Murata Software

Femtet Seminar

Understanding

Piezoelectric Analysis
&
Acoustic Analysis

202009

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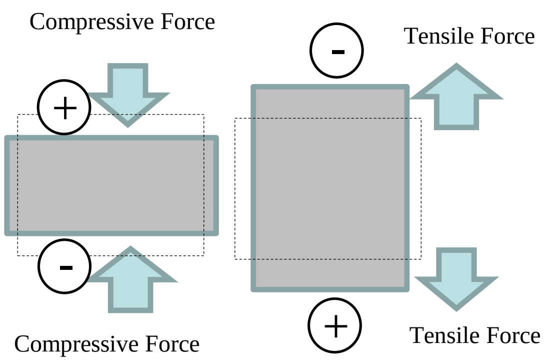
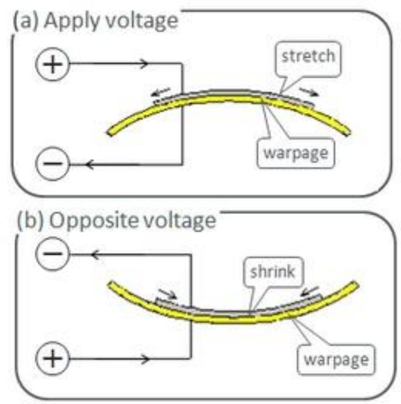
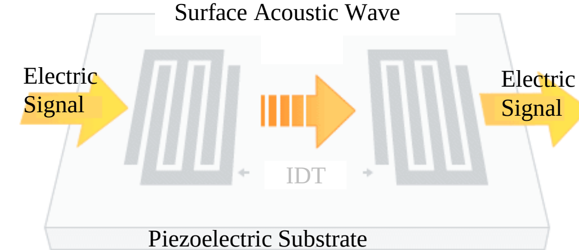
Case Studies



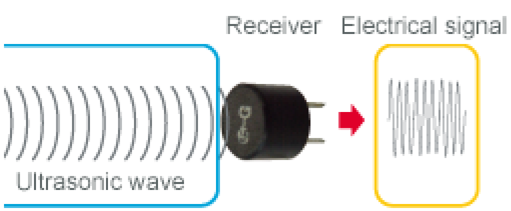




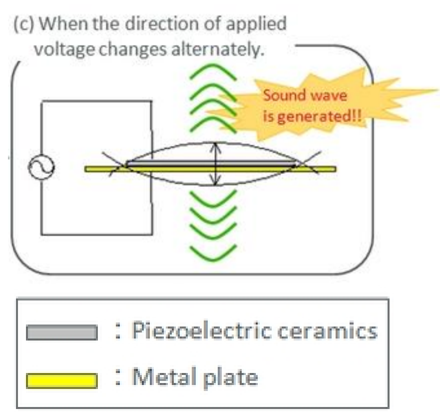
Force⇒Electricity

Electricity⇒Force

Electricity⇒Force⇒Electricity



Ultrasonic Sensor
Acceleration Sensor
Piezoelectric Gyro
Shock Sensor



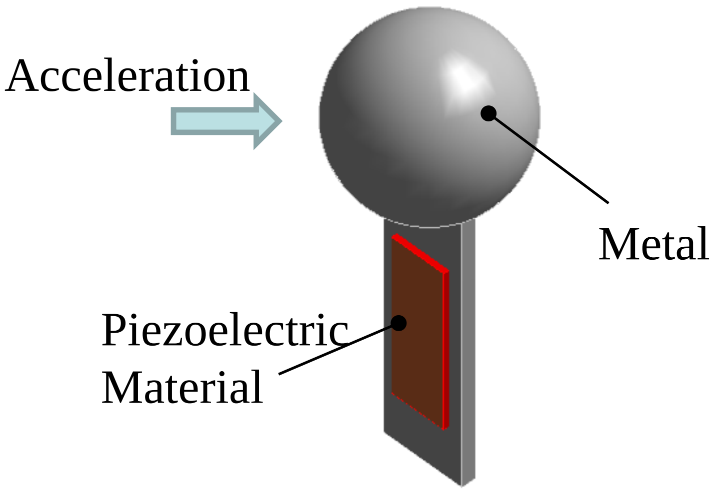
Piezoelectric Buzzer
Ultrasonic Motor
Actuator

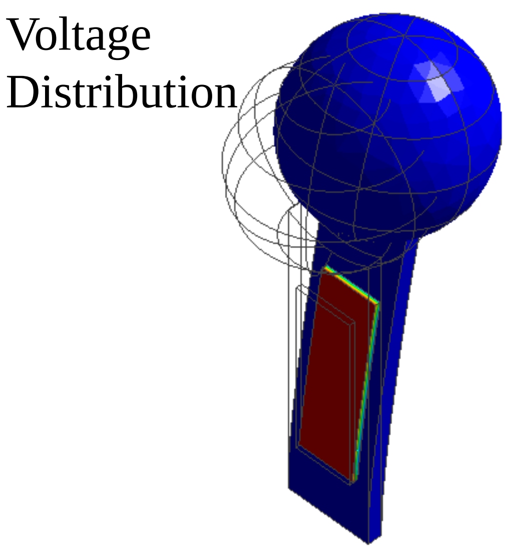
Crystal

SAW Filter
Crystal Oscillator

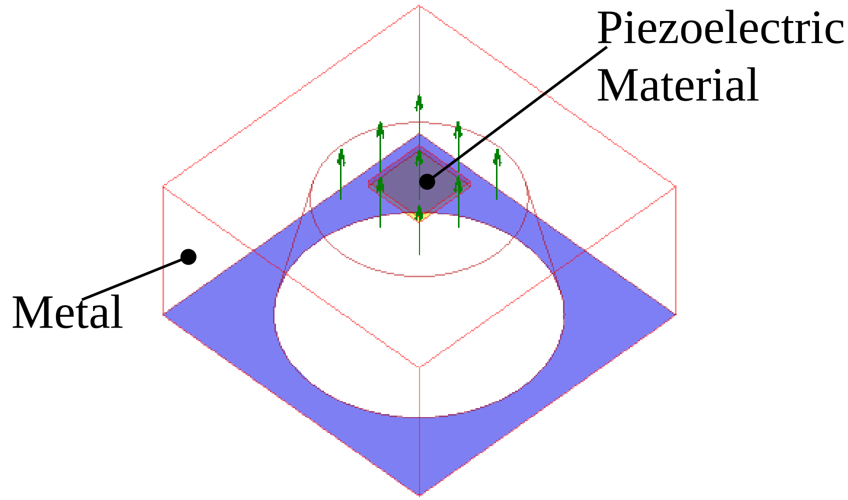
Force to Electricity

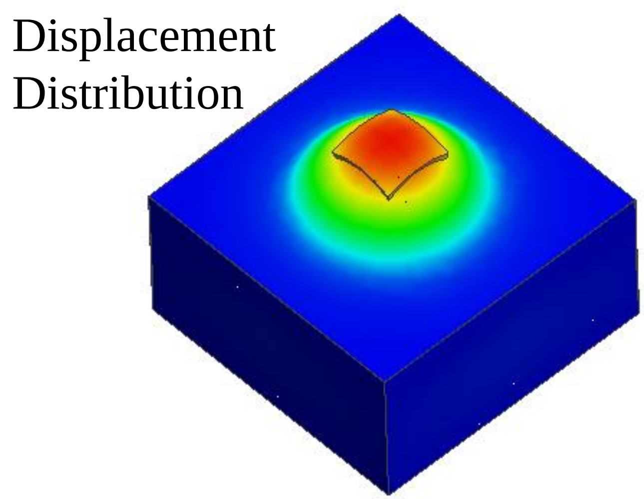
Acceleration Sensor





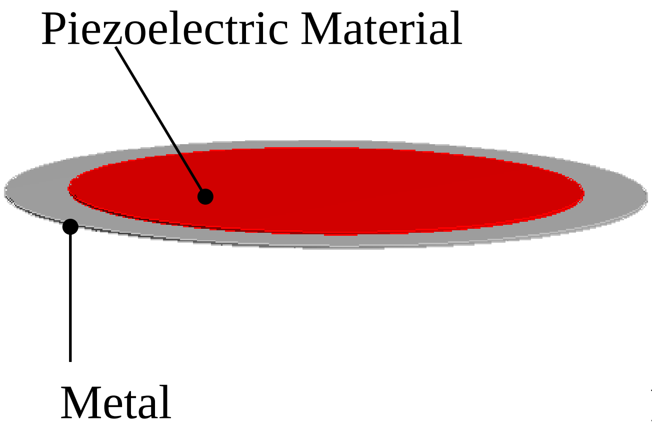
Pressure Sensor

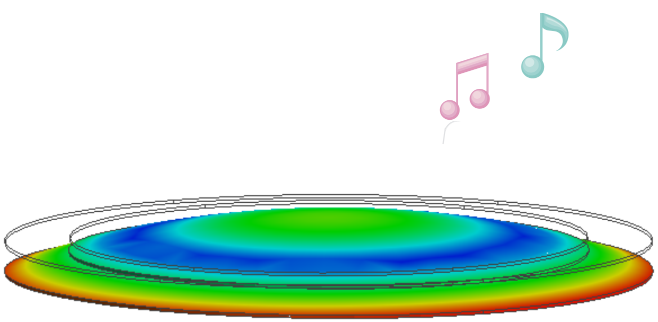




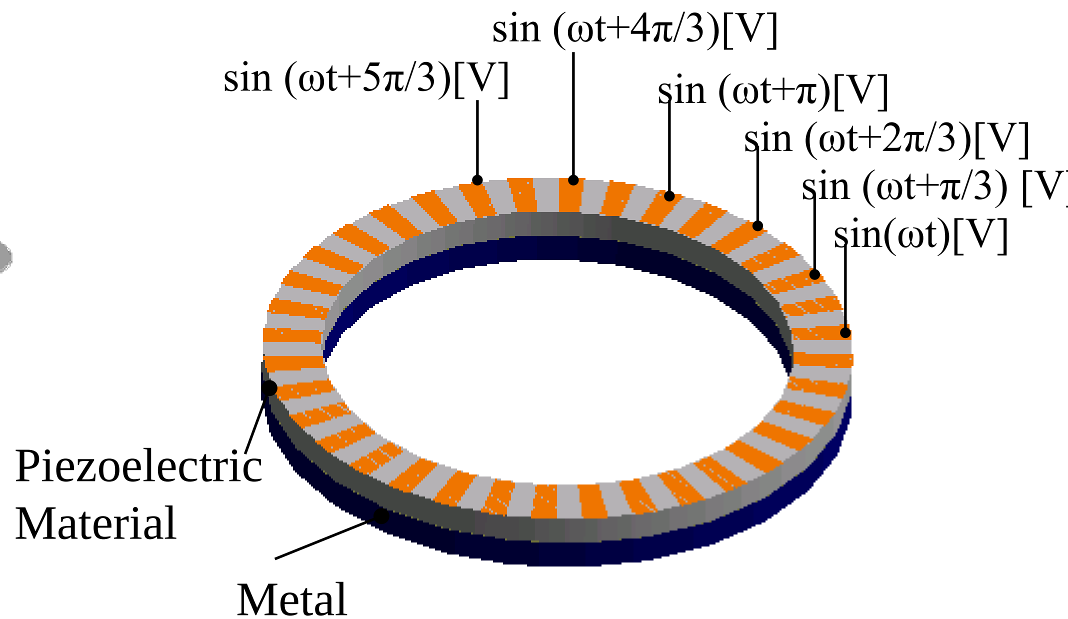
Electricity to Force

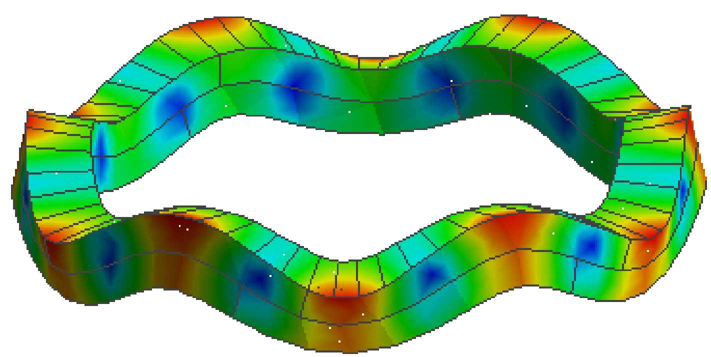
Buzzer





Ultrasonic Motor





Electricity to Force to Electricity

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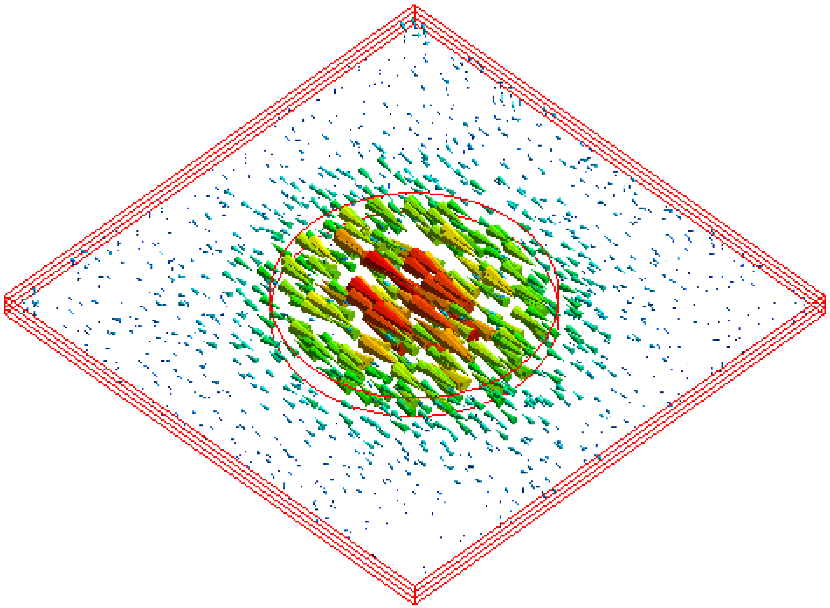
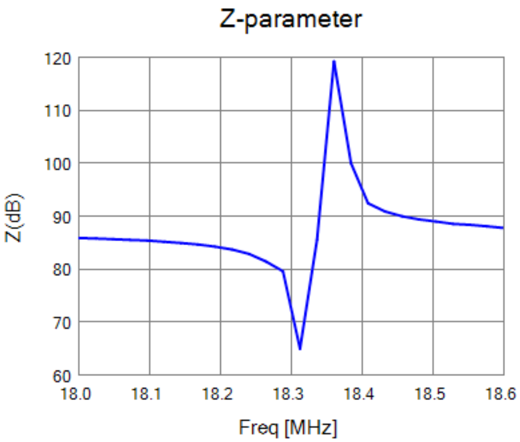
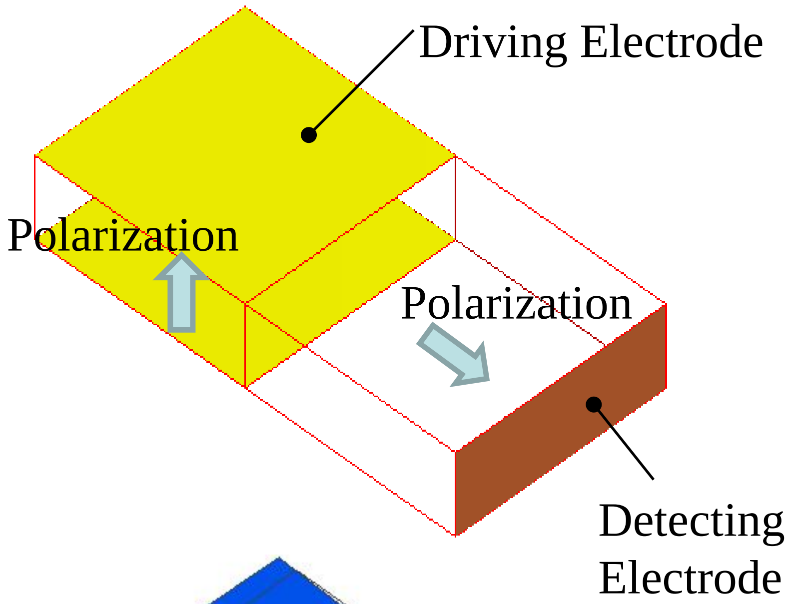
Crystal Oscillator

