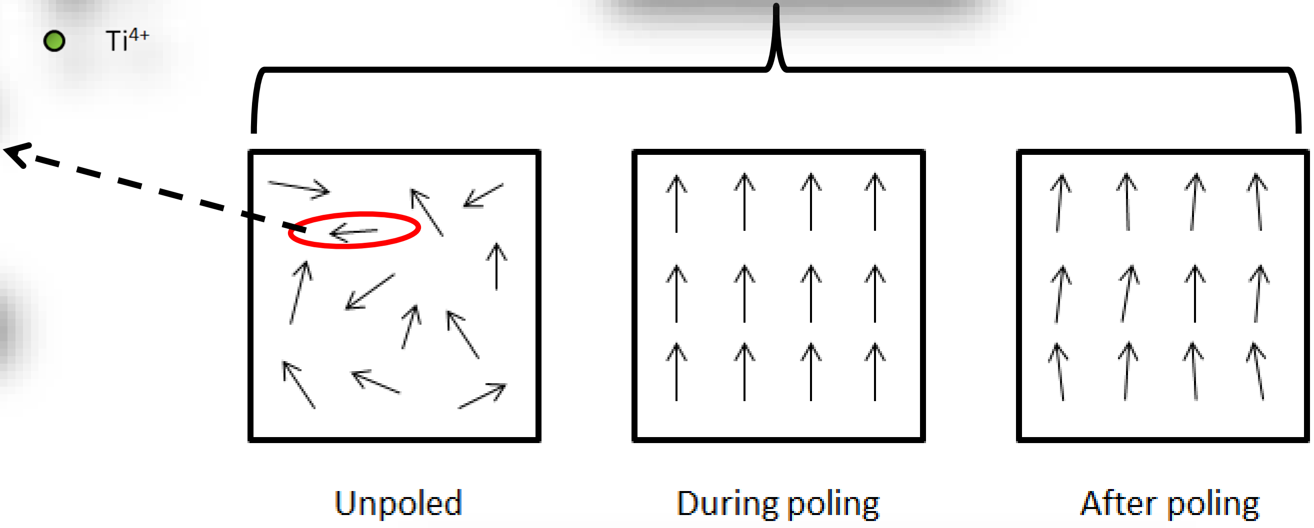
1.65e...	-4.78...	-8.45...	0[1/Pa]	0[1/Pa]	0[1/Pa]
0	1.65e...	-8.45...	0[1/Pa]	0[1/Pa]	0[1/Pa]
0	0	2.07e...	0[1/Pa]	0[1/Pa]	0[1/Pa]
0	0	0	4.35e...	0[1/Pa]	0[1/Pa]
0	0	0	0	4.35e...	0[1/Pa]
0	0	0	0	0	4.26e...

Material Anisotropy due to Poling



A perovskite unit cell

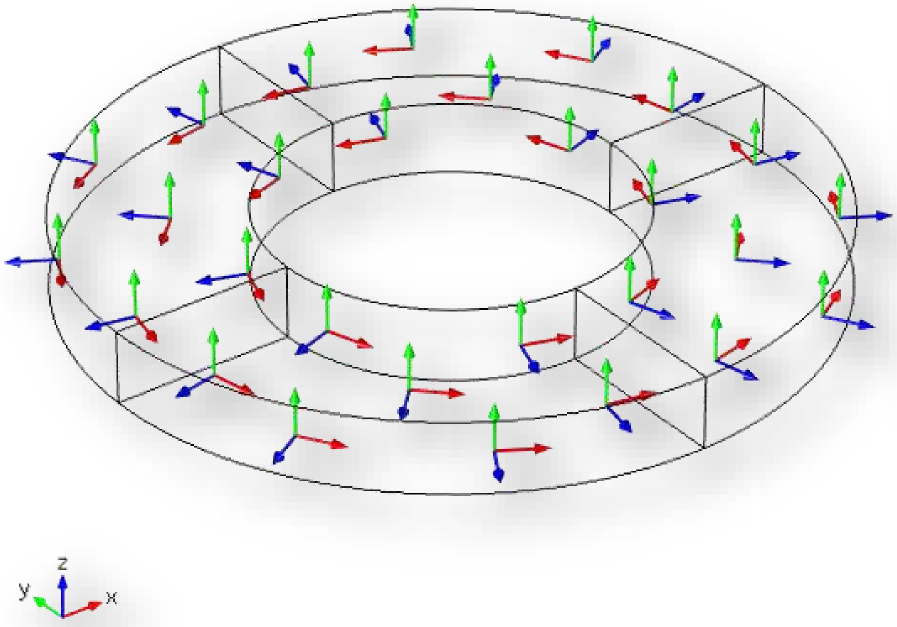
Macroscopic material with many unit cells

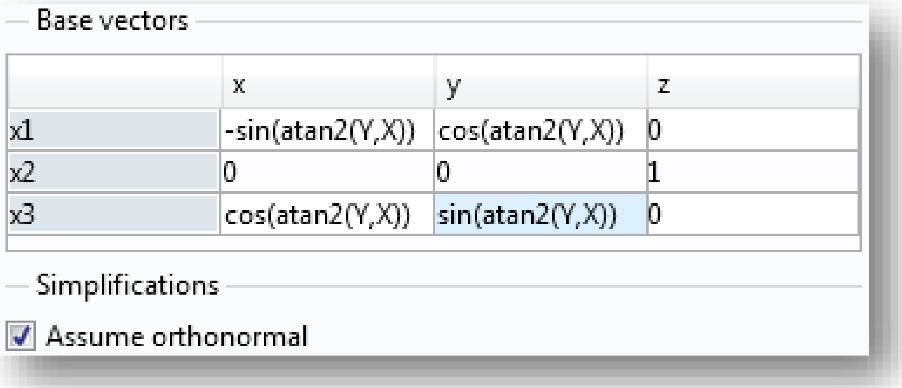


Pictorial representation of the poling process

http://www.comsol.com/blogs/piezoelectric-materials-crystal-orientation-poling-direction/

User Defined Coordinate System




Base vectors

	x	y	z
x1	-sin(atan2(Y,X))	cos(atan2(Y,X))	0
x2	0	0	1
x3	cos(atan2(Y,X))	sin(atan2(Y,X))	0

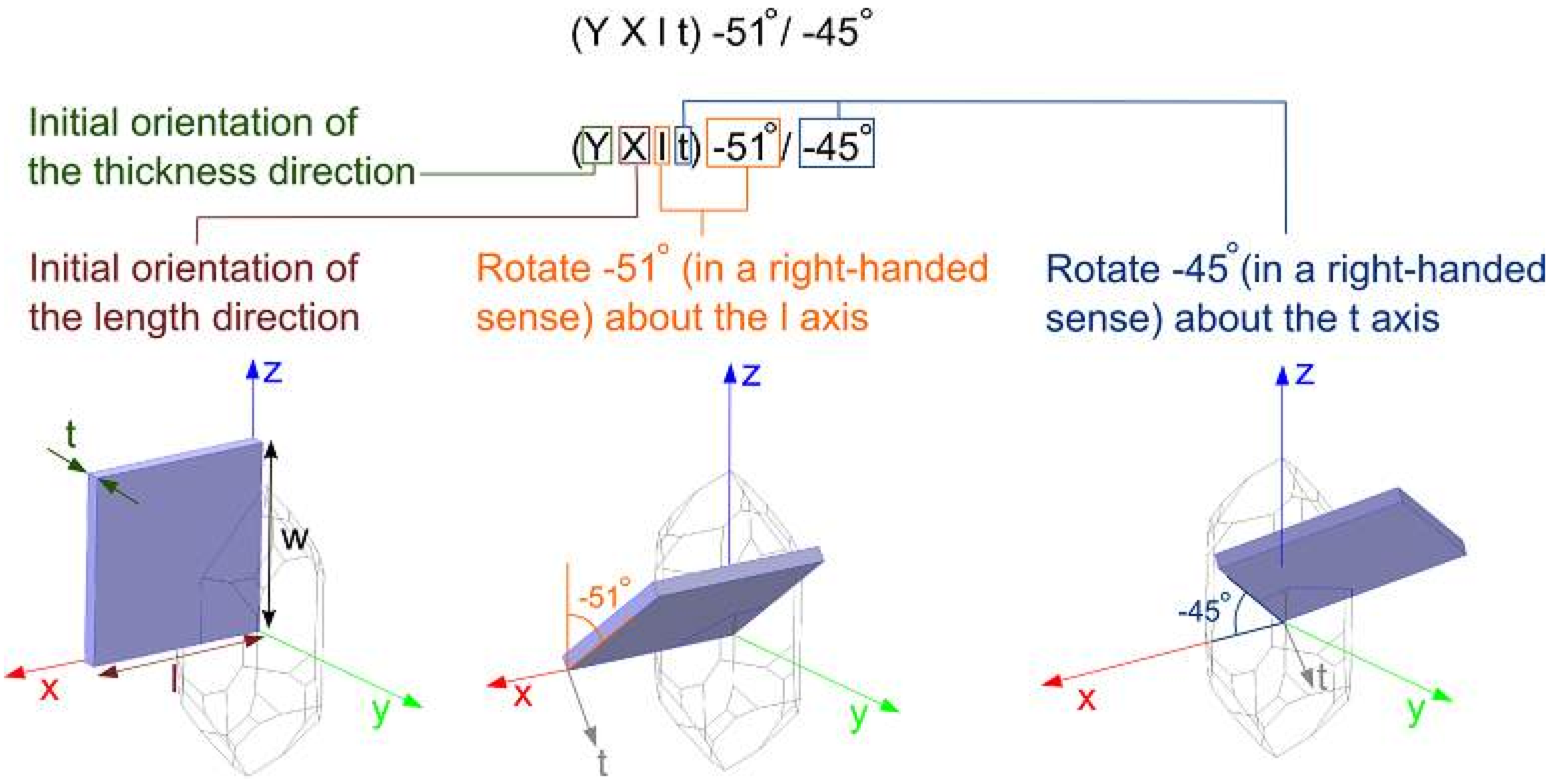
Simplifications

☑ Assume orthonormal

Radially polarized PZT disc represented using a Base Vector System

http://www.comsol.com/model/radially-polarized-piezoelectric-transducer-6147

Material Anisotropy due to Crystal Cut



(Y X l t) -51°/ -45°

Initial orientation of the thickness direction

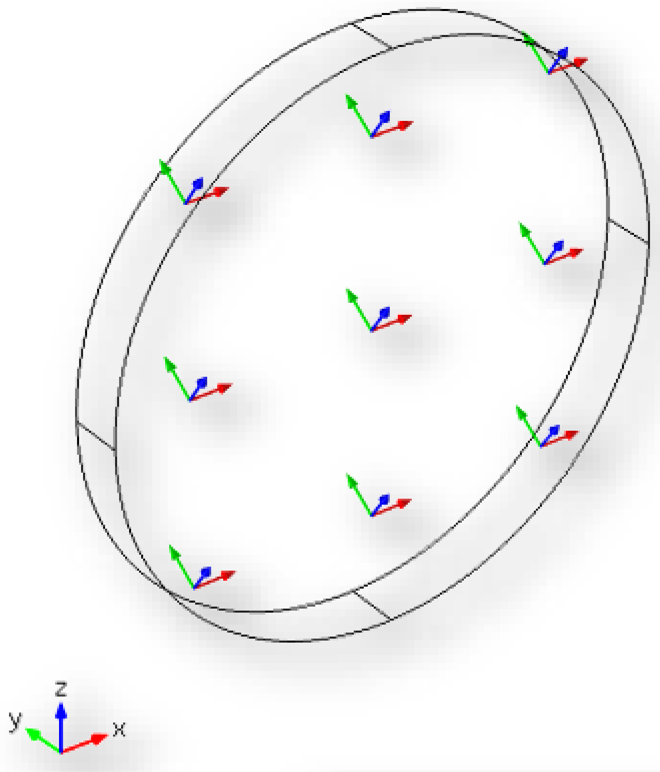
Initial orientation of the length direction

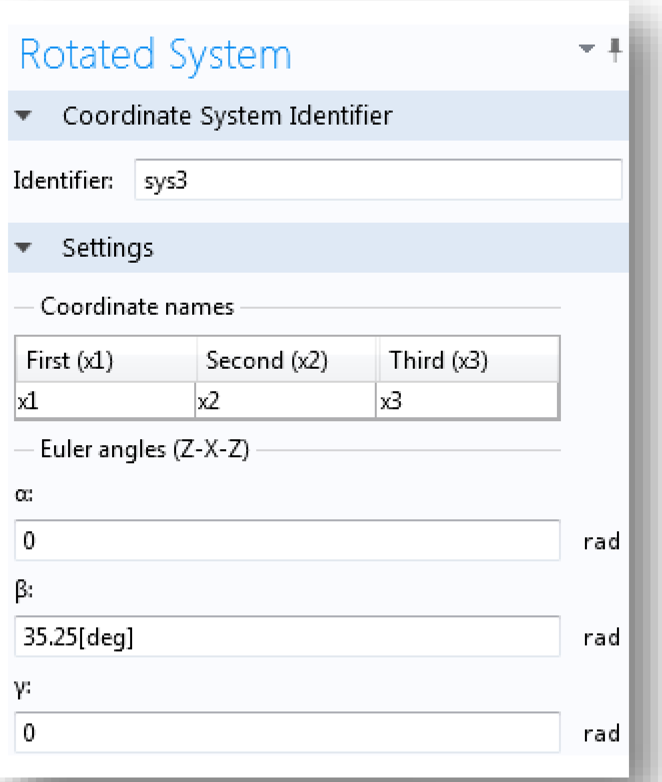
Rotate -51° (in a right-handed sense) about the l axis

Rotate -45° (in a right-handed sense) about the t axis

http://www.comsol.com/blogs/piezoelectric-materials-understanding-standards/

User Defined Coordinate System





Rotated System

Coordinate System Identifier

Identifier: sys3

Settings

Coordinate names

First (x1)	Second (x2)	Third (x3)
x1	x2	x3

Euler angles (Z-X-Z)