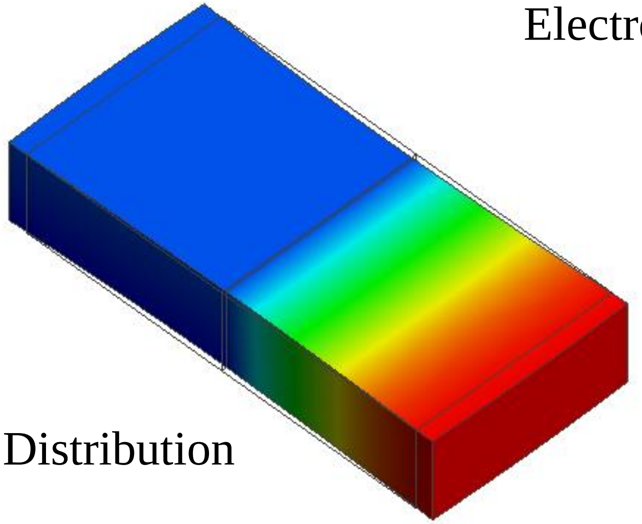


Impedance Characteristics



Piezoelectric Transformer



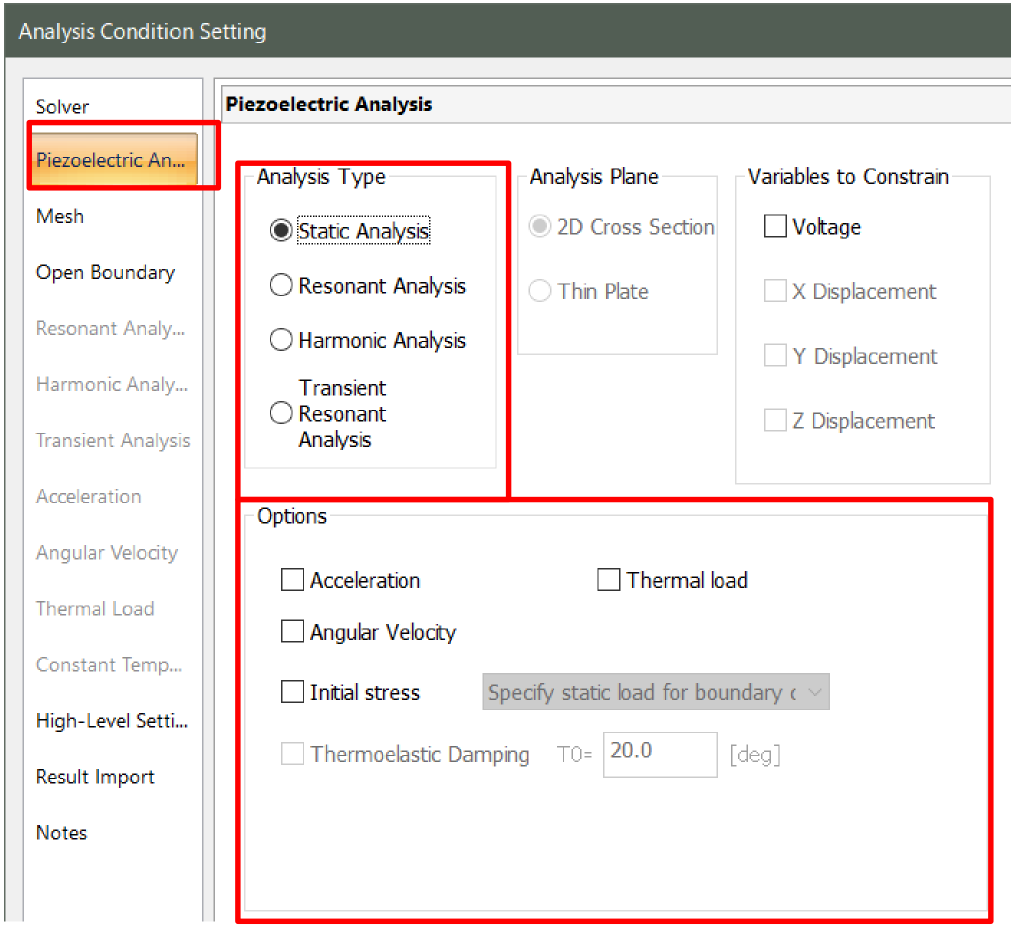


Voltage Distribution

2.Functions of Piezoelectric Analysis

(1) Analysis Condition
(2) Boundary Condition
(3) Material Property
(4) Body Attribute
(5) Results Display

(1) Analysis Condition



Analysis Type

- Static
- Harmonic
- Resonant
- Transient

Options

- Acceleration
- Thermal Load
- Angular Velocity
- Initial Stress Taken into Account

Analysis Plane

Used for 2D analysis

Variables to Constrain

Select [Voltage] to couple with acoustic analysis without taking piezoelectricity into account

Harmonic Analysis

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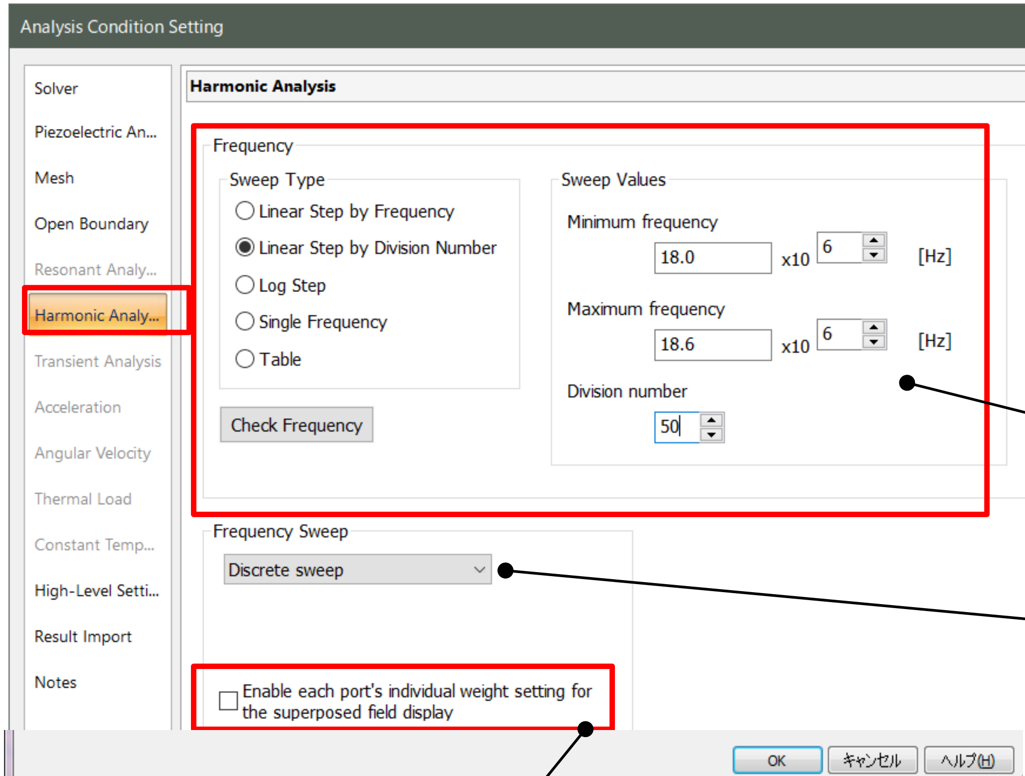
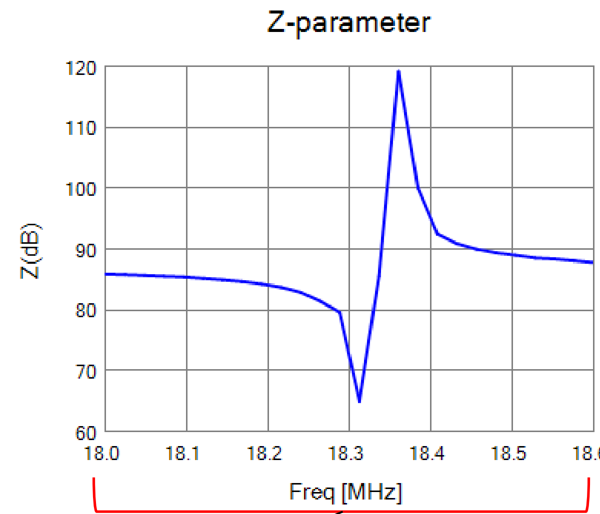




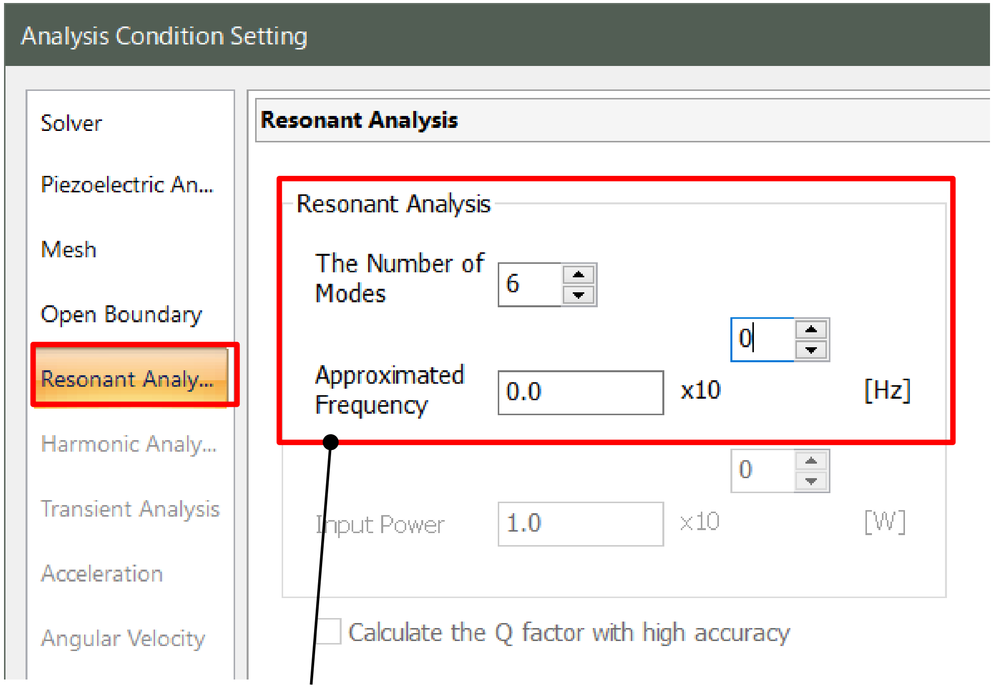
Frequency setting for calculation

[Discrete Sweep] is recommended.
[Fast Sweep] is selectable but the convergence will be deteriorated in the piezoelectric analysis.
If your PC has enough memory,
[Parallel Discrete Sweep] can be used.*

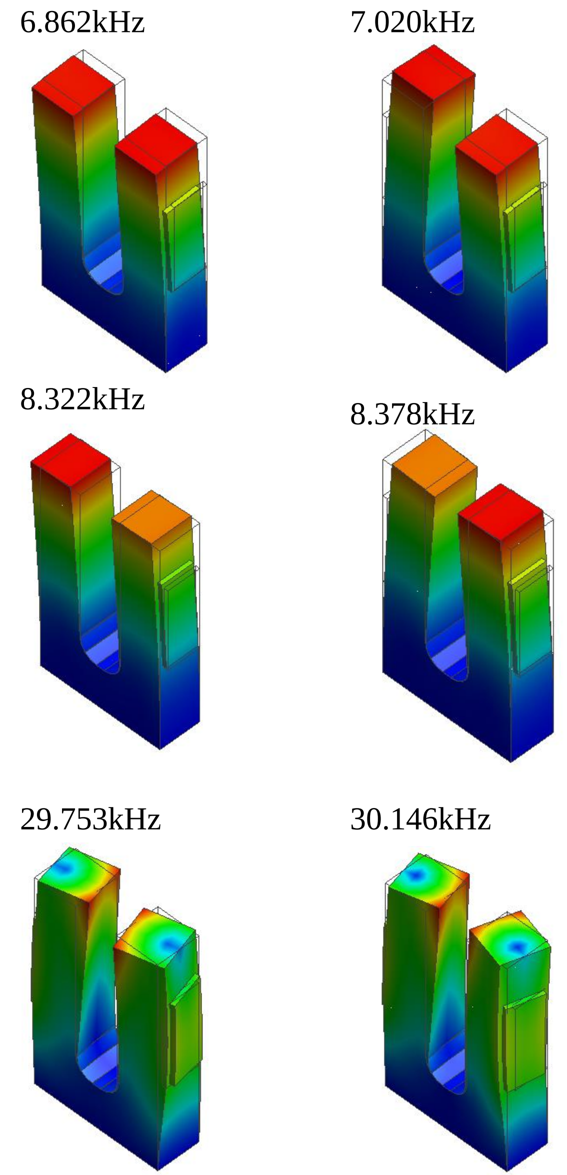
If selected, the phase of the electrode can be changed after calculation.

* Option for Accelerator is required.

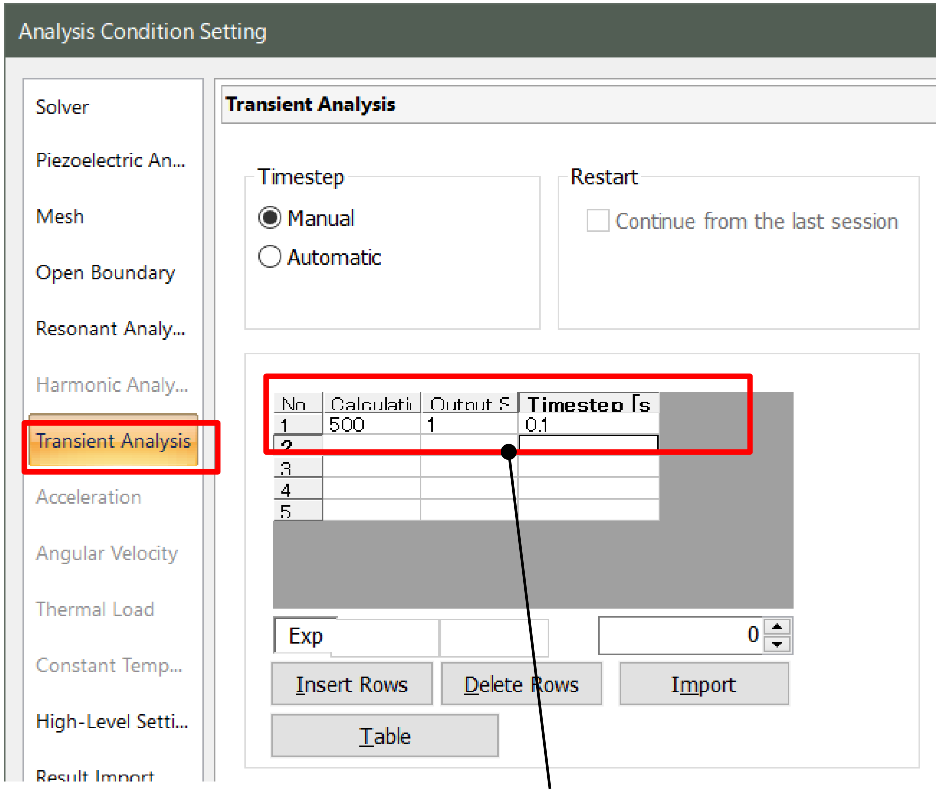
Resonant Analysis



[The Number of Modes]: Calculations done by this number
[Approximated Frequency]: Calculates frequencies near to this value



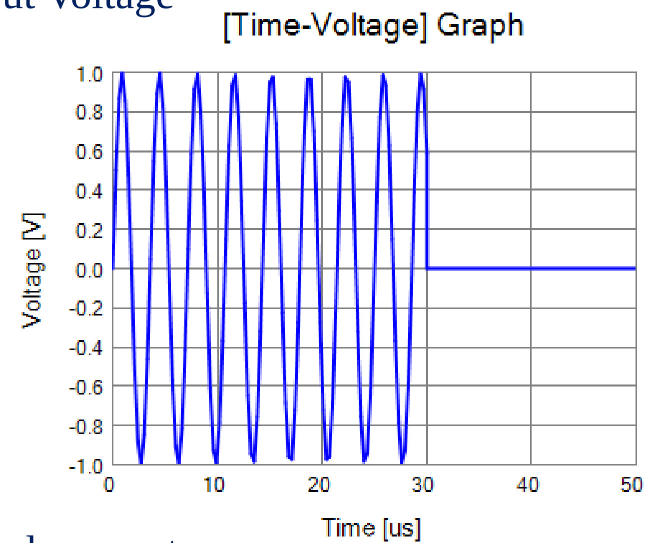
Transient Analysis



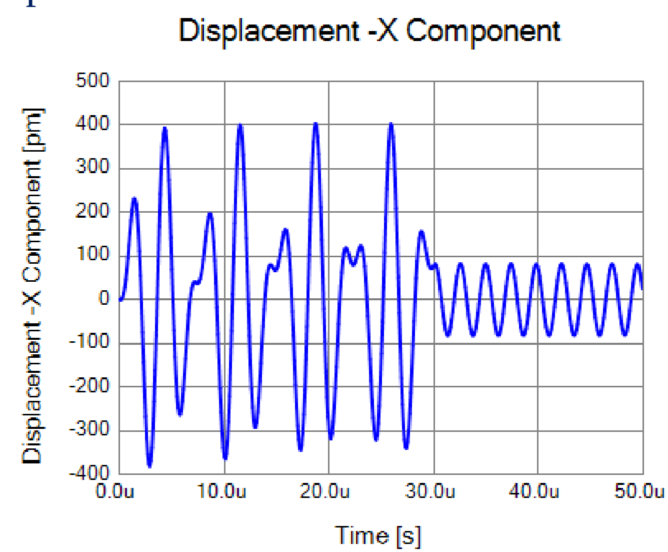
About 1/10 of the reciprocal of the resonant frequency

The modes obtained in the resonant analysis are used.
[Inverse Fourier transform] is applied.

Input Voltage

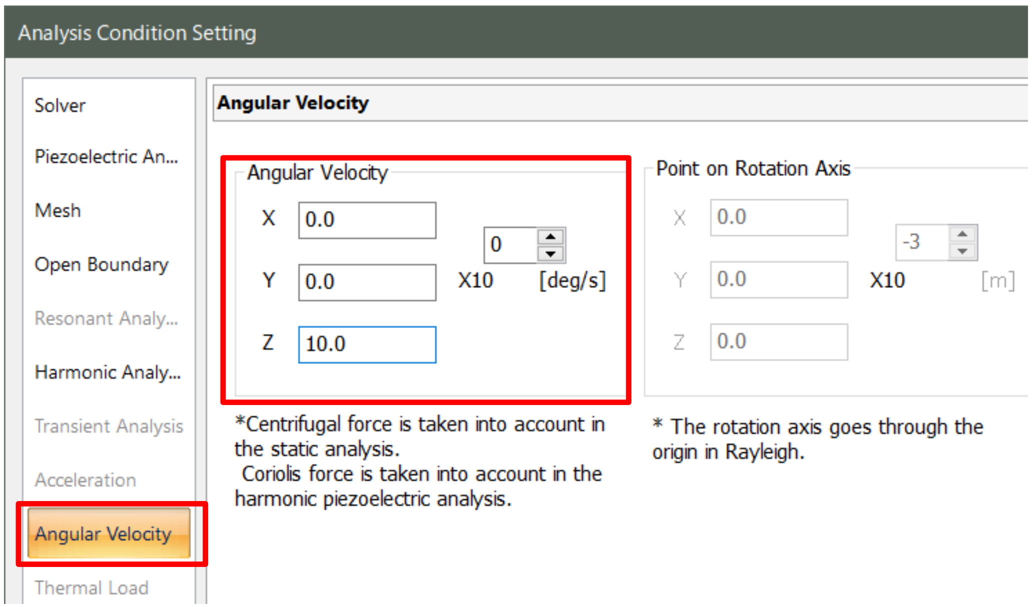


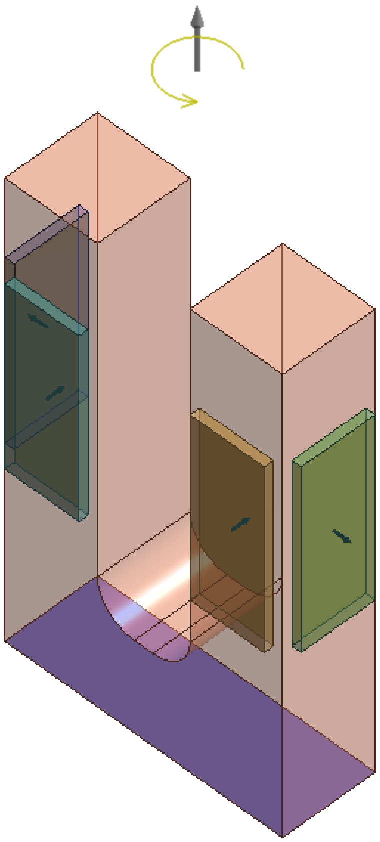
Displacement



Angular Velocity

By specifying the angular velocity, Coriolis force can be taken into account.





Analysis with Initial Stress Taken into Account

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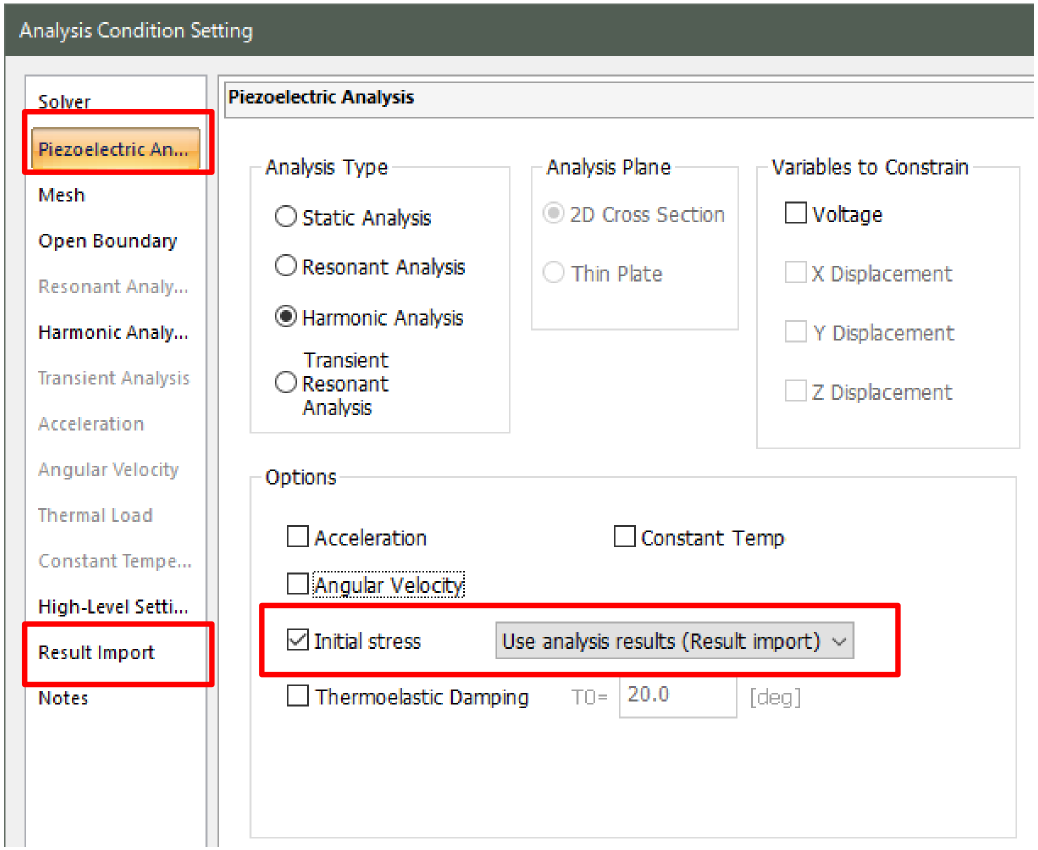

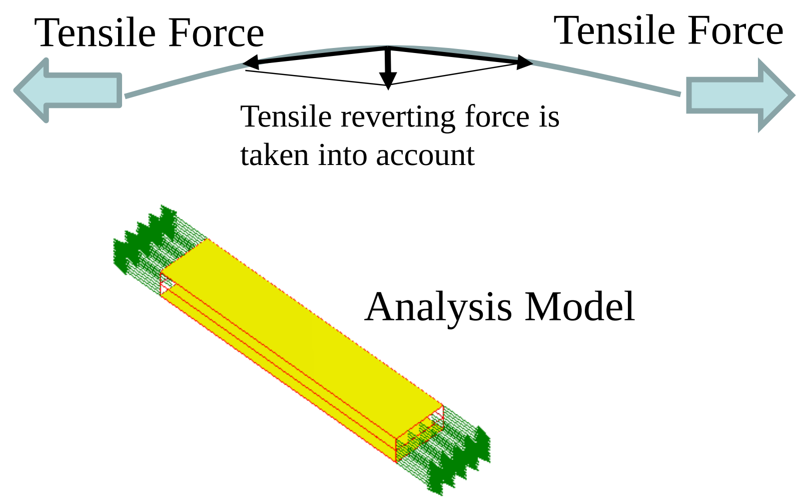

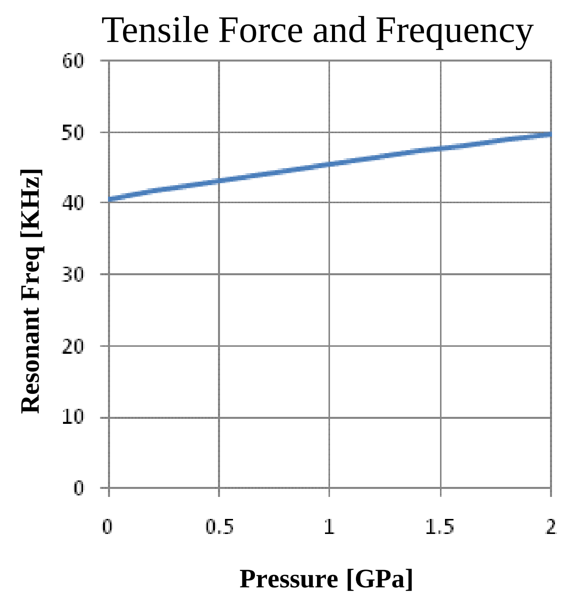

At first, static analysis is executed.
Its results are imported by [Result Import].
Harmonic and resonant analysis are executed.

(2) Boundary Condition

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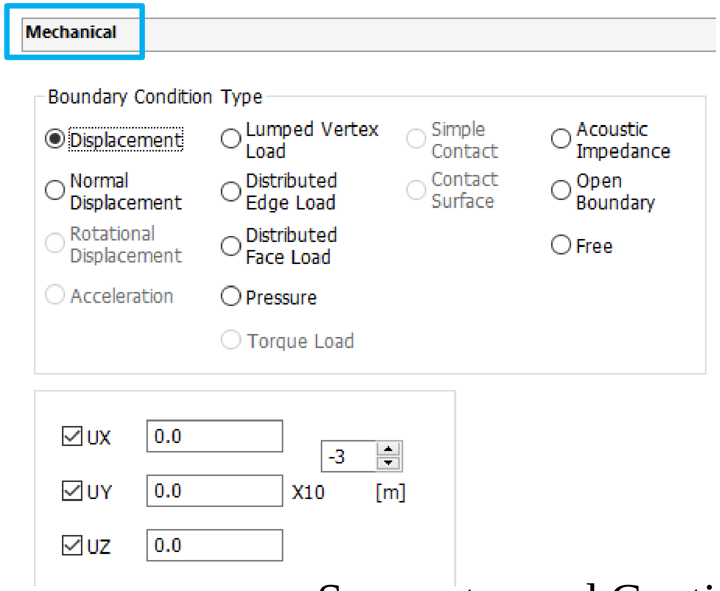
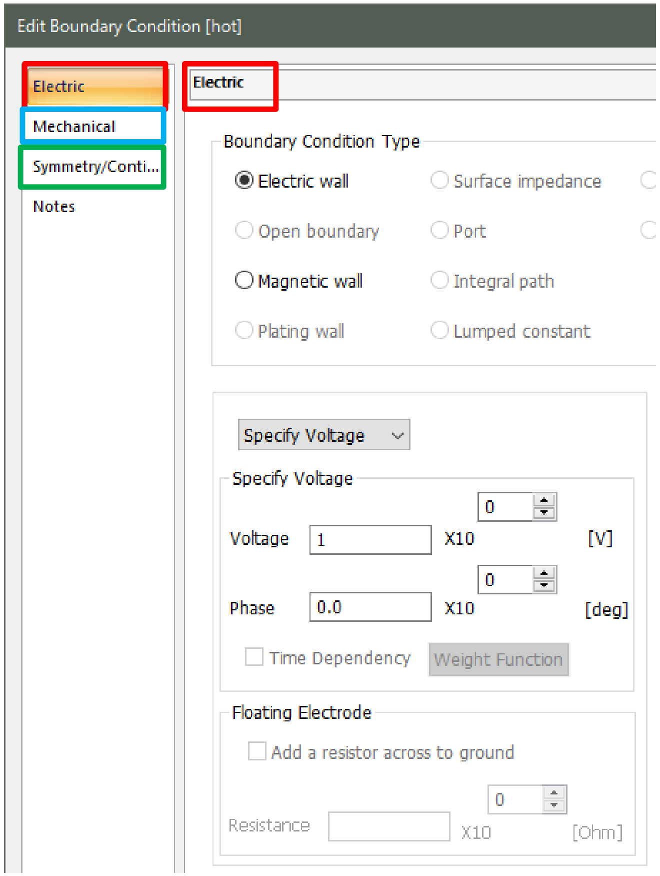
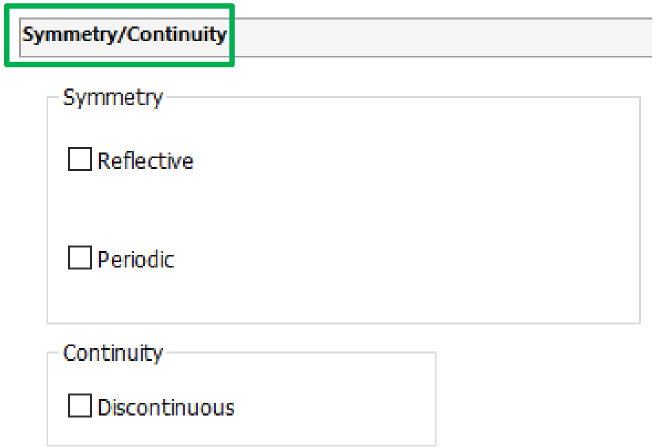
Mechanical