α: 0 rad

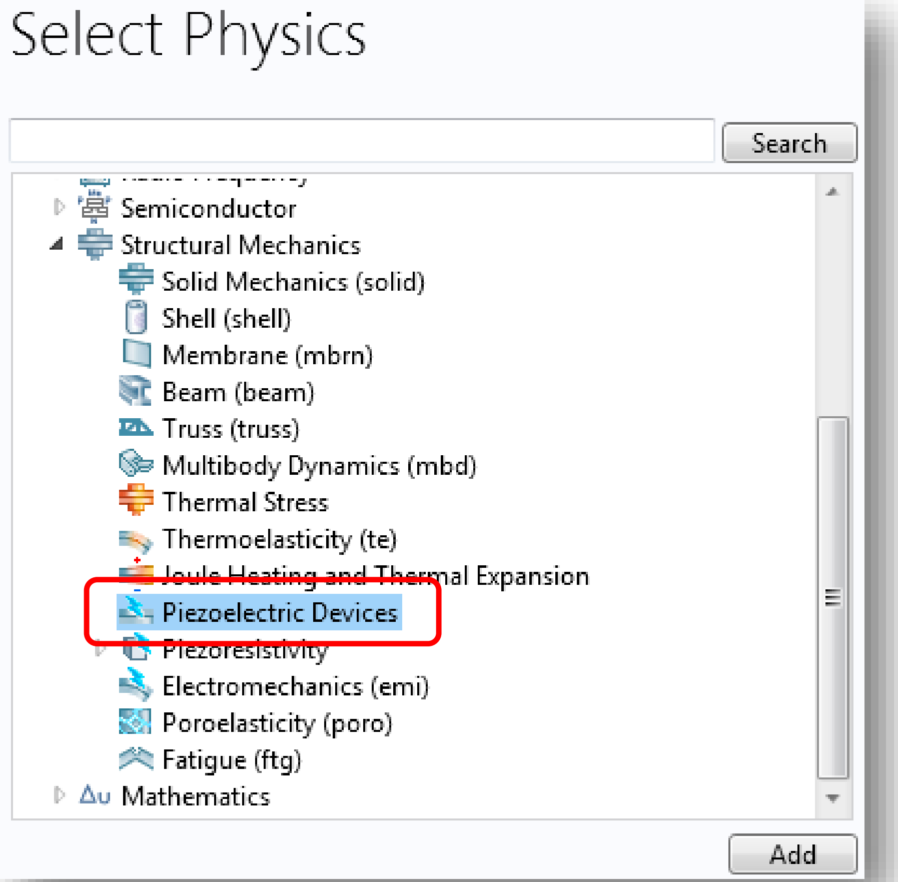
β: 35.25[deg] rad

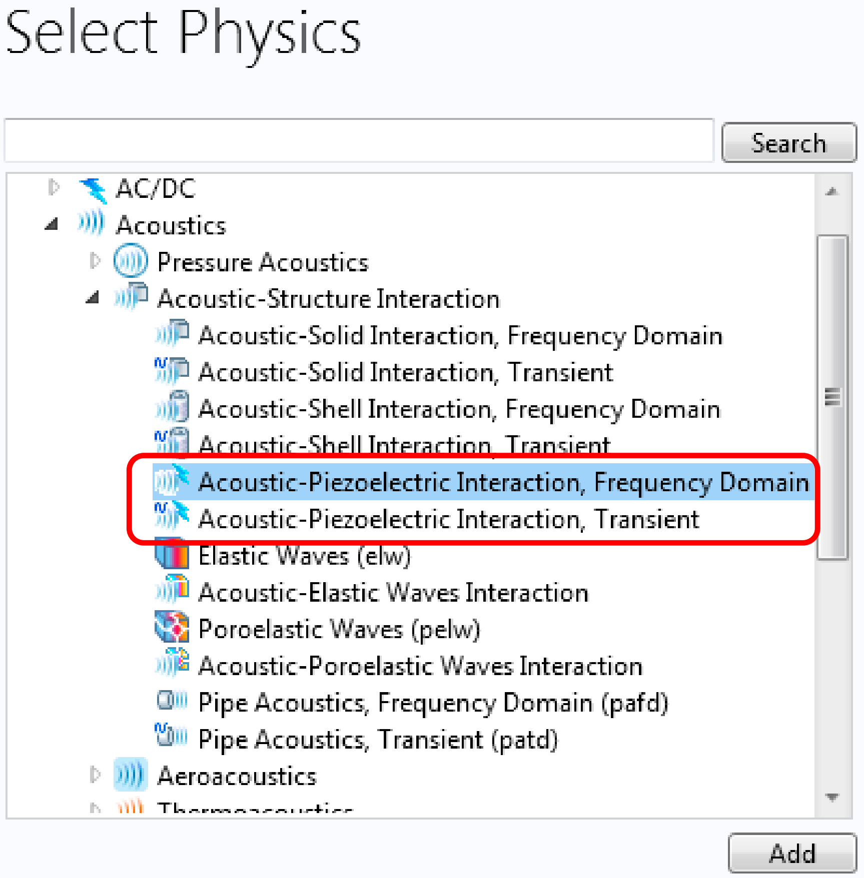
γ: 0 rad

AT cut quartz represented using Euler angles

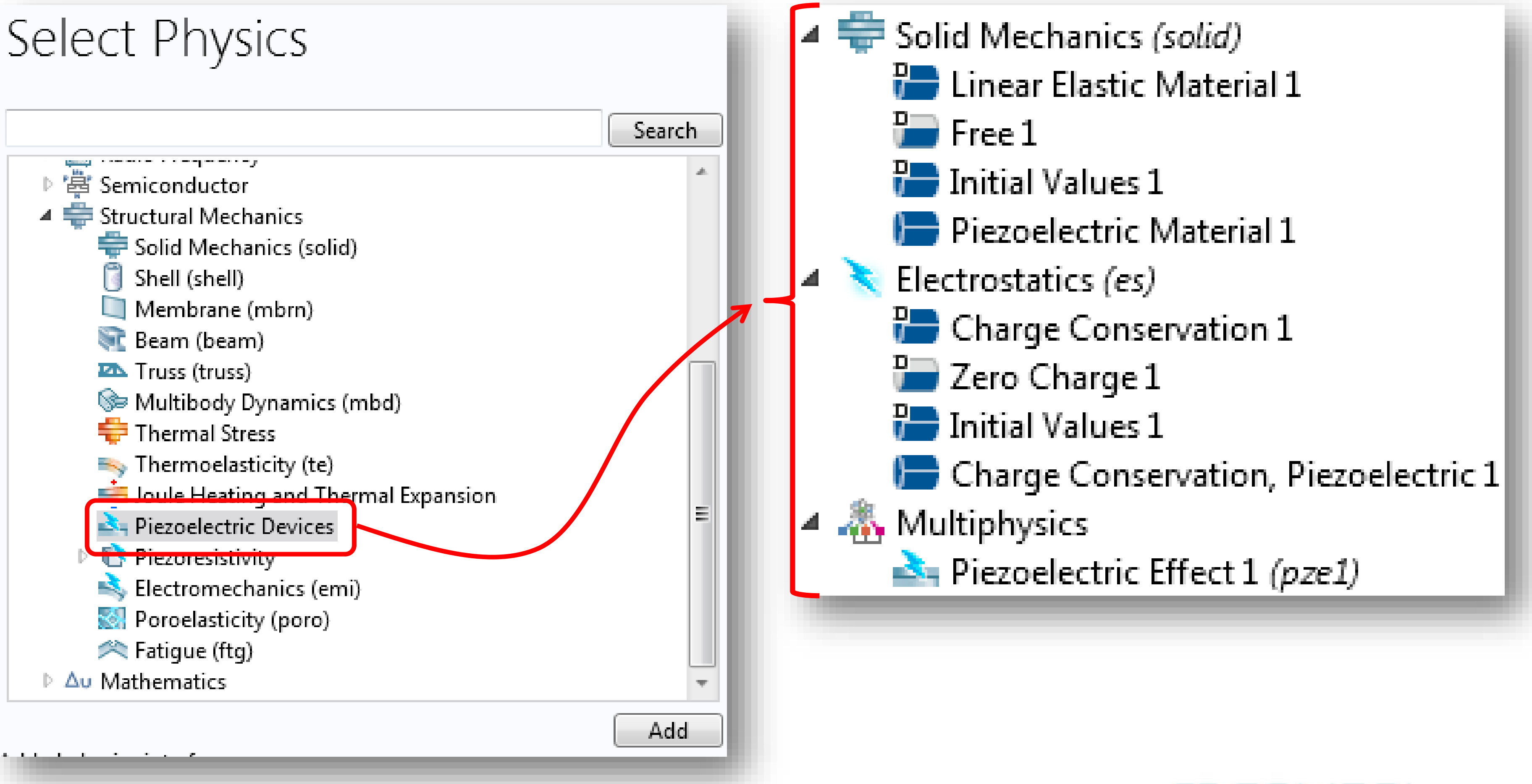
http://www.comsol.com/model/thickness-shear-mode-quartz-oscillator-4707

Physics Interfaces





Piezoelectric Devices

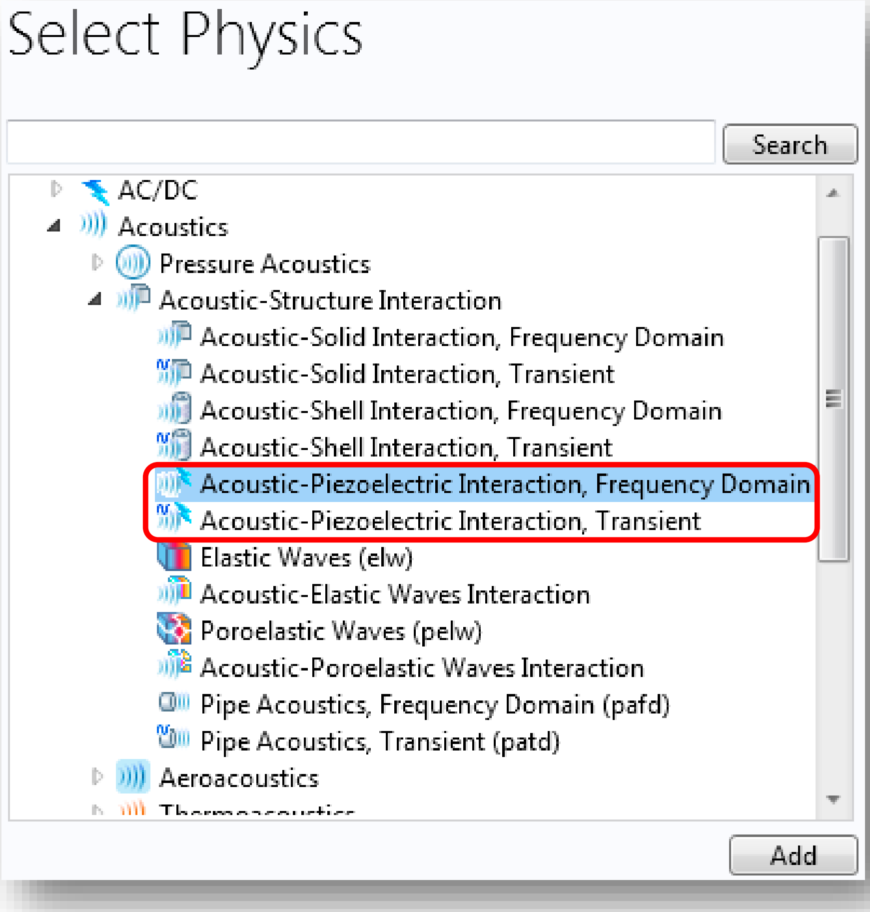


Select Physics

- Semiconductor
- Structural Mechanics
  - Solid Mechanics (solid)
  - Shell (shell)
  - Membrane (mbrn)
  - Beam (beam)
  - Truss (truss)
  - Multibody Dynamics (mbd)
  - Thermal Stress
  - Thermoelasticity (te)
  - Joule Heating and Thermal Expansion
  - Piezoelectric Devices
  - Piezoresistivity
  - Electromechanics (emi)
  - Poroelasticity (poro)
  - Fatigue (ftg)
- Mathematics