Electric



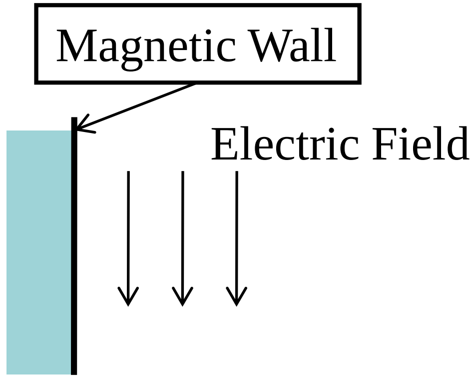
Symmetry and Continuity



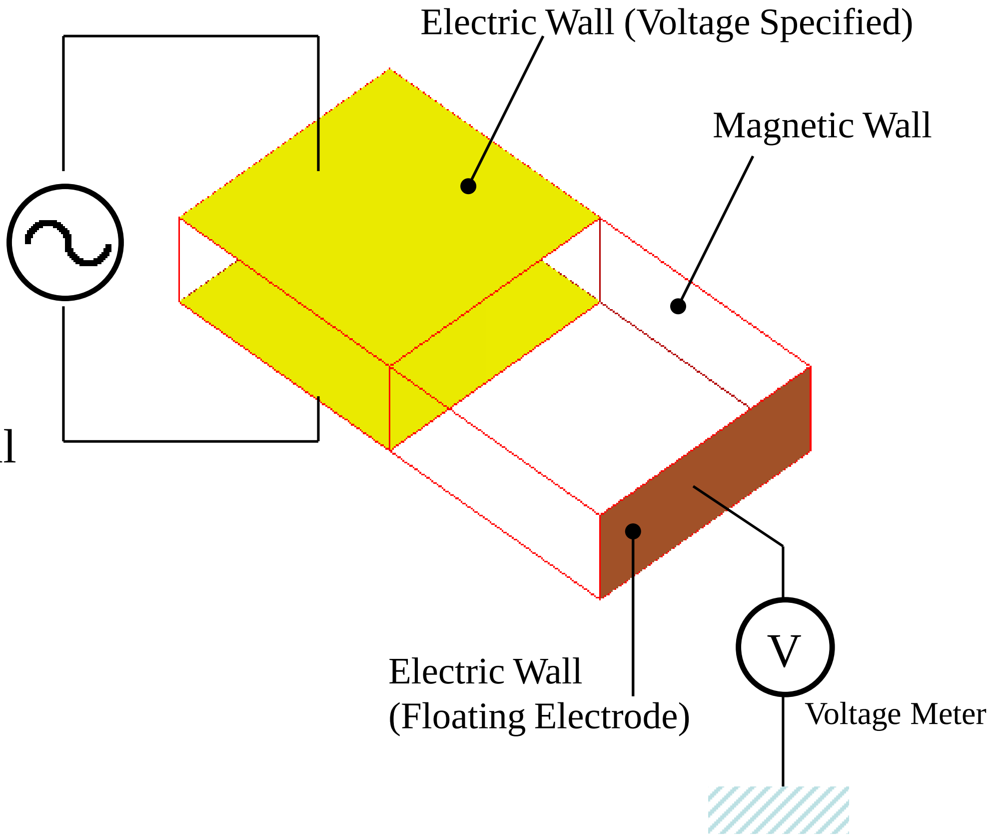
Electric Boundary Condition

Magnetic Wall

Electric field is parallel to the wall

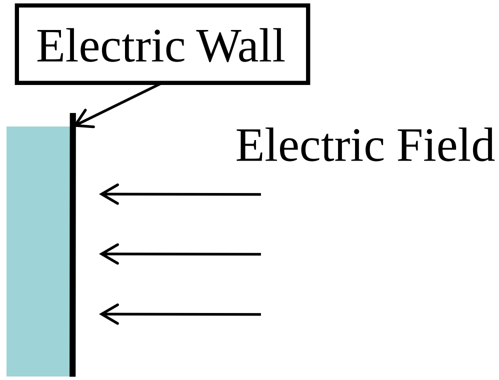


Example: Piezoelectric Transformer



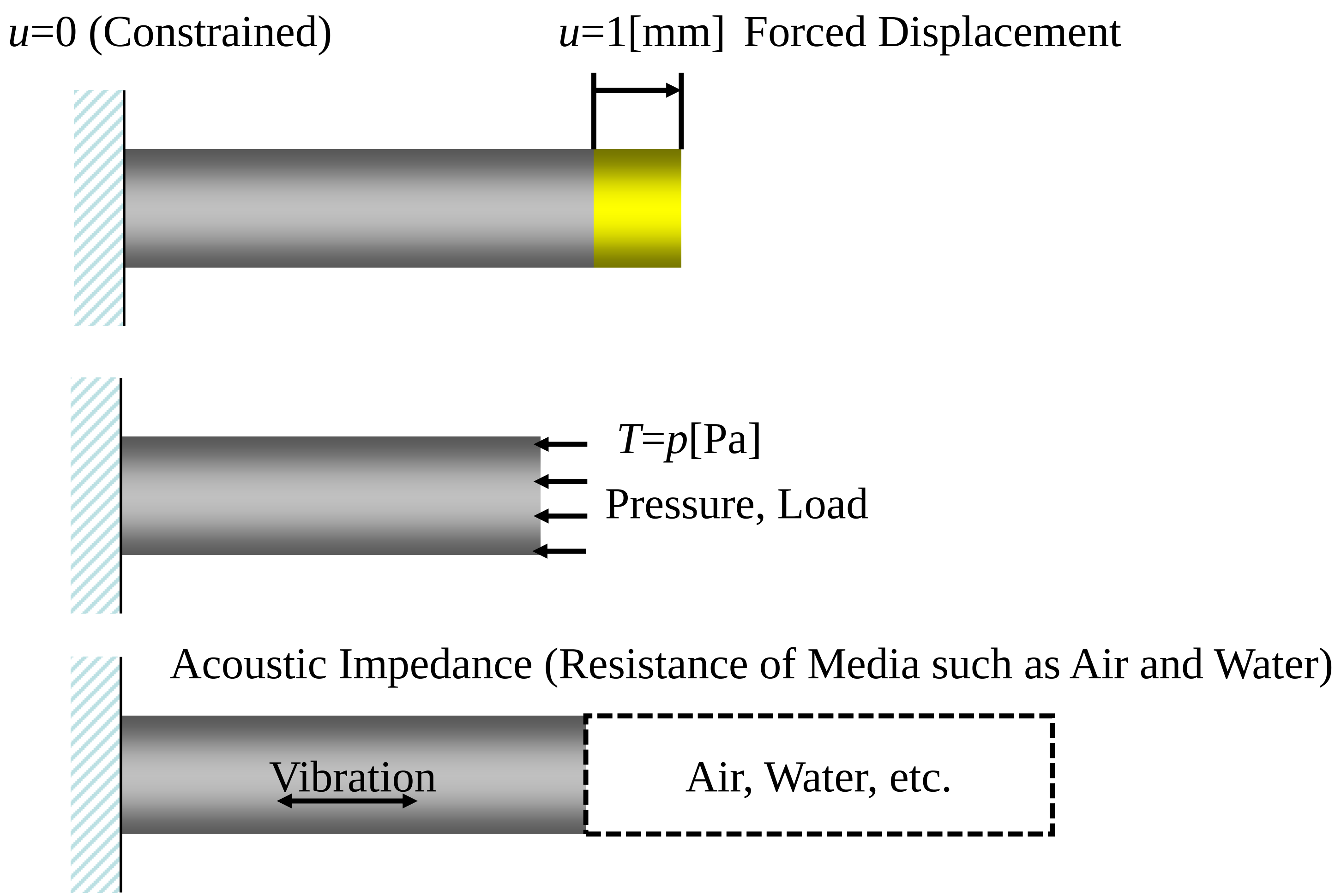
Electric Wall

Electric field is perpendicular to the wall



Mechanical Boundary Condition

Murata Software

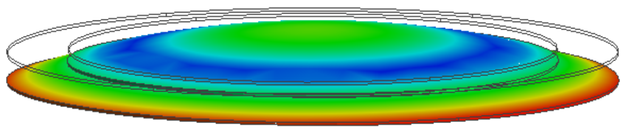


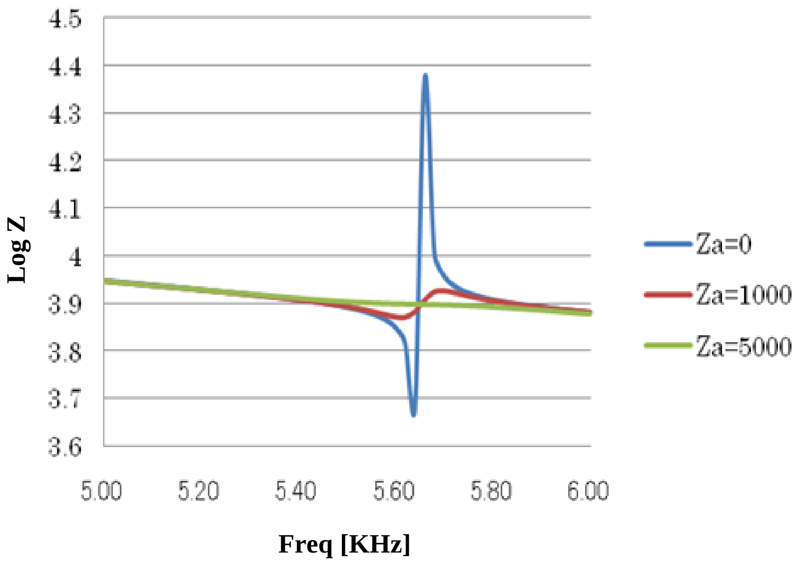
Example: Acoustic Impedance

Acoustic impedance represents the resistance of media such as air or water.
By applying the acoustic impedance as a boundary condition to the face that is in contact with the media, the resistance of air or water can be taken into account.

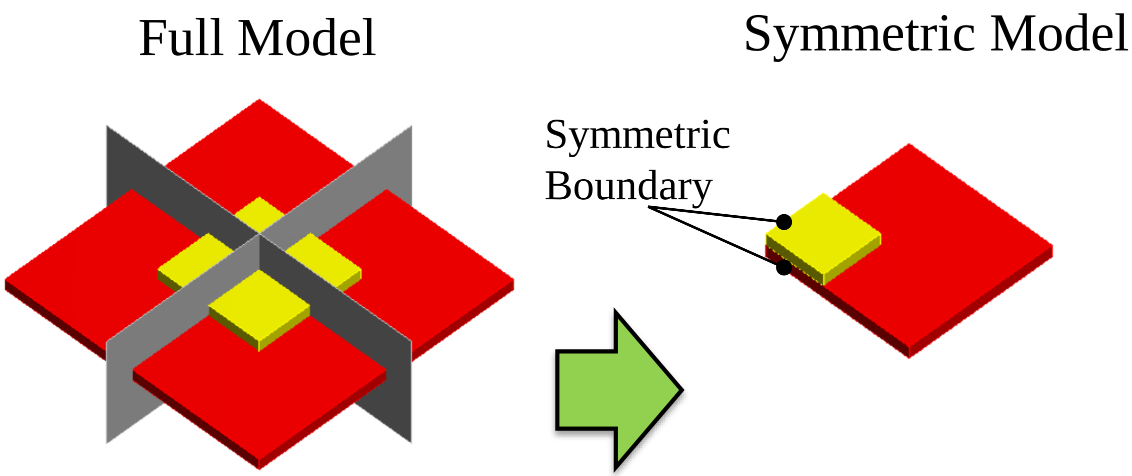
In the harmonic analysis, acoustic impedance is expressed by Z=ρc where ρ is density, c is sound speed of medium.

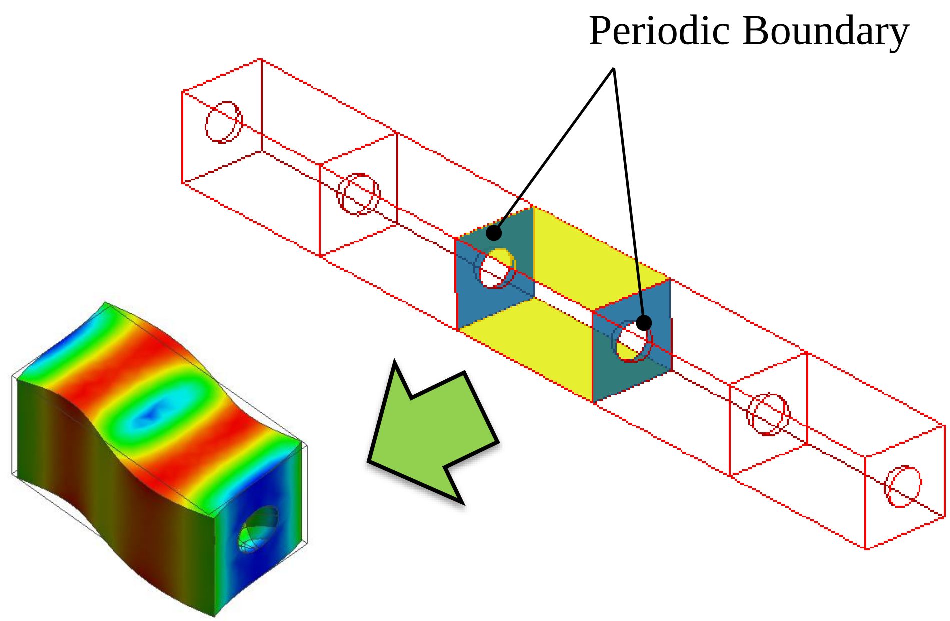
[Examples]
Air: Z = 1.205[kg/m3]*340[m/s]=409.7[kg/(m2･s)]=409.7 [N･s/m3]
Water: Z = 997[kg/m3]*1500[m/s]=1.496e6[kg/(m2･s)]=1.4596e6[N･s/m3]





Symmetric/Periodic Boundary Condition





(3) Material Property

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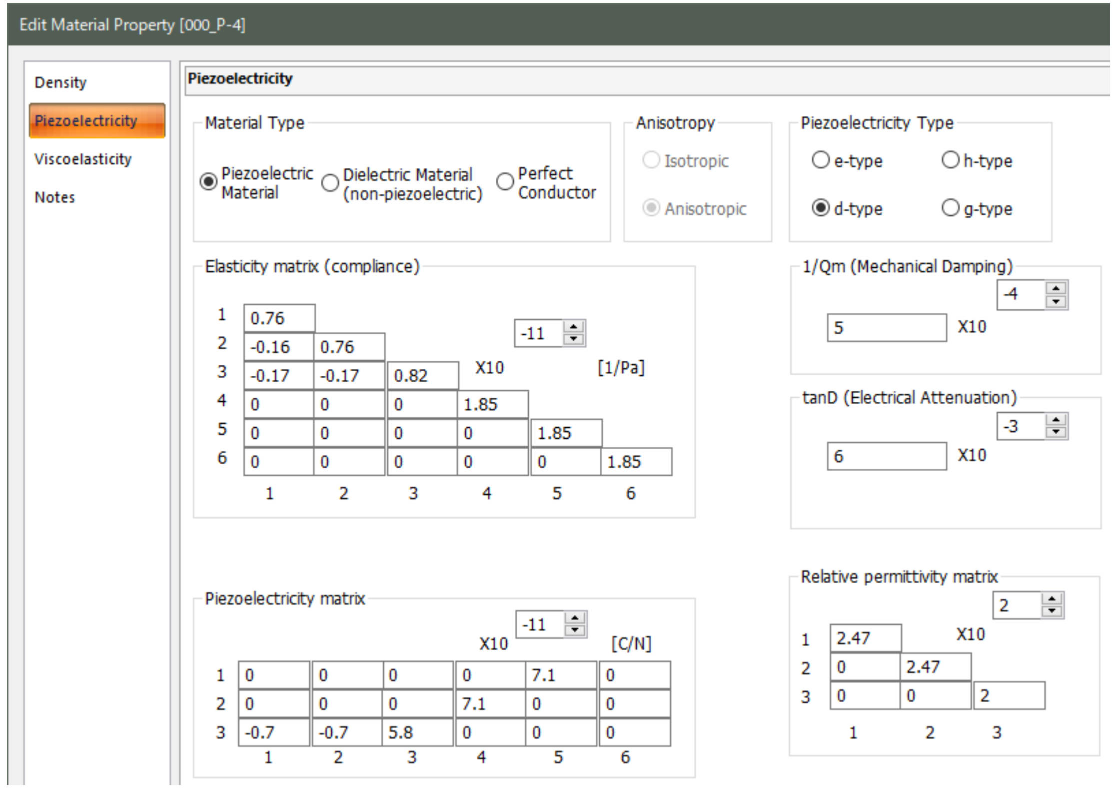
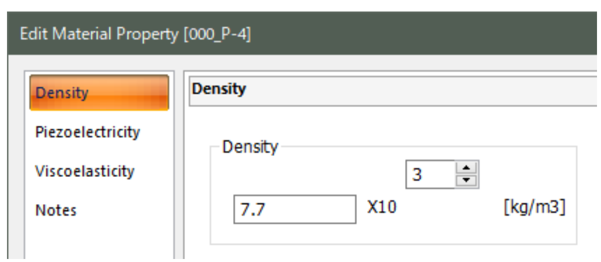
Piezoelectric Constants

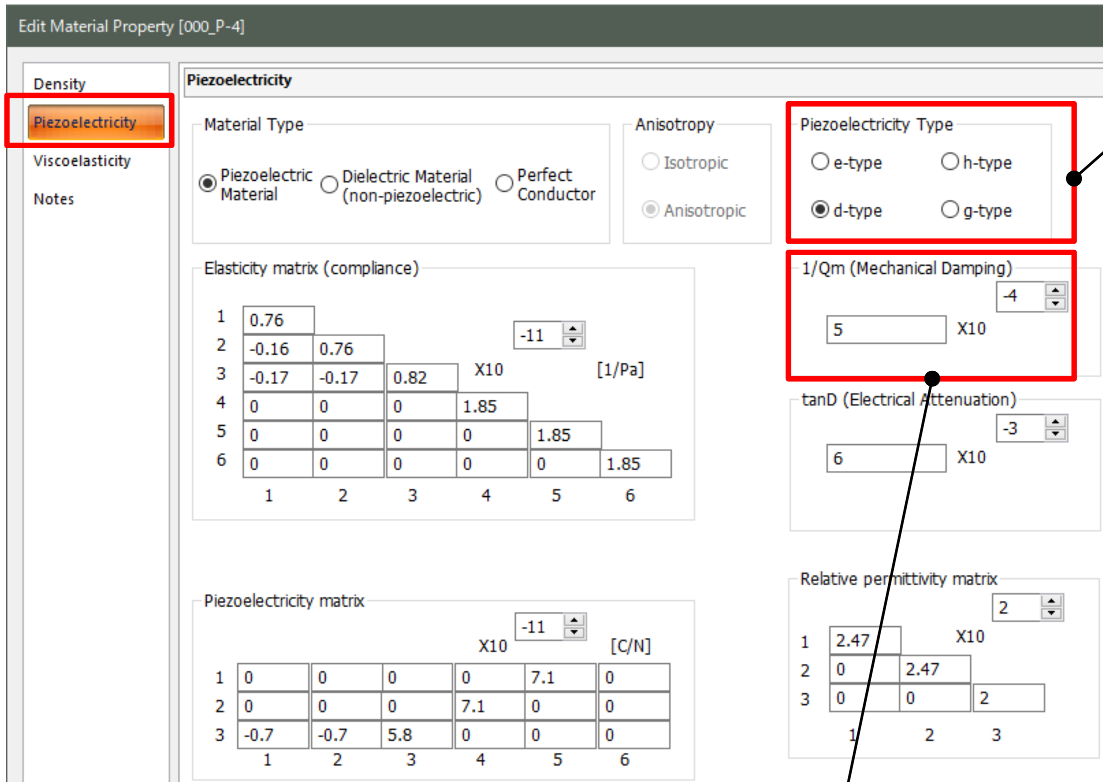
Elasticity
Piezoelectricity
Permittivity
Loss (1/Qm, tanδ)



Density



Piezoelectric Constant



e-type (often used for single-crystal)

$$[T]=[c^E][S]-[e][E]$$
$$[D]=[e_t][S]+[\varepsilon^S][E]$$

d-type (often used for ceramic)

$$[S]=[s^E][T]+[d][E]$$
$$[D]=[d_t][T]+[\varepsilon^T][E]$$

h-type

$$[T]=[c^D][S]-[h][D]$$
$$[E]=-[h_t][S]+[\beta^S][D]$$

g-type

$$[S]=[s^D][T]+[g][D]$$
$$[E]=-[g_t][T]+[\beta^T][D]$$

where
T: stress,
S: strain,
D: electric flux density,
E: electric field

- Set the value for each vibration mode
- The resonant amplitude is proportional to Qm
- Resonant resistance is inversely proportional to Qm

Piezoelectric Materials in the Database

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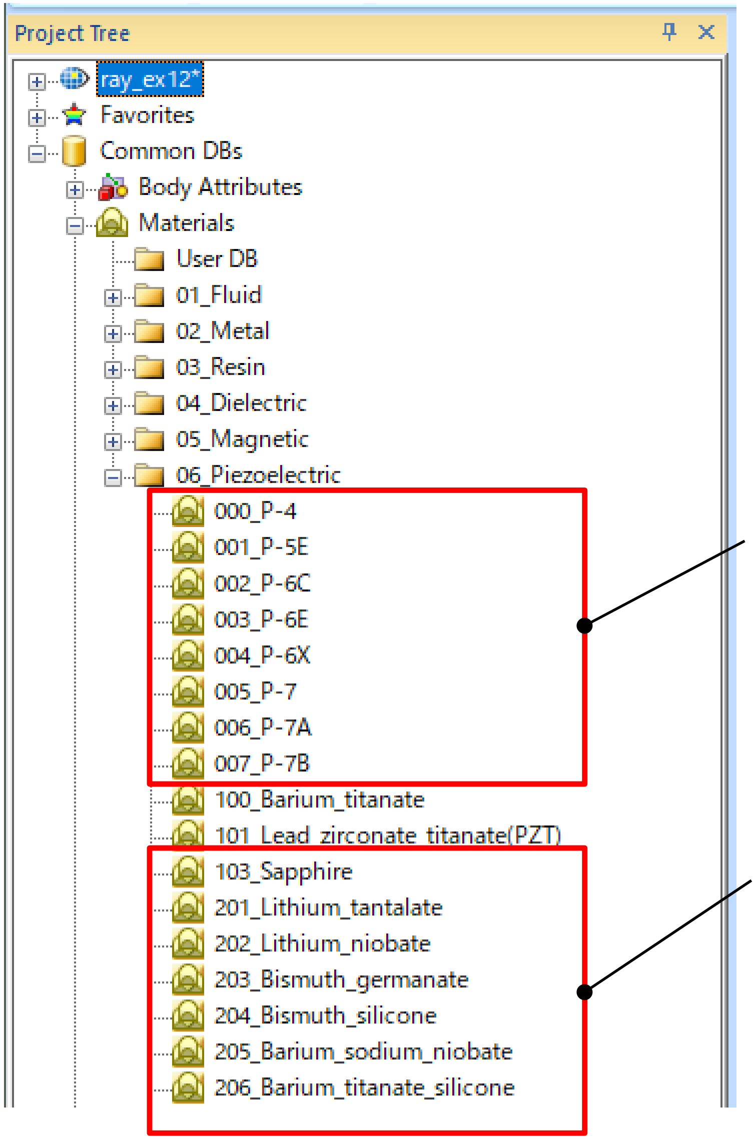
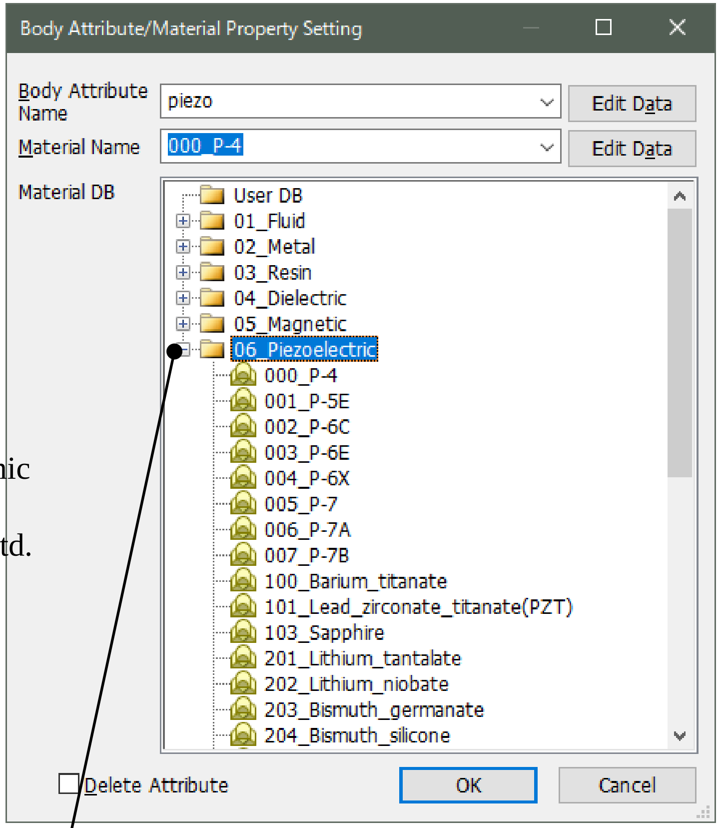


Piezoelectric Ceramic made by Murata Mfg. Co., Ltd. (not for sale)

Single-crystal



Click on “+”.
The list of materials shows up.

(4) Body Attribute

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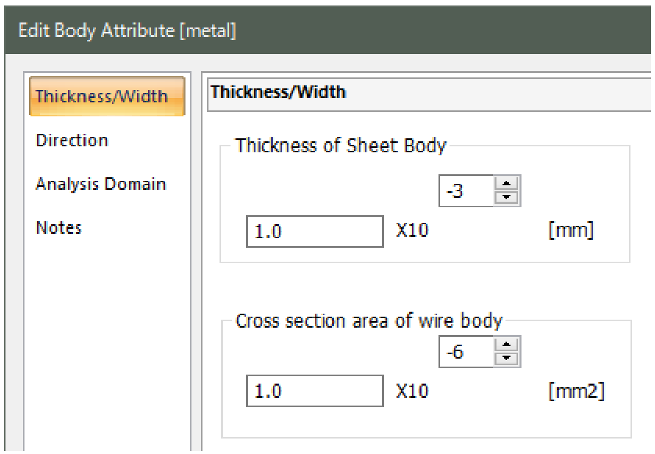
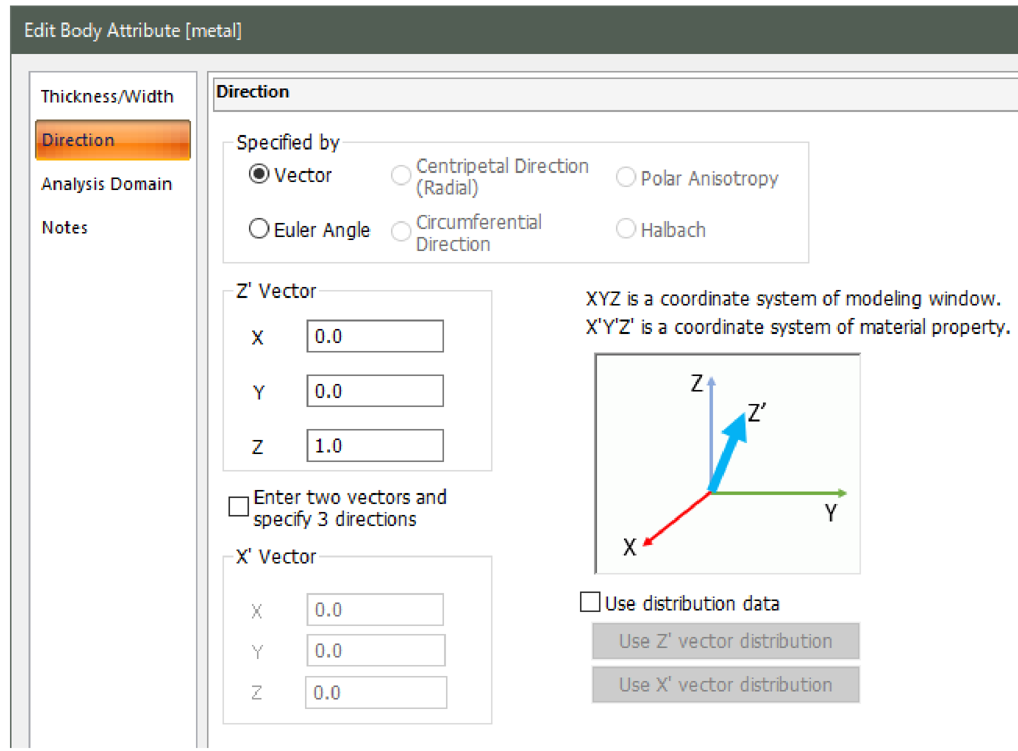
Thickness/Width

The thickness of sheet body is for the 3D analysis.



Direction

The axis direction of polarization and crystallization is specified.



Crystallization Axis Setting by Vector

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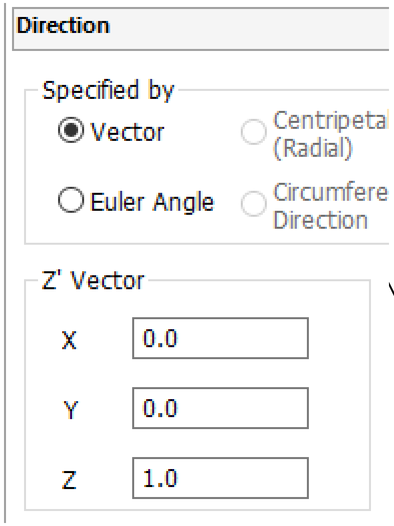
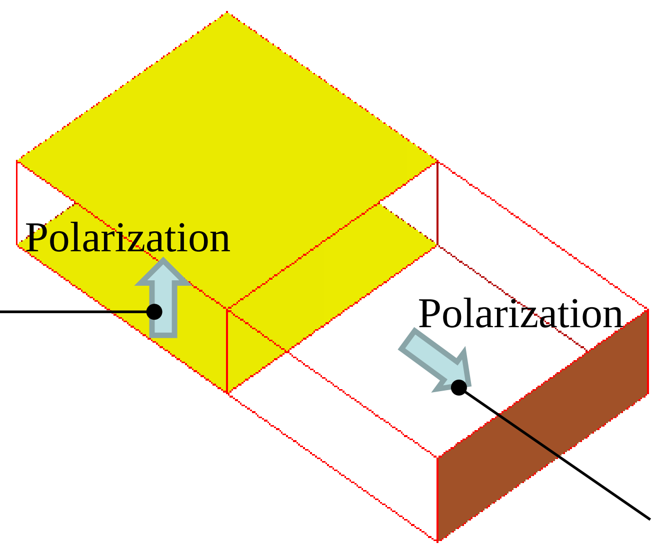
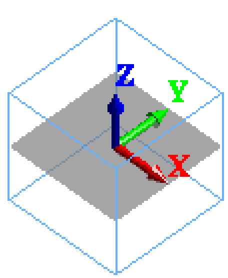
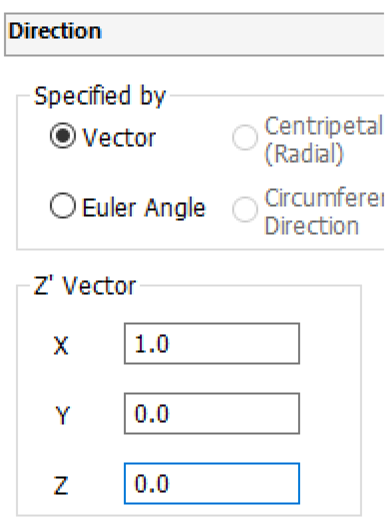
Default Setting



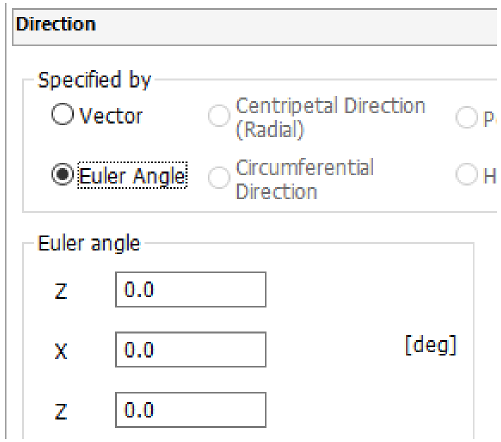
Piezoelectric Transformer





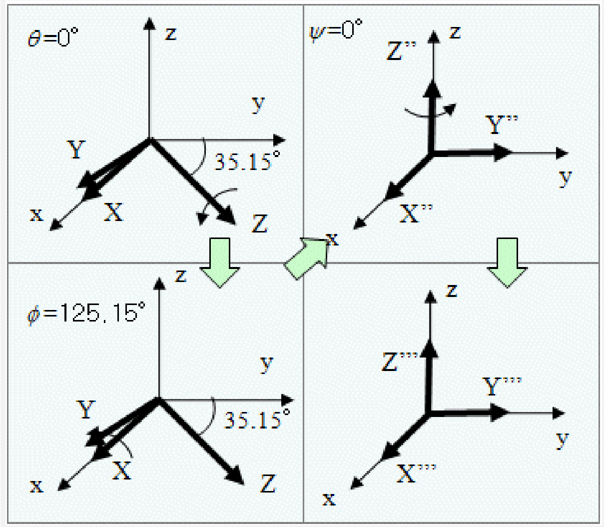


Crystallization Axis Setting by Euler Angle

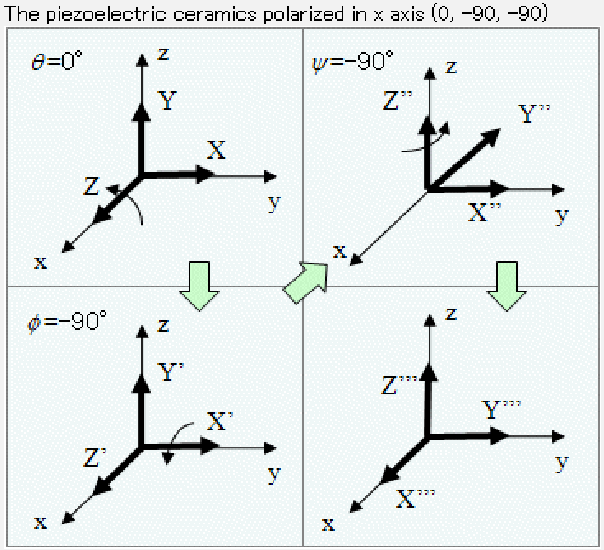


Euler angle (θ, φ, ψ) is an angle rotated around Z axis by angle θ, around X' axis by angle φ, and around Z" axis by angle ψ.

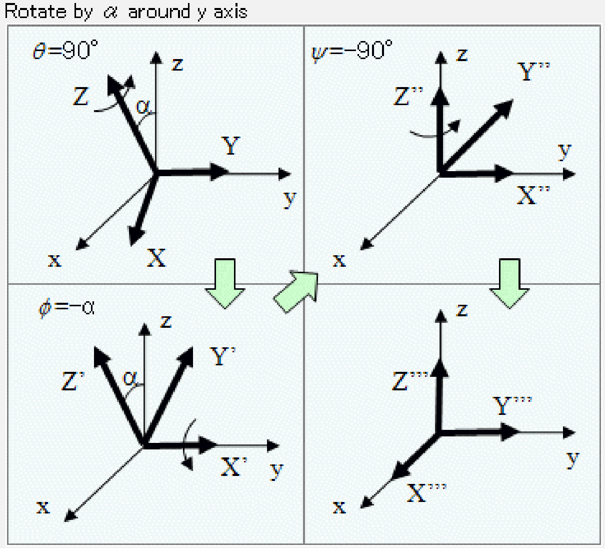
AT-cut quartz (0, 125.15, 0)



The piezoelectric ceramics polarized in x axis (0, -90, -90)



Rotate by α around y axis



(5) Results Display - Field

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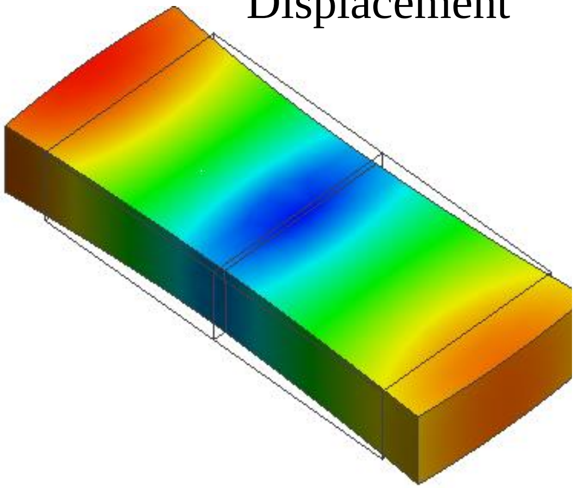
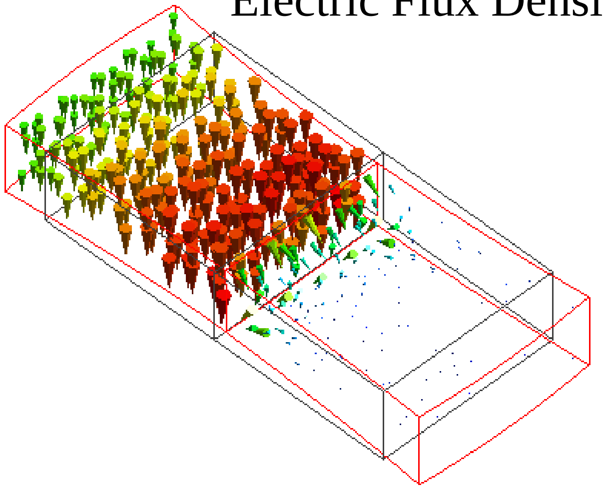
- Displacement [m]
- Strain
- Mechanical Stress [Pa]
- Potential [V]
- Electric Field [V/m]
- Electric Flux Density [C/m^2]

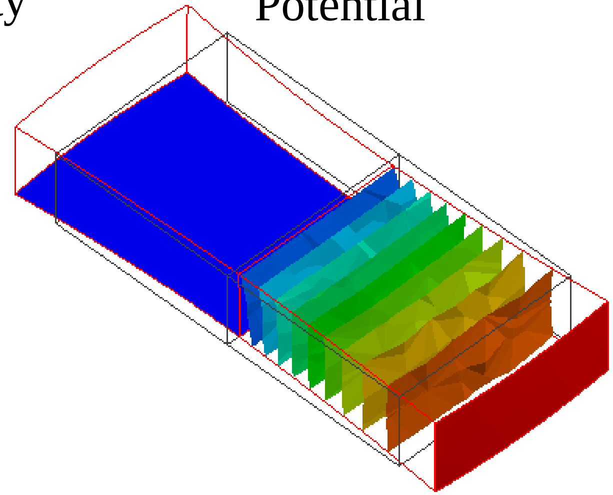
Displacement



Electric Flux Density



Potential



The charge on the electrode is not uniform.

Numerical Summary of Harmonic Analysis

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- Charge of electrode with voltage specified [C]
- Current of electrode with voltage specified [A]
- Voltage of floating electrode [V]

*[Add a resistor across to ground] is deselected.

The sum of charges on the floating electrode is zero.
The current is zero as well.