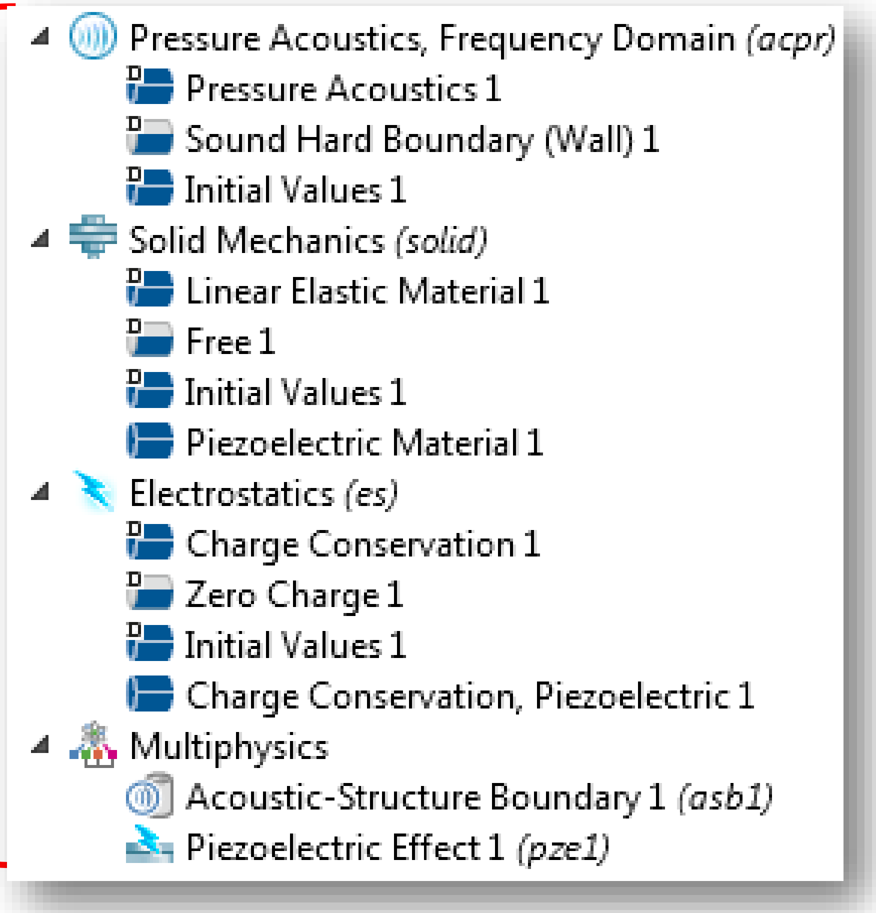
- Solid Mechanics *(solid)*
  - Linear Elastic Material 1
  - Free 1
  - Initial Values 1
  - Piezoelectric Material 1
- Electrostatics *(es)*
  - Charge Conservation 1
  - Zero Charge 1
  - Initial Values 1
  - Charge Conservation, Piezoelectric 1
- Multiphysics
  - Piezoelectric Effect 1 *(pze1)*

Acoustic-Piezoelectric Interaction



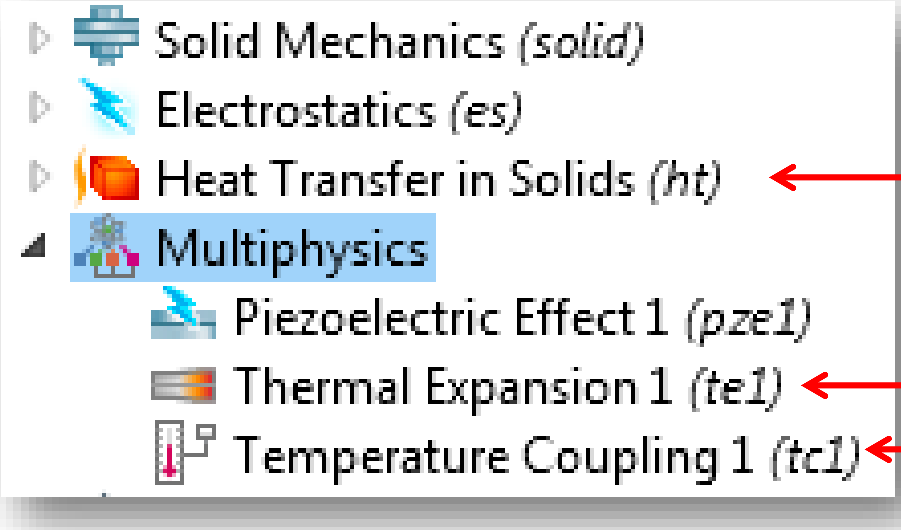
Select Physics

- AC/DC
- Acoustics
  - Pressure Acoustics
  - Acoustic-Structure Interaction
    - Acoustic-Solid Interaction, Frequency Domain
    - Acoustic-Solid Interaction, Transient
    - Acoustic-Shell Interaction, Frequency Domain
    - Acoustic-Shell Interaction, Transient
    - Acoustic-Piezoelectric Interaction, Frequency Domain
    - Acoustic-Piezoelectric Interaction, Transient
    - Elastic Waves (elw)
    - Acoustic-Elastic Waves Interaction
    - Poroelastic Waves (pelw)
    - Acoustic-Poroelastic Waves Interaction
    - Pipe Acoustics, Frequency Domain (pafd)
    - Pipe Acoustics, Transient (patd)
  - Aeroacoustics
  - Thermoacoustics



- Pressure Acoustics, Frequency Domain *(acpr)*
  - Pressure Acoustics 1
  - Sound Hard Boundary (Wall) 1
  - Initial Values 1
- Solid Mechanics *(solid)*
  - Linear Elastic Material 1
  - Free 1
  - Initial Values 1
  - Piezoelectric Material 1
- Electrostatics *(es)*
  - Charge Conservation 1
  - Zero Charge 1
  - Initial Values 1
  - Charge Conservation, Piezoelectric 1
- Multiphysics
  - Acoustic-Structure Boundary 1 *(asb1)*
  - Piezoelectric Effect 1 *(pze1)*

Combining With More Physics



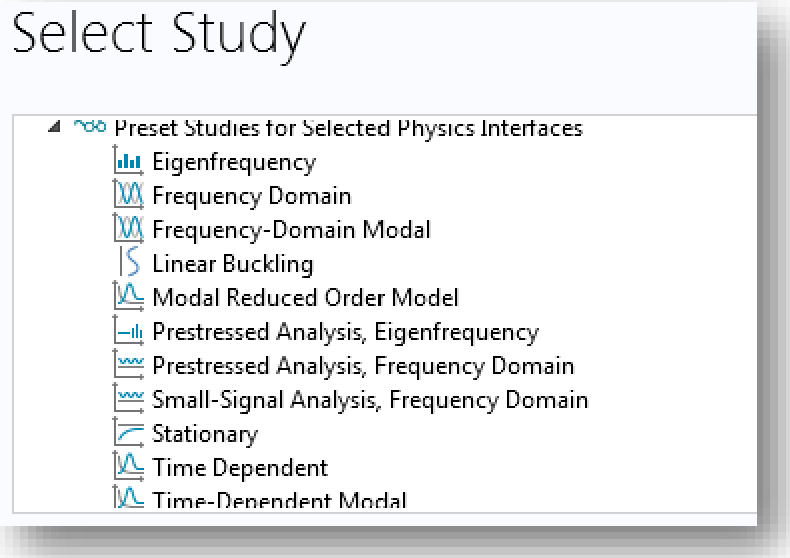
Add a Heat Transfer physics interface

Add thermal expansion effect

Add temperature coupling to model temperature-dependent material property

Basic Analysis Types

- Stationary
  - Static and quasi-static analysis
- Time-Dependent
  - Full transient analysis
  - Can include damping
- Eigenfrequency
  - Find resonance frequencies and mode shapes
  - Include damping to find Q-factor
- Frequency Domain
  - Frequency response analysis
  - Include damping
  - Include phase difference between loads
- Linear Buckling
  - Obtain critical buckling load

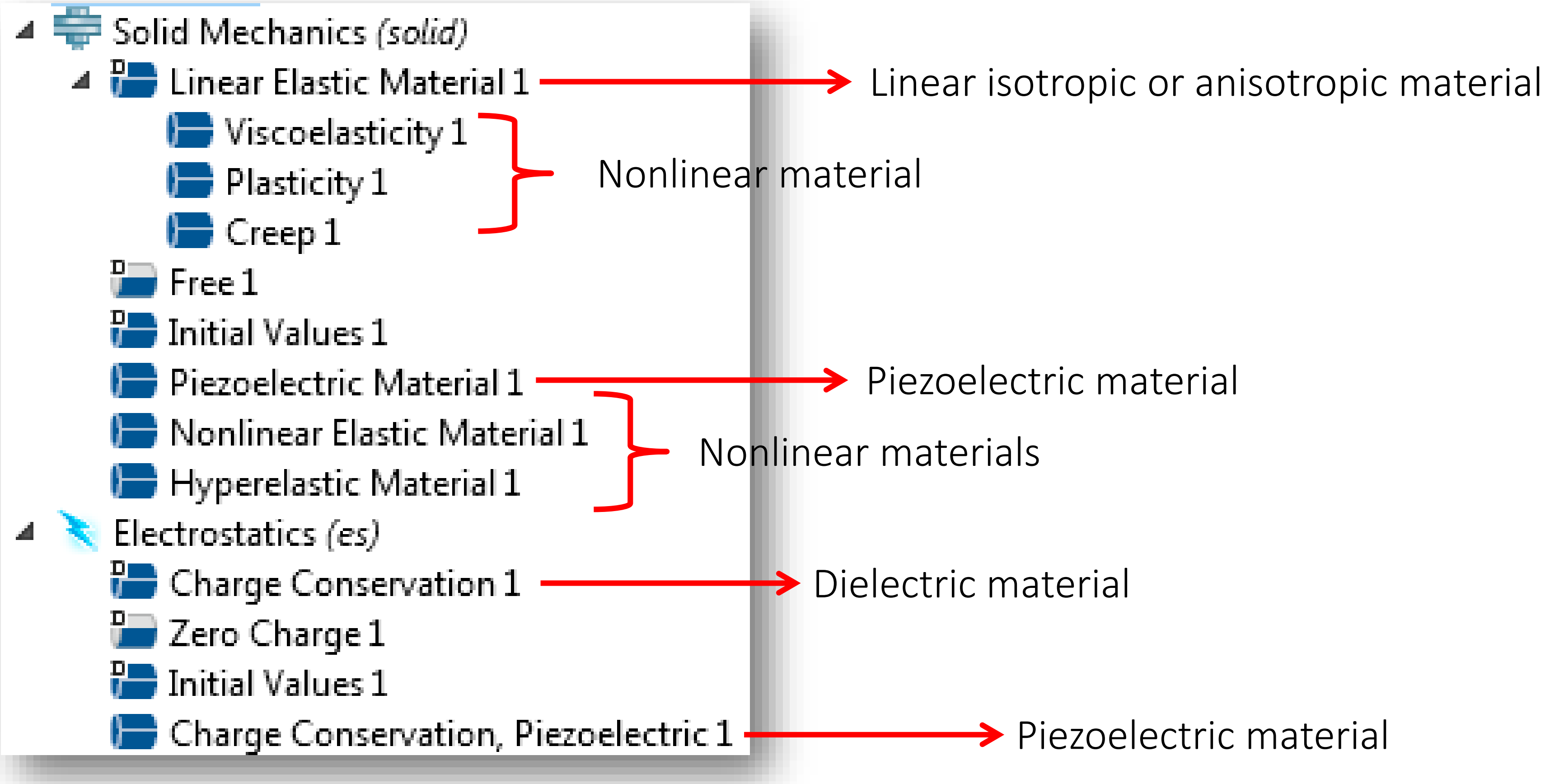


Select Study

- Preset Studies for Selected Physics Interfaces
  - Eigenfrequency
  - Frequency Domain
  - Frequency-Domain Modal
  - Linear Buckling
  - Modal Reduced Order Model
  - Prestressed Analysis, Eigenfrequency
  - Prestressed Analysis, Frequency Domain
  - Small-Signal Analysis, Frequency Domain
  - Stationary
  - Time Dependent
  - Time-Dependent Modal

More Details On Features

Working With Mixed Materials



- Solid Mechanics *(solid)*
  - Linear Elastic Material 1
    - Viscoelasticity 1
    - Plasticity 1
    - Creep 1
  - Free 1
  - Initial Values 1
  - Piezoelectric Material 1
  - Nonlinear Elastic Material 1
  - Hyperelastic Material 1
- Electrostatics *(es)*
  - Charge Conservation 1
  - Zero Charge 1
  - Initial Values 1
  - Charge Conservation, Piezoelectric 1

Linear isotropic or anisotropic material

Nonlinear material

Piezoelectric material

Nonlinear materials

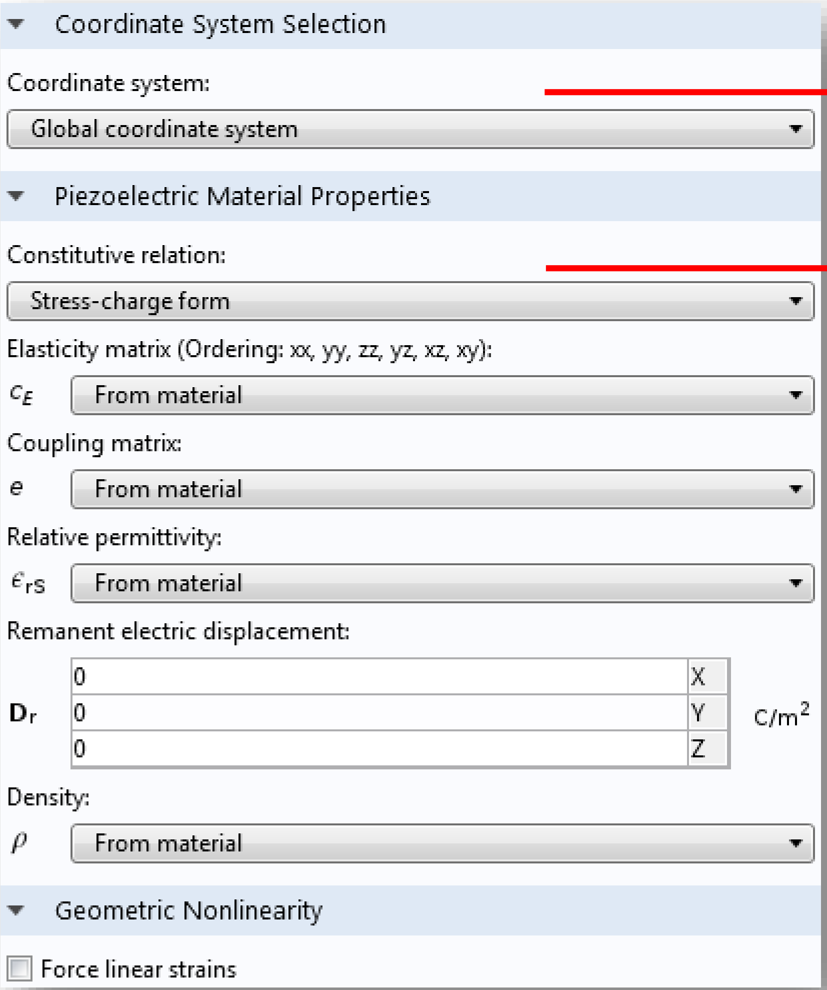
Dielectric material

Piezoelectric material

Different Material Models

- Different material models allow easy implementation of multi-layered and multi-material structures
- Important functionality for modeling sandwiched structures for transducers, resonators, BAW, SAW and similar acoustic devices and RF filters
- Different damping models can also be added

Details Of Piezoelectric Material



▾ Coordinate System Selection

Coordinate system:

Global coordinate system ▾

▾ Piezoelectric Material Properties

Constitutive relation:

Stress-charge form ▾

Elasticity matrix (Ordering: xx, yy, zz, yz, xz, xy):

c_E From material ▾

Coupling matrix:

e From material ▾

Relative permittivity:

ϵ_{rS} From material ▾

Remanent electric displacement:

$\mathbf{D}_r$	0	X	C/m^2
	0	Y	
	0	Z	

Density:

ρ From material ▾

▾ Geometric Nonlinearity

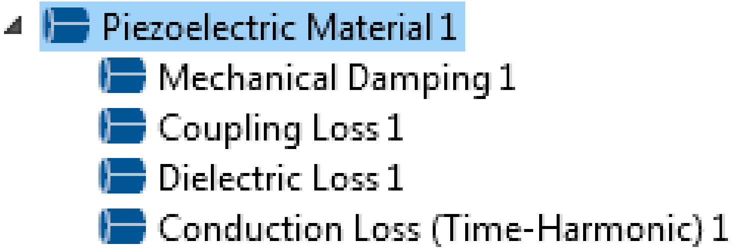
☐ Force linear strains

Use this to implement effect of poling direction and crystal orientation on material properties

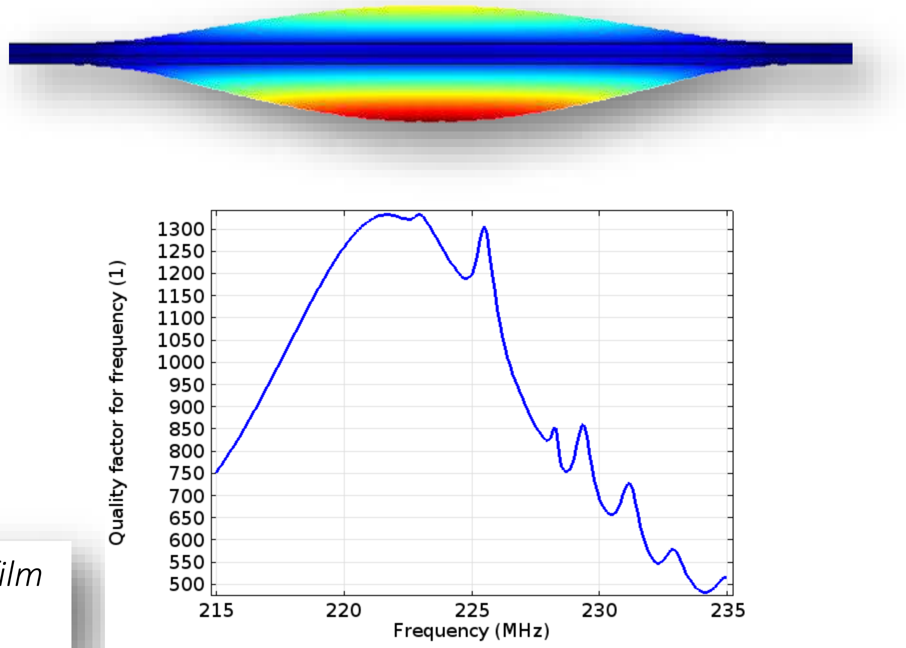
Use this to change the equation form based on the material properties available to you

This is useful to model any electrical bias or residual polarization in the piezoelectric material