The data of the numerical table can be exported to csv file and used on Excel

"Admittance" Tab

Table — Admittance

	Frequency [Hz]	Port 1	Y(1,1) / Real part	Y(1,1) / Imaginary part
0: 5.600000e+03Hz	5.600e+3	hot	1.496e−6	1.270e−4
1: 5.602000e+03Hz	5.602e+3	hot	1.506e−6	1.270e−4
2: 5.604000e+03Hz	5.604e+3	hot	1.517e−6	1.271e−4
3: 5.606000e+03Hz	5.606e+3	hot	1.527e−6	1.271e−4

"Charge [C]" Tab

Table — Charge [C]

	Frequency [Hz]	hot / Real part
0: 5.600000e+03Hz	5.600e+3	3.609e−9
1: 5.602000e+03Hz	5.602e+3	3.609e−9
2: 5.604000e+03Hz	5.604e+3	3.609e−9
3: 5.606000e+03Hz	5.606e+3	3.609e−9

"Floating electrode potential [V]" Tab

Table — Floating electrode potential [V]

	Frequency [Hz]	float / Real part	float / Imaginary part
0: 5.600000e+03Hz	5.600e+3	0	0
1: 5.602000e+03Hz	5.602e+3	0	0
2: 5.604000e+03Hz	5.604e+3	0	0
3: 5.606000e+03Hz	5.606e+3	0	0

"Current [A]" Tab

Table — Current [A]

	Frequency [Hz]	hot / Real part
0: 5.600000e+03Hz	5.600e+3	1.496e−6
1: 5.602000e+03Hz	5.602e+3	1.506e−6
2: 5.604000e+03Hz	5.604e+3	1.517e−6
3: 5.606000e+03Hz	5.606e+3	1.527e−6

Piezoelectric Analy | Show all results summary | Display Options | Graph | Export

Results Display
Numerical Summary of Resonant Analysis

Murata Software

- Damping capacitance: Cd [pF]
- Free capacitance: Cf [pF]
- Resonant frequency: Fr[Hz]
- Difference between resonant freq. and anti-resonant freq.: DF[Hz]
- Coupling coefficient: k [%]
- Resonant resistance: Rn[ohm]
- Equivalent capacitance: Cn[pF]
- Equivalent inductance: Ln[H]

"Damping Capacitance [F]" Tab

Table

Damping capacitance [F]

	Frequency [Hz]	Damping capacitance [F]
0: 3.371928e+03Hz	3.372e+3	2.716e-9
1: 3.434018e+03Hz	3.434e+3	2.716e-9
2: 5.926161e+03Hz	5.926e+3	2.716e-9

"Resonant Frequency [Hz]" Tab

Table

Resonant frequency [Hz]

	Frequency [Hz]	Resonant frequency [Hz] / Real part	Resonant frequency [Hz] / Imaginary part
0: 3.371928e+03Hz	3.372e+3	3.372e+3	0.286
1: 3.434018e+03Hz	3.434e+3	3.434e+3	0.281
2: 5.926161e+03Hz	5.926e+3	5.926e+3	0.593

"Coupling Coefficient [%]" Tab

Table

Coupling coefficient[%]

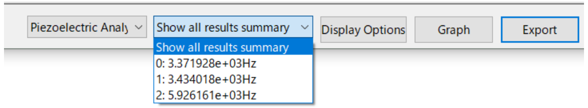
	Frequency [Hz]	Coupling coefficient [%]
0: 3.371928e+03Hz	3.372e+3	1.786e-1
1: 3.434018e+03Hz	3.434e+3	1.749e-2
2: 5.926161e+03Hz	5.926e+3	4.674e+0

"Equivalent Capacitance [F]" Tab

Table

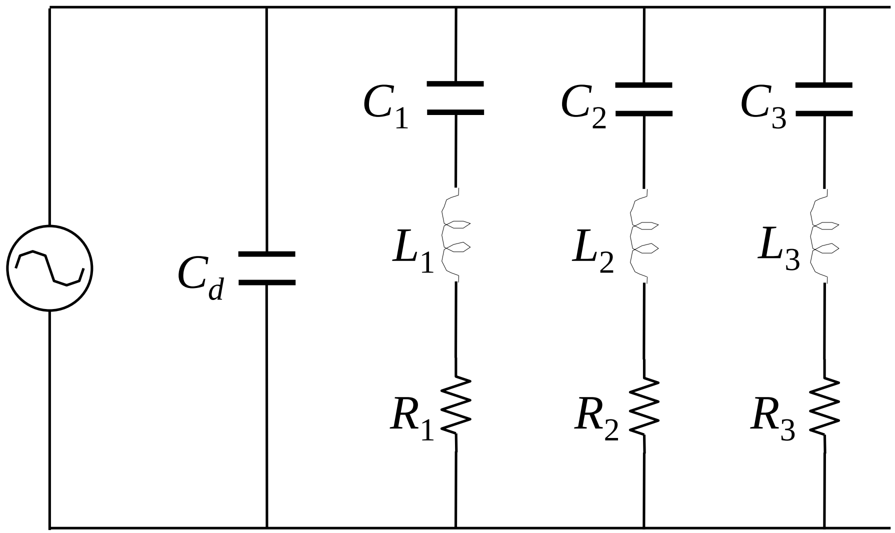
Equivalent capacitance [F]

	Frequency [Hz]	Equivalent capacitance [F]
0: 3.371928e+03Hz	3.372e+3	1.134e-14
1: 3.434018e+03Hz	3.434e+3	1.087e-16
2: 5.926161e+03Hz	5.926e+3	7.766e-12



Equivalent Circuit

Equivalent circuit is obtained in the resonant analysis.

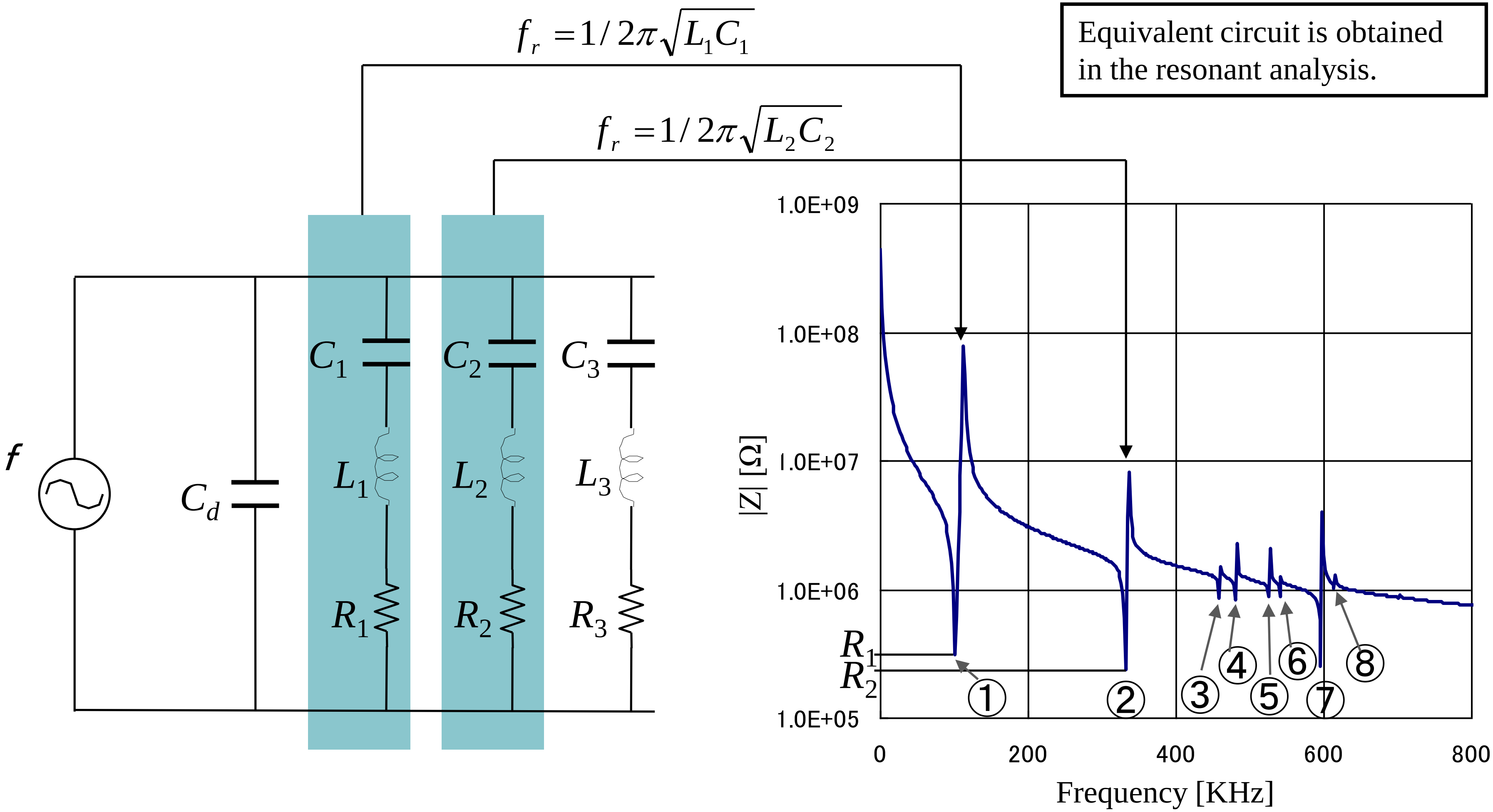


C_k : equivalent series capacitance
Lk : equivalent series inductance
Rk : equivalent series resistance
Cd : damping capacitance
C f : free capacitance

Equivalent Circuit & Resonance

Murata Software

Equivalent circuit is obtained in the resonant analysis.

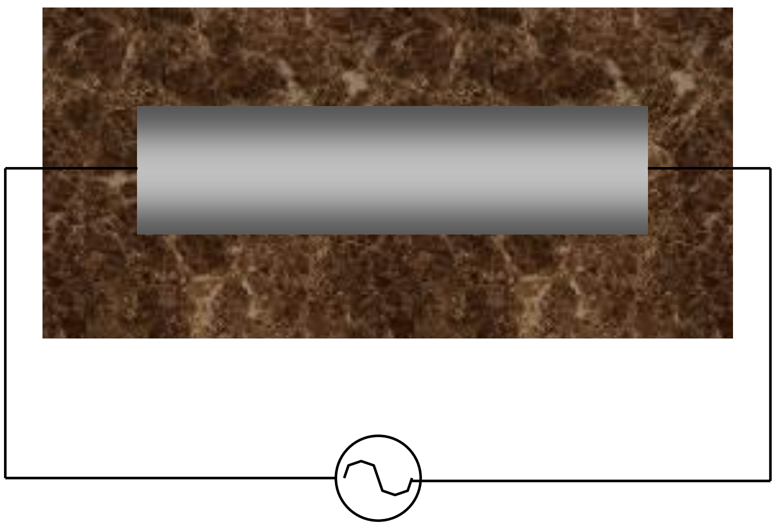


The equivalent circuit has multiple resonators. The number of resonators corresponds to the number of modes which is defined on the [Resonant Analysis] tab of the analysis condition setting. In the right figure above shows 8 resonant points, which means the calculation was performed with at least 8 modes.
The harmonic analysis results take into account all modes included in the range of analysis frequencies.

Damping Capacitance & Free Capacitance

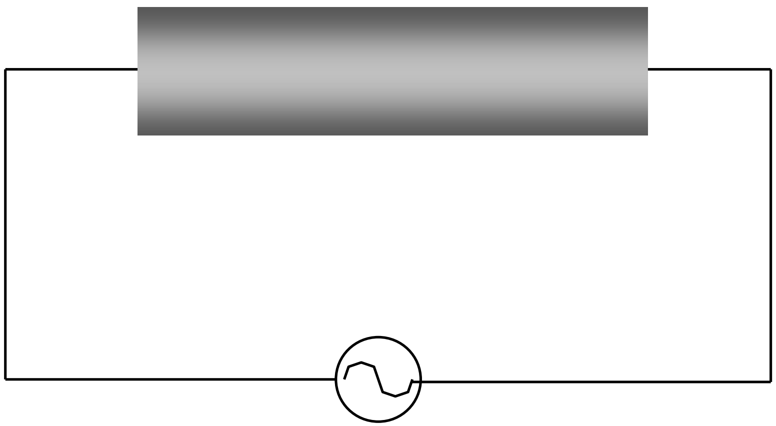
Equivalent circuit is obtained in the resonant analysis.

C_d : Damping Capacitance
Cannot move freely



C_f : Free Capacitance
Freely moving

$$C_f = C_d + \sum_k C_k$$



Other Parameters

In the resonant analysis, resonant frequency, difference of the resonant frequency and anti-resonant frequency, and coupling coefficient are output.

<u>Resonant Frequency</u>

The resistance is at its minimum.

$$f_r$$

<u>Anti-resonant Frequency</u>

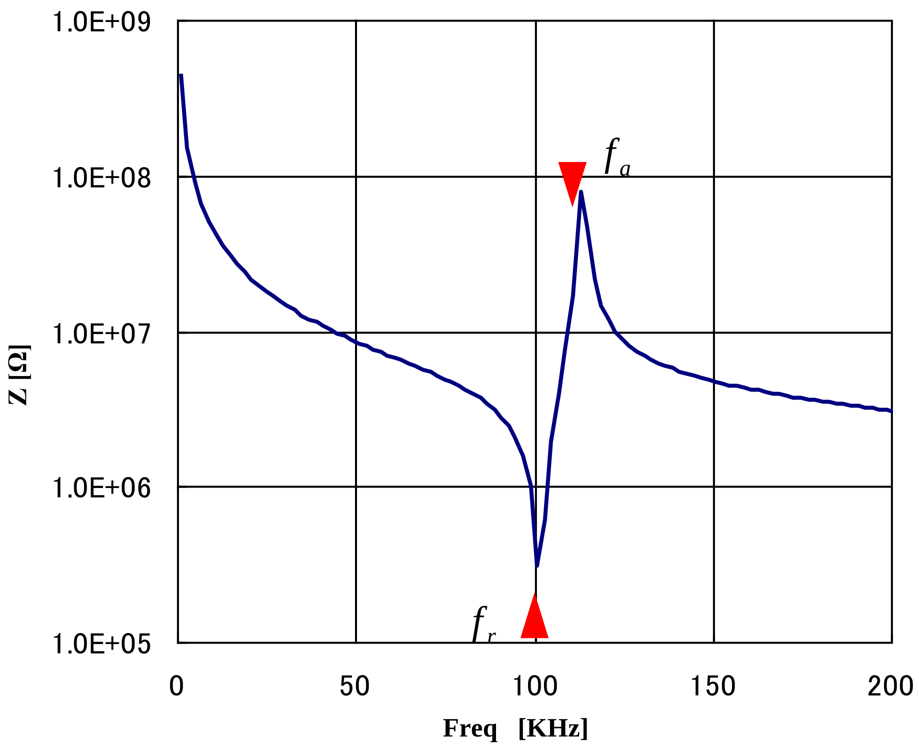
The resistance is at is maximum.

$$f_a = f_r\sqrt{1 + C_k / C_d}$$

<u>Coupling Coefficient</u>

Conversion efficiency between electrical and mechanical

$$k = \sqrt{C_k / C_f}$$



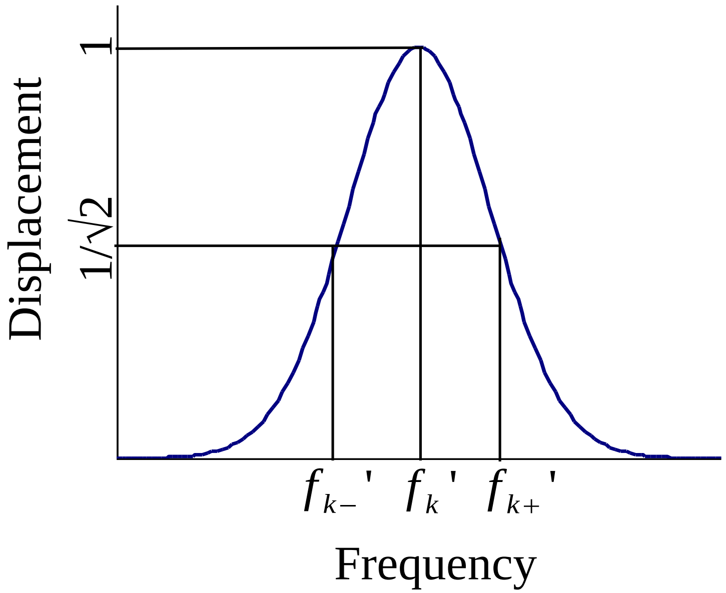
Complex Resonant Frequency & Q

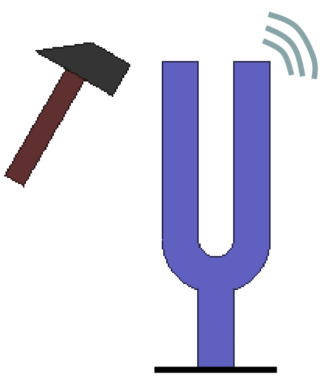
In the resonant analysis, complex resonant frequency is obtained by entering Q of material, tanδ, and acoustic impedance. Frequency response of displacement is obtained in the harmonic analysis.