Material Losses and Damping



- Piezoelectric Material 1
  - Mechanical Damping 1
  - Coupling Loss 1
  - Dielectric Loss 1
  - Conduction Loss (Time-Harmonic) 1



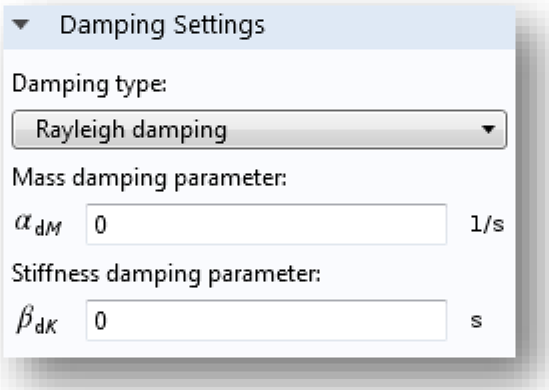
Displacement profile and Q factor of a thin-film Bulk Acoustic Wave composite resonator

http://www.comsol.com/model/thin-film-baw-composite-resonator-5784

Different Damping Models

- Mechanical Damping
  - Allows you to add purely structural damping
- Coupling Loss
  - Allows you to add electromechanical coupling loss
- Dielectric Loss
  - Allows you to add dielectric or polarization loss
- Conduction Loss (Time-Harmonic)
  - Allows you to add energy loss due to electrical resistance in a harmonically vibrating piezoelectric material

Mechanical Damping



Damping Settings

Damping type: Rayleigh damping

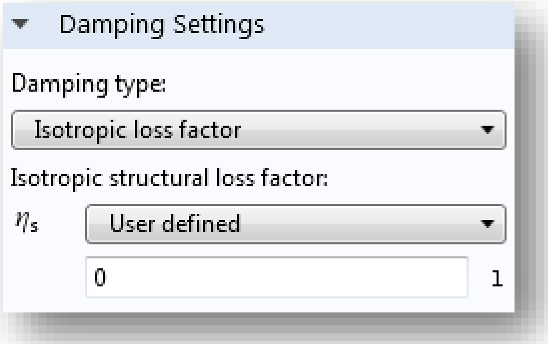
Mass damping parameter:

α_{dM} 0 1/s

Stiffness damping parameter:

β_{dK} 0 s

Rayleigh Damping
(Time domain and
Frequency Domain)



Damping Settings

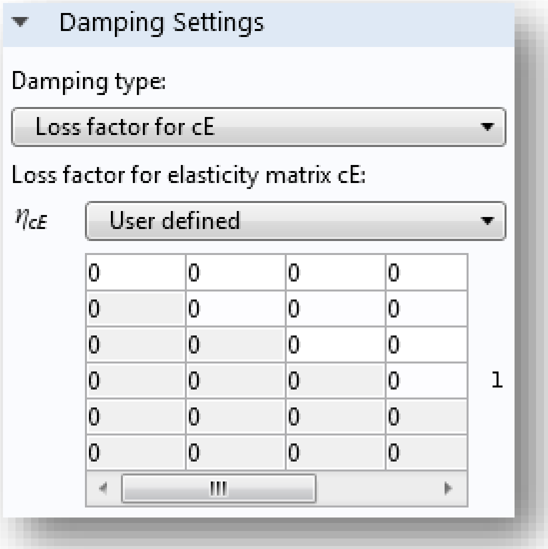
Damping type: Isotropic loss factor

Isotropic structural loss factor:

η_s User defined

0 1

Isotropic Loss Factor
(Frequency Domain only)



Damping Settings

Damping type: Loss factor for cE

Loss factor for elasticity matrix cE:

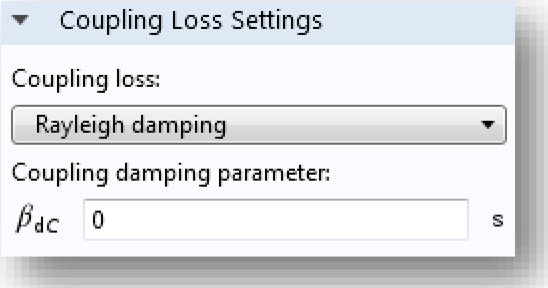
η_{cE} User defined

0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0

1

Anisotropic Loss Factor
(Frequency Domain only)

Coupling Loss

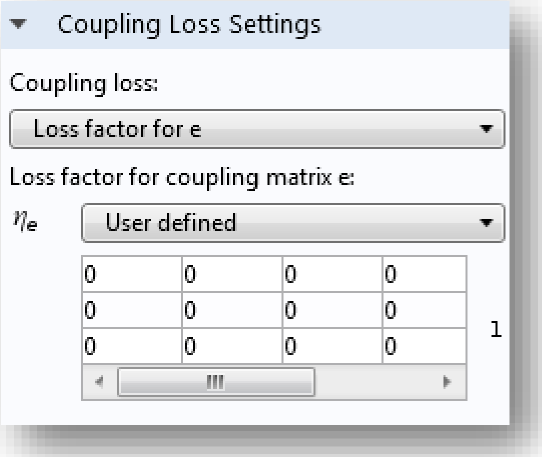


Coupling Loss Settings

Coupling loss: Rayleigh damping

Coupling damping parameter:

β_{dc} 0 s



Coupling Loss Settings

Coupling loss: Loss factor for e

Loss factor for coupling matrix e:

η_e User defined

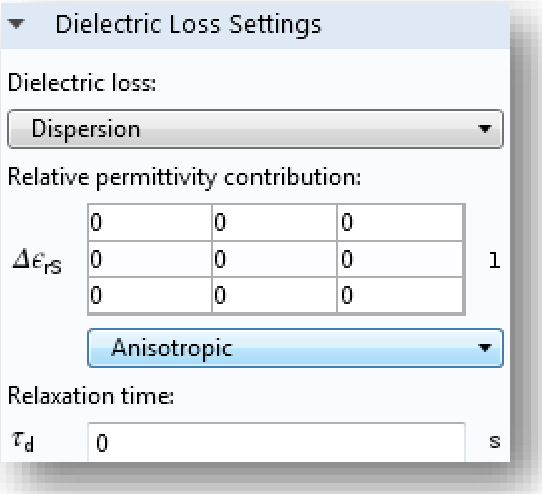
0	0	0	0
0	0	0	0
0	0	0	0

1

Rayleigh Damping
(Time domain and
Frequency Domain)

Anisotropic Loss Factor
(Frequency Domain only)

Dielectric Loss



Dielectric Loss Settings

Dielectric loss:

Dispersion

Relative permittivity contribution:

$\Delta\epsilon_{rS}$

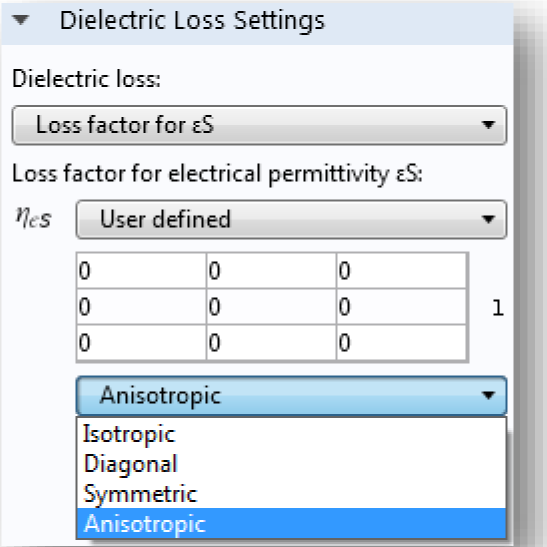
0	0	0	
0	0	0	1
0	0	0	

Anisotropic

Relaxation time:

τ_d 0 s

Dispersion
(Time domain and
Frequency Domain)



Dielectric Loss Settings

Dielectric loss:

Loss factor for εS

Loss factor for electrical permittivity εS:

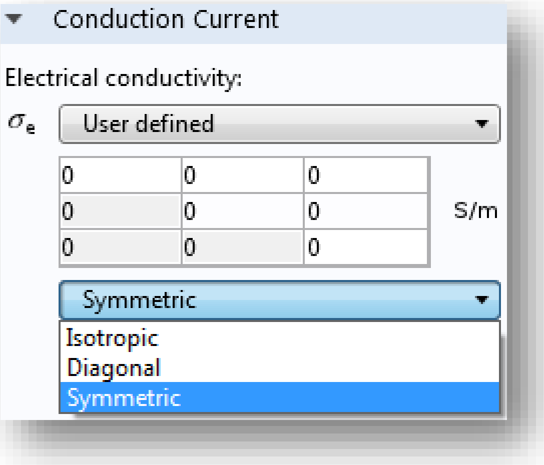
$\eta_{\varepsilon S}$ User defined

0	0	0	
0	0	0	1
0	0	0	

Anisotropic

Anisotropic Loss Factor
(Frequency Domain only)

Conduction Loss (Frequency Domain)