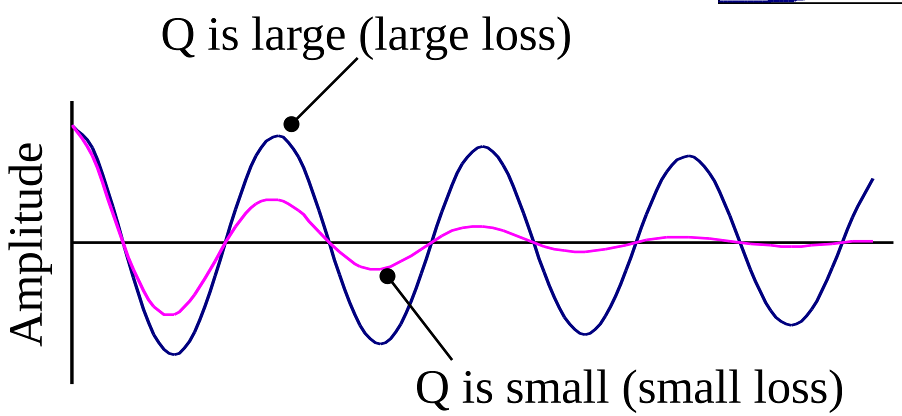
Q is the ratio of the real part and the imaginary part.

$$f_k = f_k' + j f_k''$$

$$Q = \frac{f_k'}{f_{k+}' - f_{k-}'} = \frac{1}{R_k}\sqrt{\frac{L_k}{C_k}} = \frac{f_k'}{2 f_k''}$$





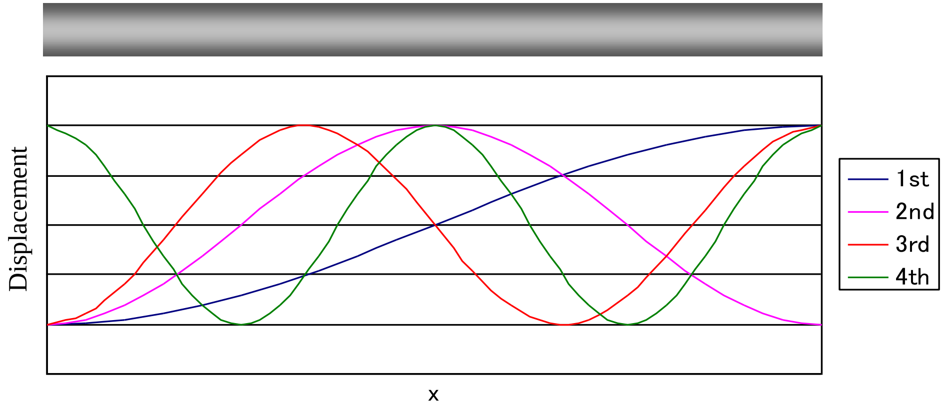


3.Points of Piezoelectric Analysis

(1) Mesh Size
(2) Symmetric Model

(1) Mesh Size

Elongation of a Bar



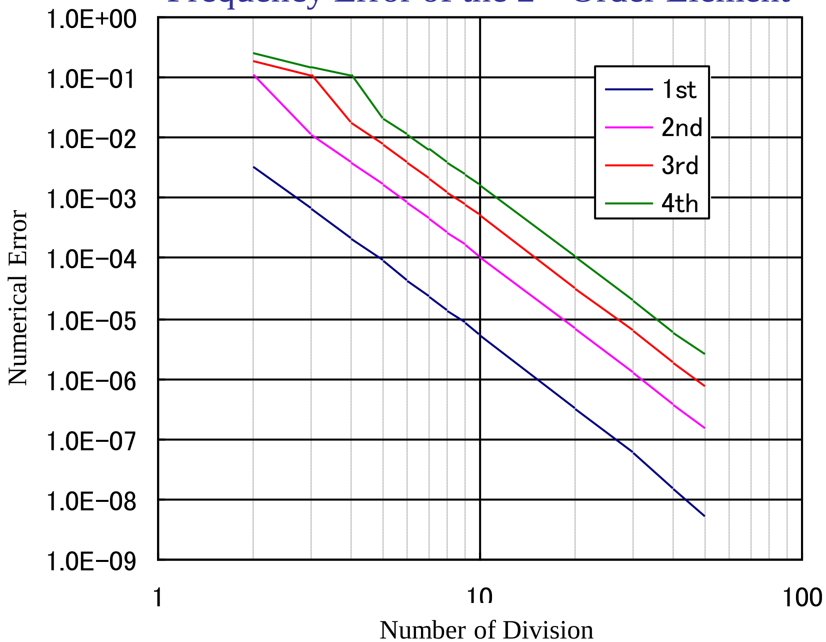
Frequency of the vertical vibration

$$f_n = \frac{n}{2L}\sqrt{\frac{E}{\rho}} \qquad (n = 1,2,3,4)$$

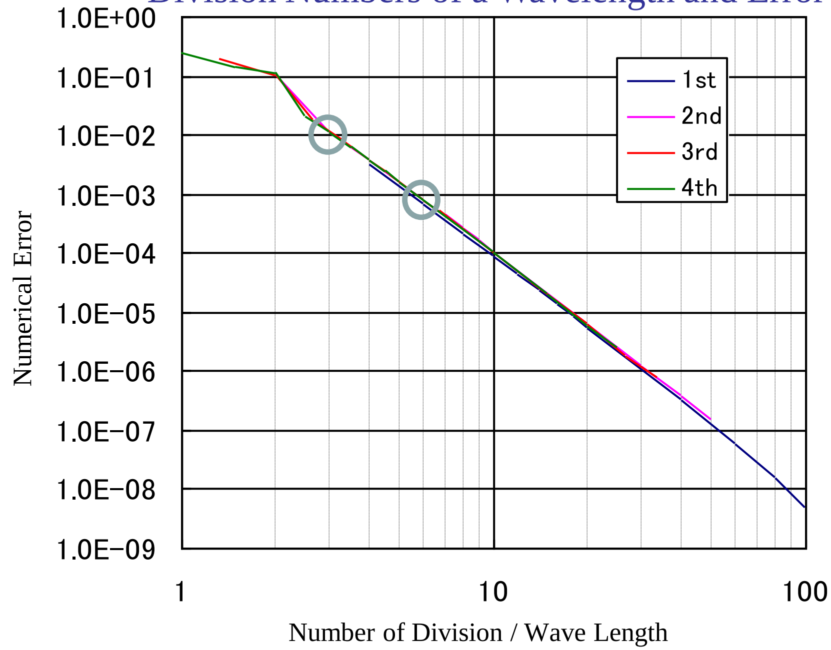
3 divisions of a wavelength:1%

6 divisions of a wavelength: 0.1%

Frequency Error of the 2nd Order Element



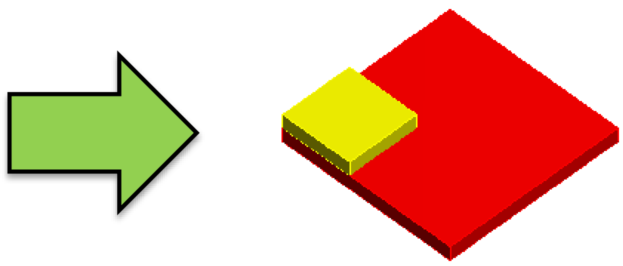
Division Numbers of a Wavelength and Error



(2) Symmetric Model

By analyzing a part of the domain, calculation is performed in shorter time with less memory usage.

Full Model



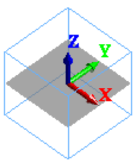
Symmetric Model

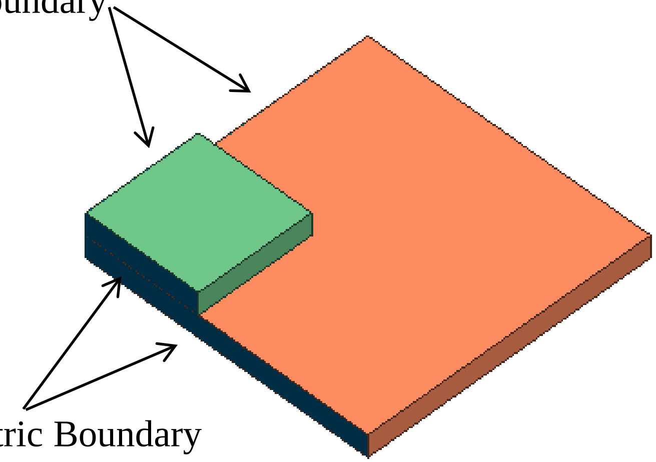
Domain	Memory	Time
1/2	1/2	1/4 (25.0%)
1/4	1/4	1/16 (6.3%)
1/8	1/8	1/64 (1.6%)

(2) Symmetric Model

Set symmetric boundary condition on the faces of symmetry.

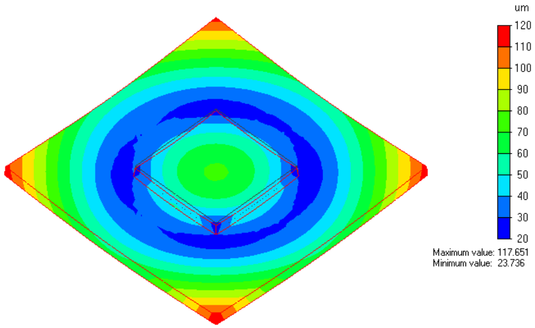
Symmetric Boundary

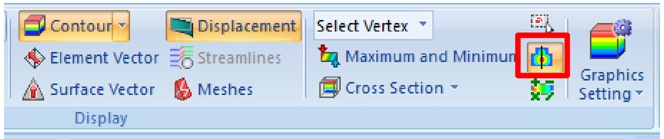




Symmetric Boundary

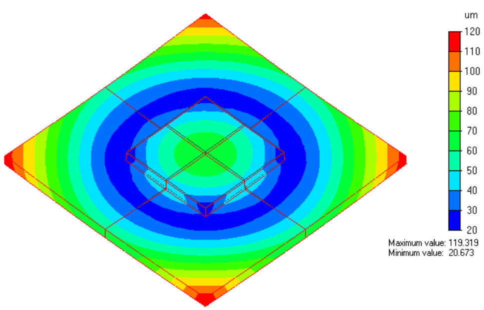
Calculation with a Full Model

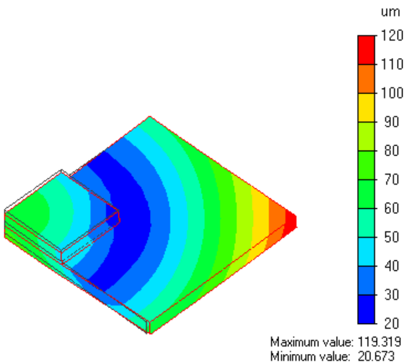




Z displacement matches

Convert the symmetric model to the full model





Calculation with a symmetric model

(2) Symmetric Model

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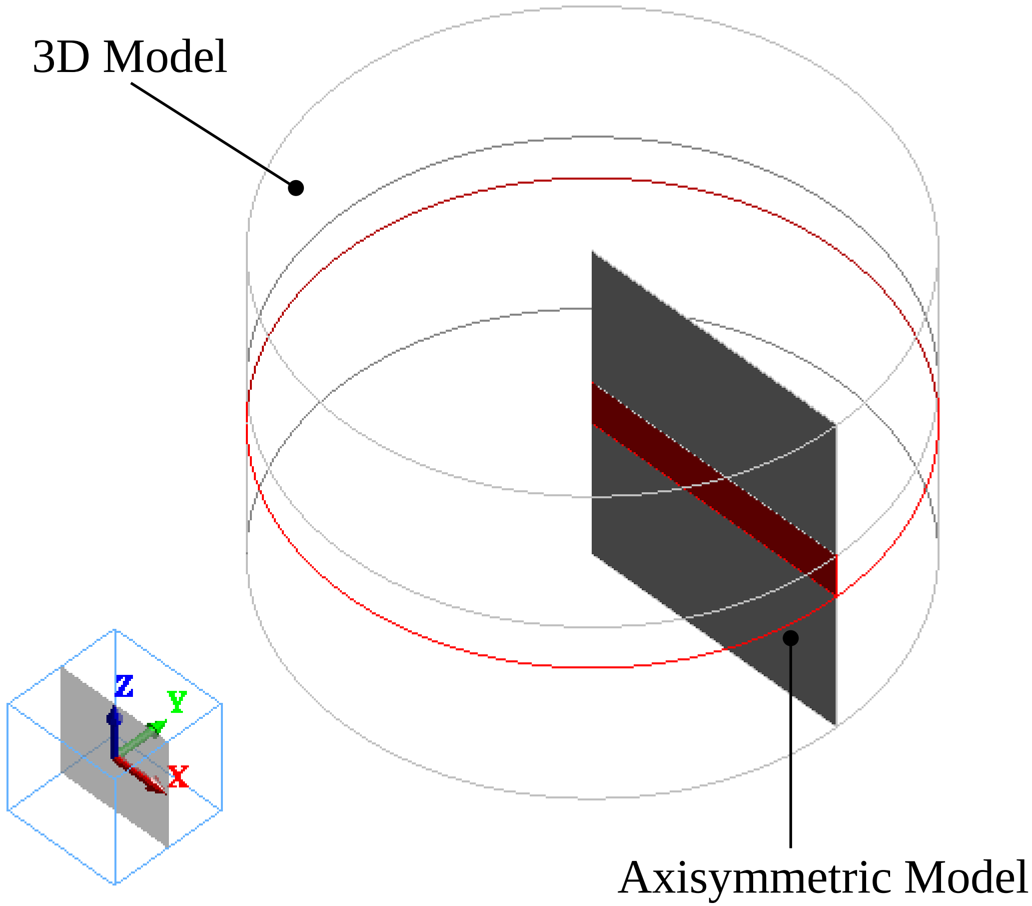
In the axisymmetric analysis of XZ plane, the analysis time is greatly reduced.



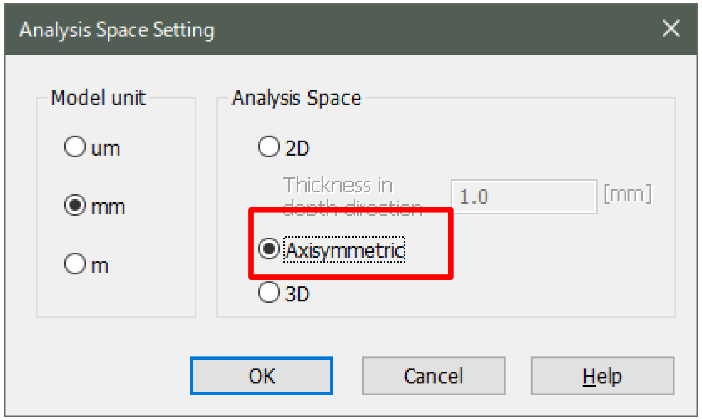


Table of Contents

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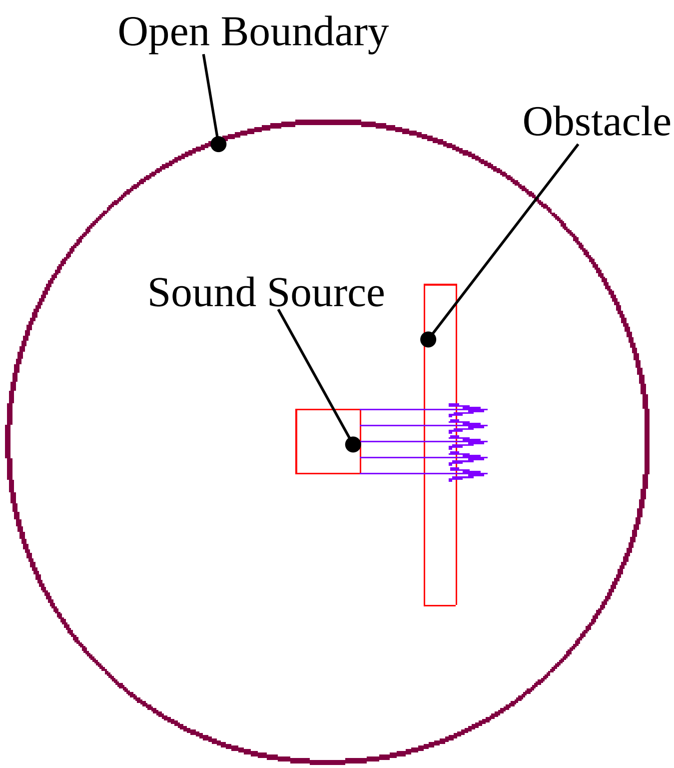
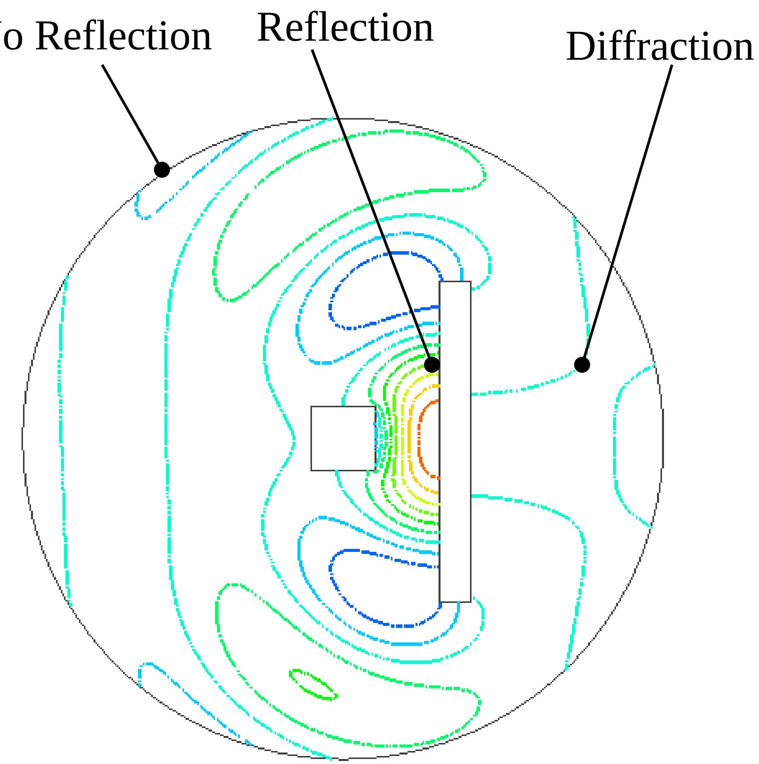
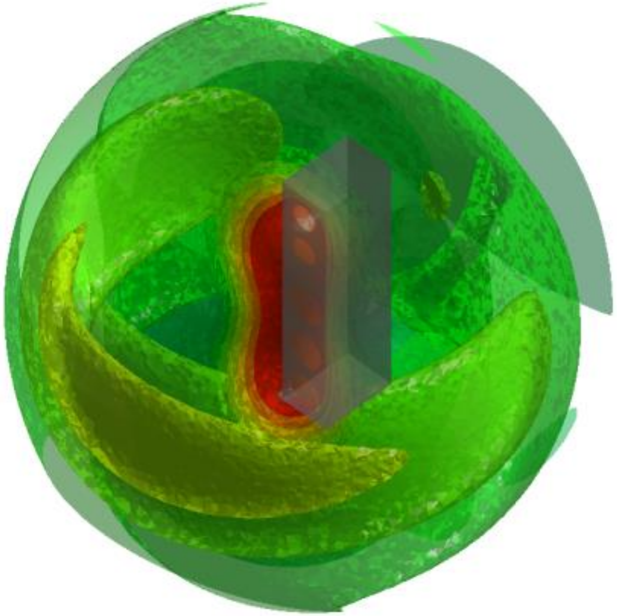
Reflection and Diffraction