Conduction Current

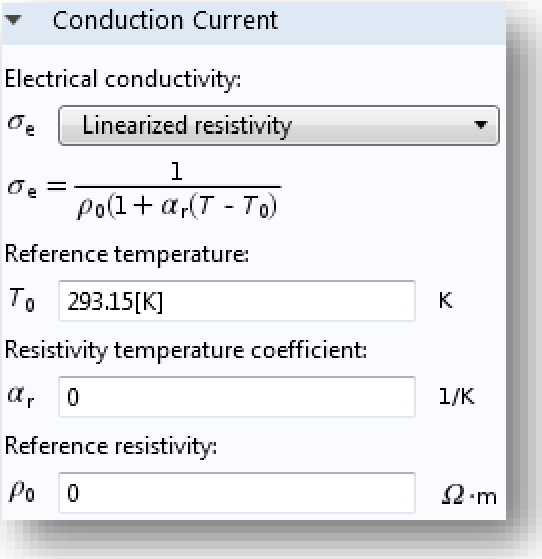
Electrical conductivity:

σ_e User defined

0	0	0	
0	0	0	S/m
0	0	0	

Symmetric

Electrical Conductivity



Conduction Current

Electrical conductivity:

σ_e Linearized resistivity

$$\sigma_e = \frac{1}{\rho_0(1 + \alpha_r(T - T_0))}$$

Reference temperature:

T_0 293.15[K] K

Resistivity temperature coefficient:

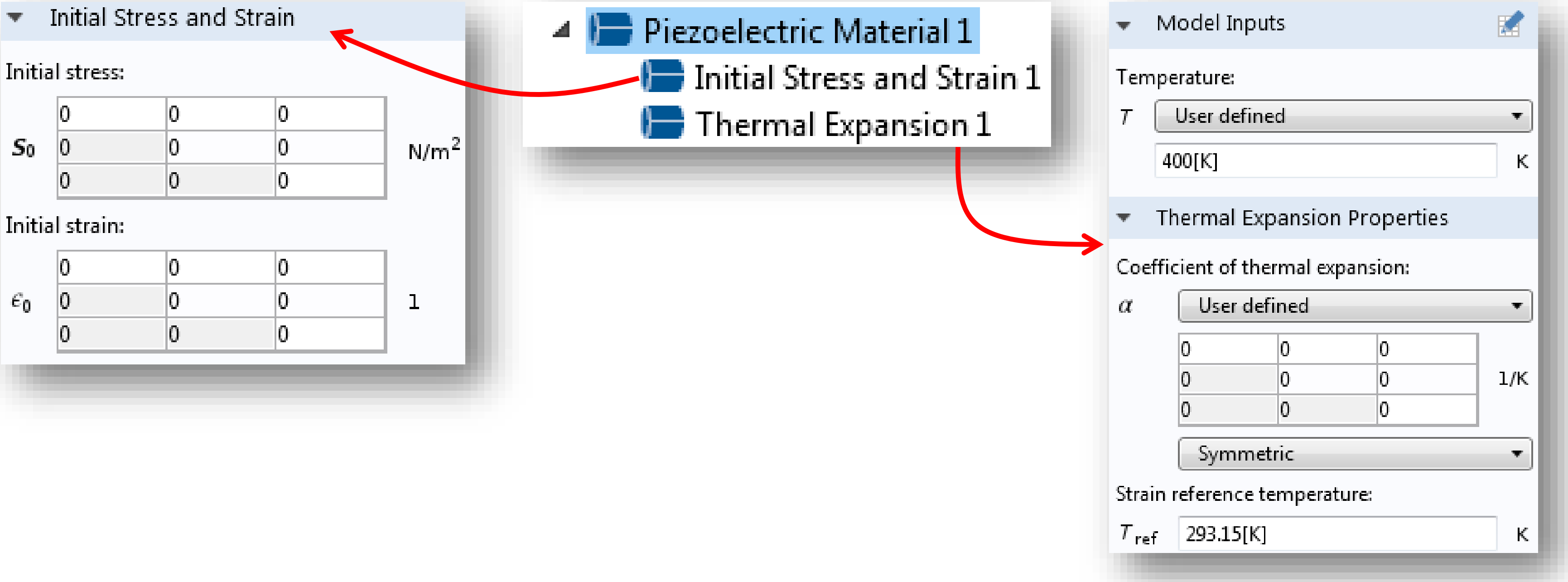
α_r 0 1/K

Reference resistivity:

ρ_0 0 $\Omega \cdot$m

Linearized Resistivity

Additional Sources of Stress and Strain



Initial Stress and Strain

Initial stress:

S_0

0	0	0
0	0	0
0	0	0

N/m^2

Initial strain:

ϵ_0

0	0	0
0	0	0
0	0	0

1

Model Inputs

Temperature:

T User defined

400[K] K

Thermal Expansion Properties

Coefficient of thermal expansion:

α User defined

0	0	0
0	0	0
0	0	0

1/K

Symmetric

Strain reference temperature:

T_{ref} 293.15[K] K

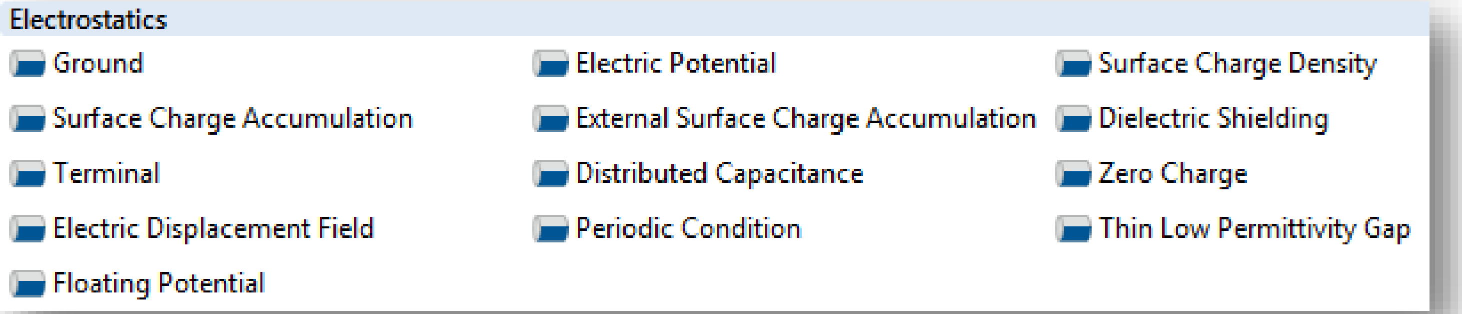
Initial Stress and Strain

Useful for adding pre-stress, pre-strain and any inelastic strain

Thermal Expansion

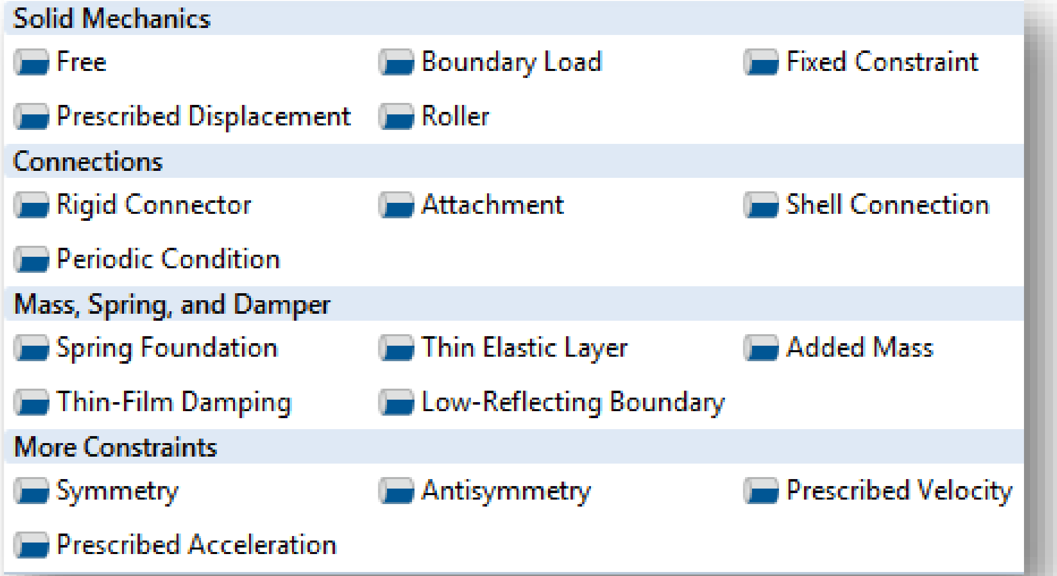
Useful for adding stress or strain due to temperature difference

Electrical and Structural Boundary Conditions



Electrostatics

- Ground
- Surface Charge Accumulation
- Terminal
- Electric Displacement Field
- Floating Potential
- Electric Potential
- External Surface Charge Accumulation
- Distributed Capacitance
- Periodic Condition
- Surface Charge Density
- Dielectric Shielding
- Zero Charge
- Thin Low Permittivity Gap



Solid Mechanics

- Free
- Prescribed Displacement
- Boundary Load
- Roller
- Fixed Constraint

Connections

- Rigid Connector
- Periodic Condition
- Attachment
- Shell Connection

Mass, Spring, and Damper

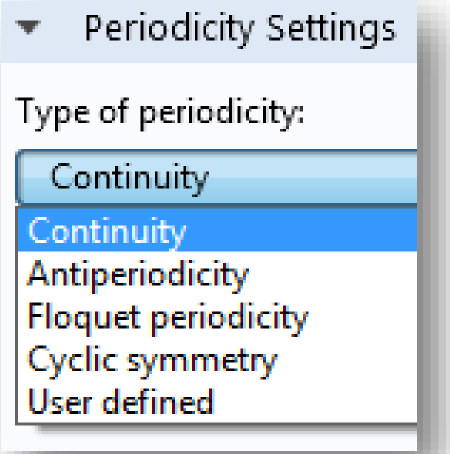
- Spring Foundation
- Thin-Film Damping
- Thin Elastic Layer
- Low-Reflecting Boundary
- Added Mass

More Constraints

- Symmetry
- Prescribed Acceleration
- Antisymmetry
- Prescribed Velocity

Periodic Boundary Conditions

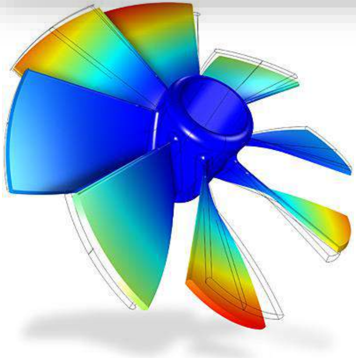
- Model only a periodic segment
- Computationally efficient
- Can also be used in frequency domain and eigenfrequency studies to capture asymmetric modes
- Use advanced postprocessing to visualize solution in full geometry



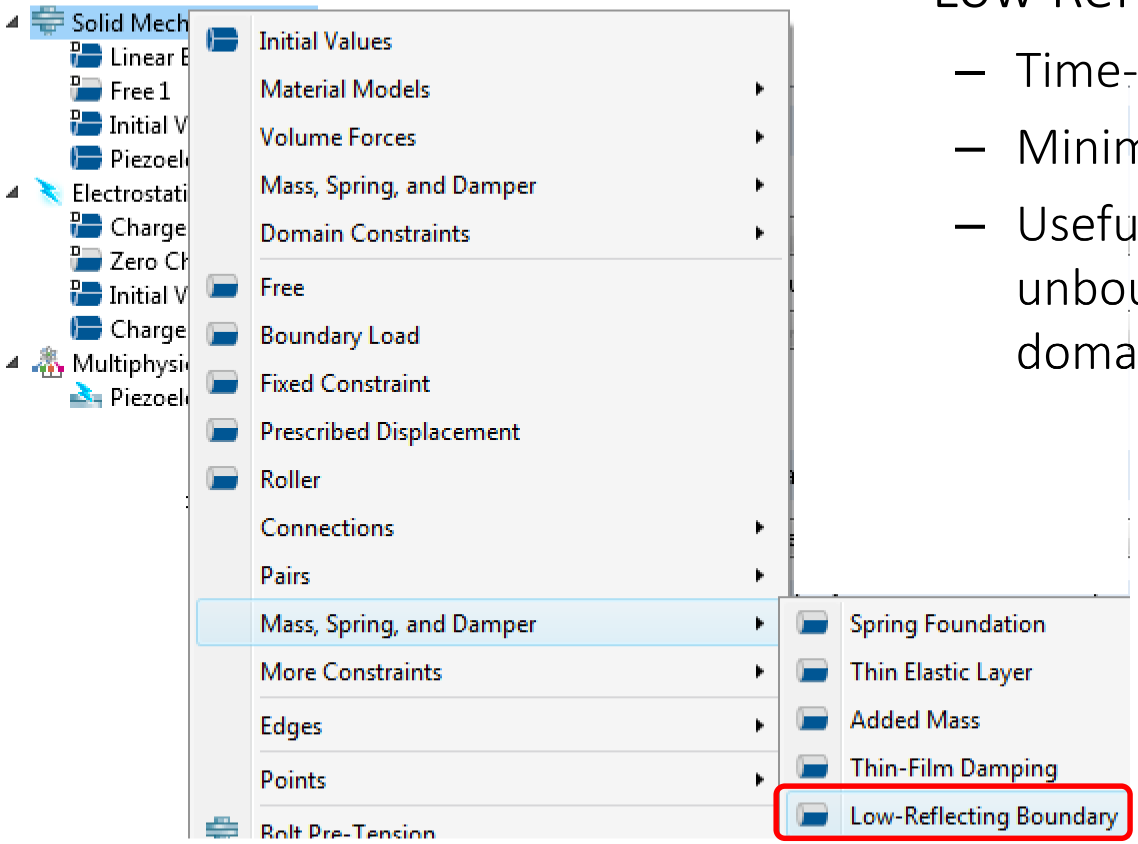
Periodicity Settings

Type of periodicity:

Continuity



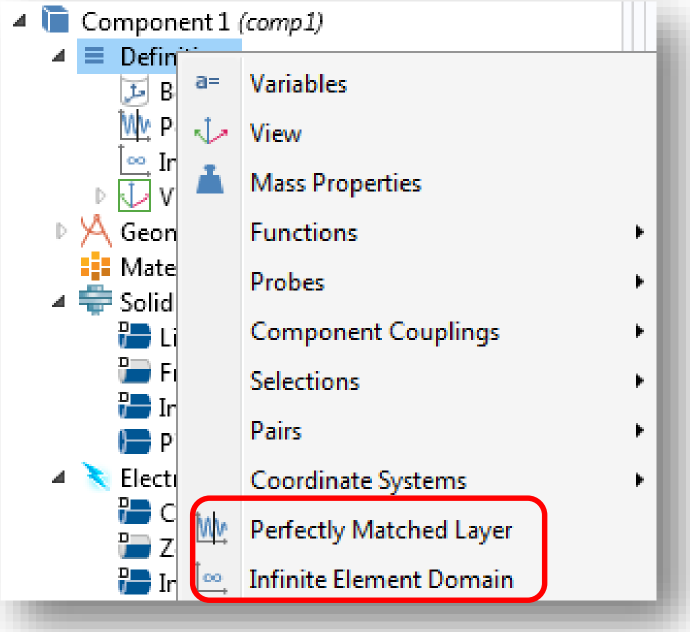
Low Reflecting Boundary



- Low Reflecting Boundary
  - Time-dependent analysis
  - Minimize reflection of waves
  - Useful for modeling large unbounded space in time domain

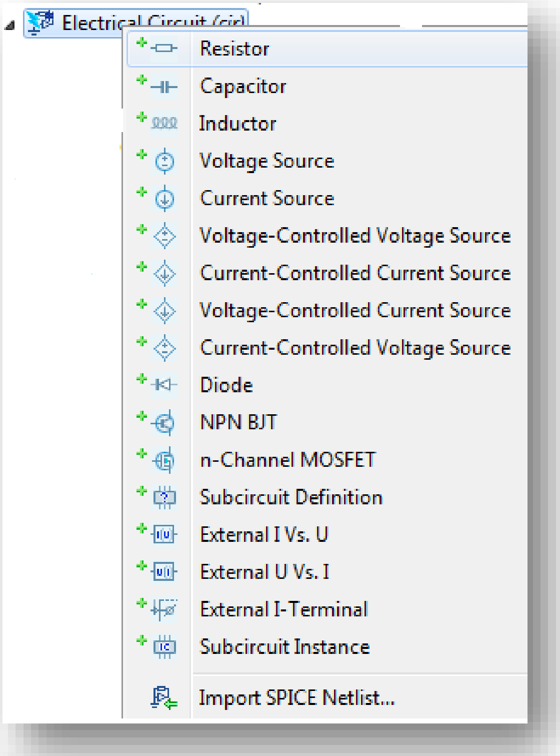
Modeling Large Regions

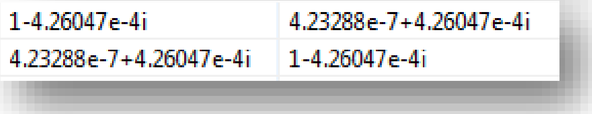
- Infinite Element Domain
  - Static analysis
  - Solution incorporates the effect of an infinitely extended region
- Perfectly Matched Layer
  - Frequency domain and eigenfrequency analysis
  - Absorbs elastic and acoustic waves



Special Electrical Features

- Terminal
  - Advanced boundary condition
  - Obtain impedance (Z), admittance (Y) and S-parameters
- Terminal Sweep
  - Feature for obtaining lumped parameter matrix in a multi-terminal system
- Electrical Circuit
  - Interface to create a lumped electrical circuit model that can be connected to the FEA model
  - Circuit can be created using features in COMSOL or by importing a SPICE netlist
- * These features require the *MEMS Module*





1-4.26047e-4i	4.23288e-7+4.26047e-4i
4.23288e-7+4.26047e-4i	1-4.26047e-4i

S-parameter matrix

More Information

- COMSOL Documentation
  - COMSOL Multiphysics Reference Manual
  - Structural Mechanics Module User’s Guide
  - MEMS Module User’s Guide
  - Acoustics Module User’s Guide
- Tutorials: http://www.comsol.com/models
- Blogs: http://www.comsol.com/blogs/
- Videos: http://www.comsol.com/video/
- Webinars: http://www.comsol.com/events/webinars