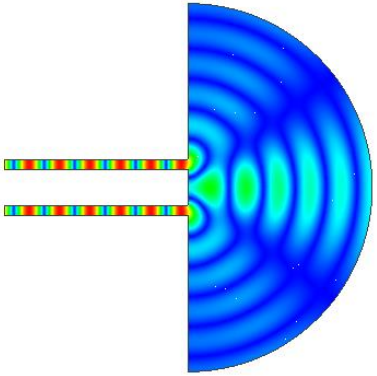
Speaker and Interference of Sound Waves

Sound Pressure of Speaker

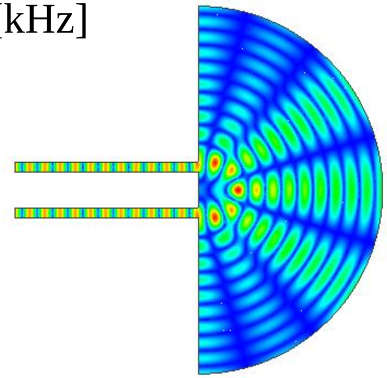


Interference of Sound Waves

1[kHz]



2[kHz]

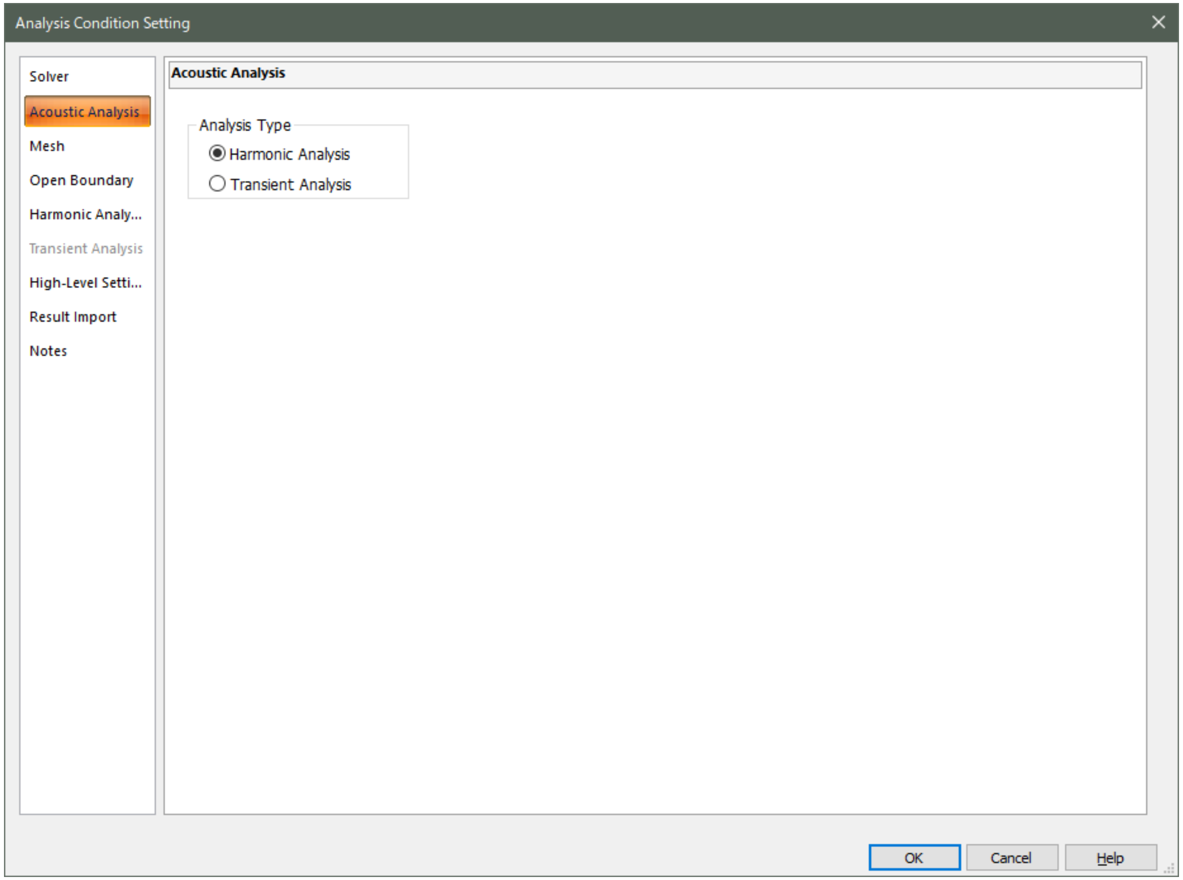


5. Functions of Acoustic Analysis

Murata Software

(1) Analysis Condition
(2) Boundary Condition
(3) Material Property
(4) Body Attribute
(5) Results Display

(1) Analysis Condition



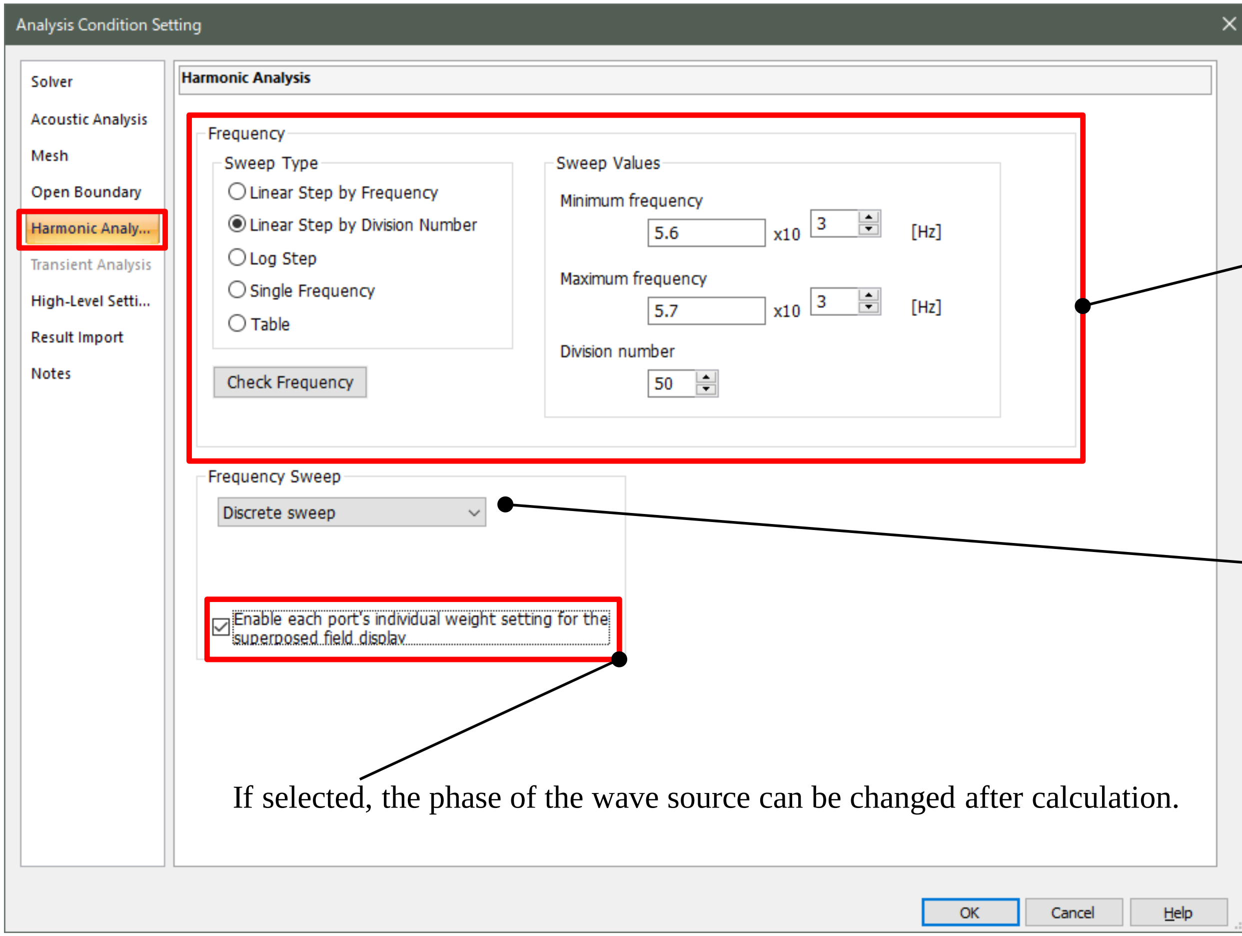
Analysis Type

Harmonic

Transient

Harmonic Analysis

Murata Software



Setting of Frequency for Calculation

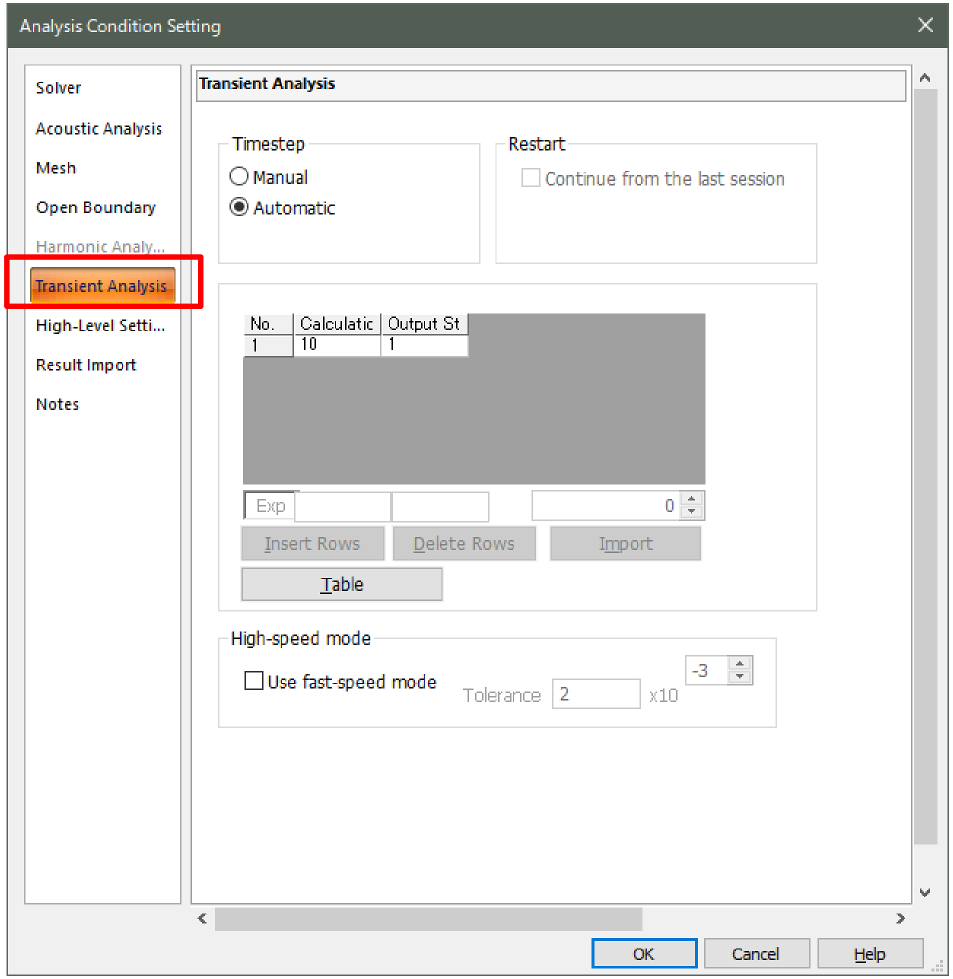
Select [Discrete Sweep] or [Fast Sweep].
If using high-spec computer with enough memory, [Parallel Discrete Sweep] is available*

If selected, the phase of the wave source can be changed after calculation.

*Option for Accelerator is required.

Transient Analysis

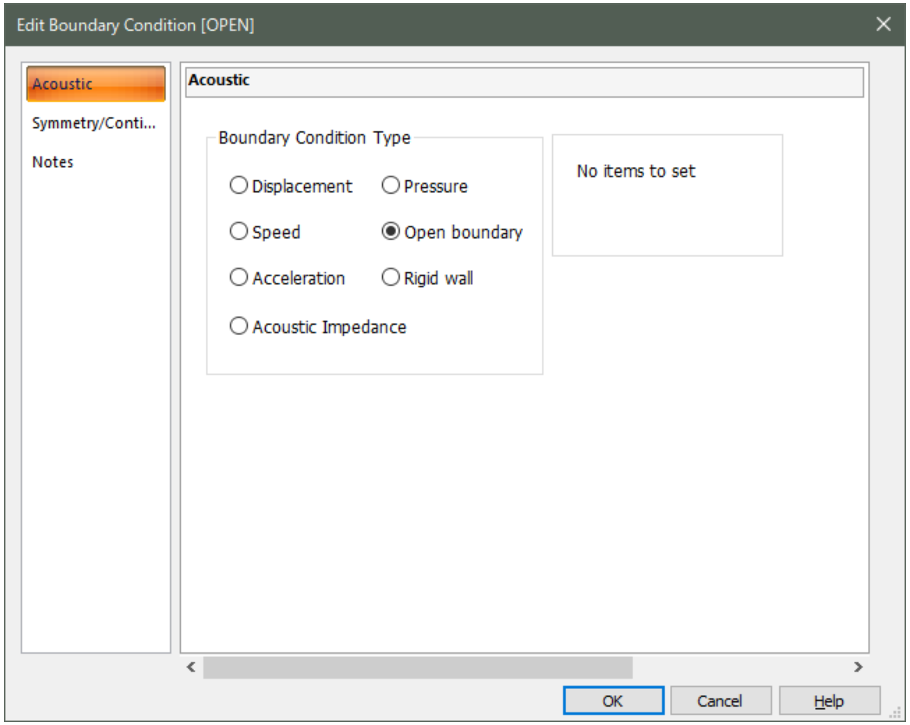
Murata Software

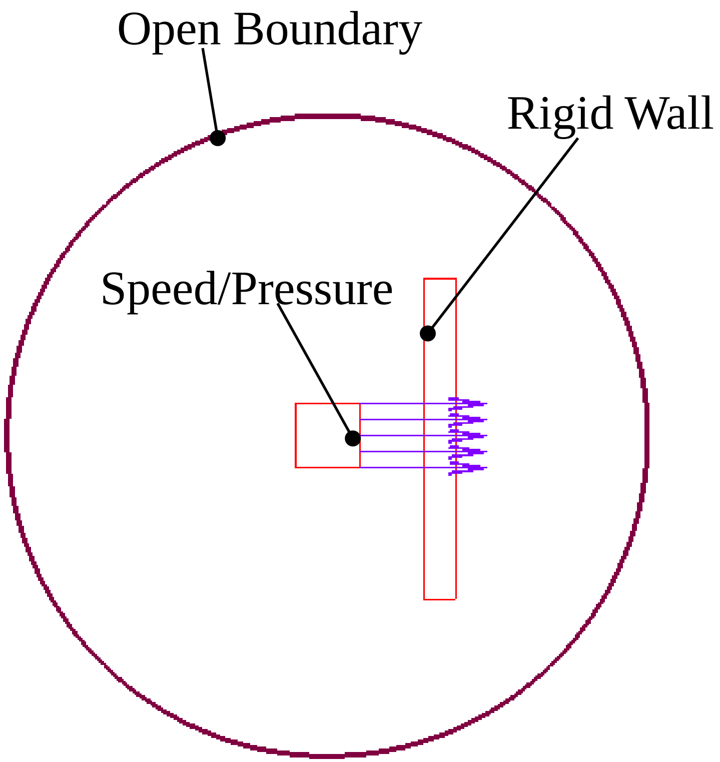


In the acoustic transient analysis, if timestep is set [Automatic], timestep is set based on the CFL number so as to prevent numerical instability.

*CFL Number is the number of meshes that travel during one timestep. If the number is too large, numerical instability occurs. The number is determined by the mesh size and the sound speed.

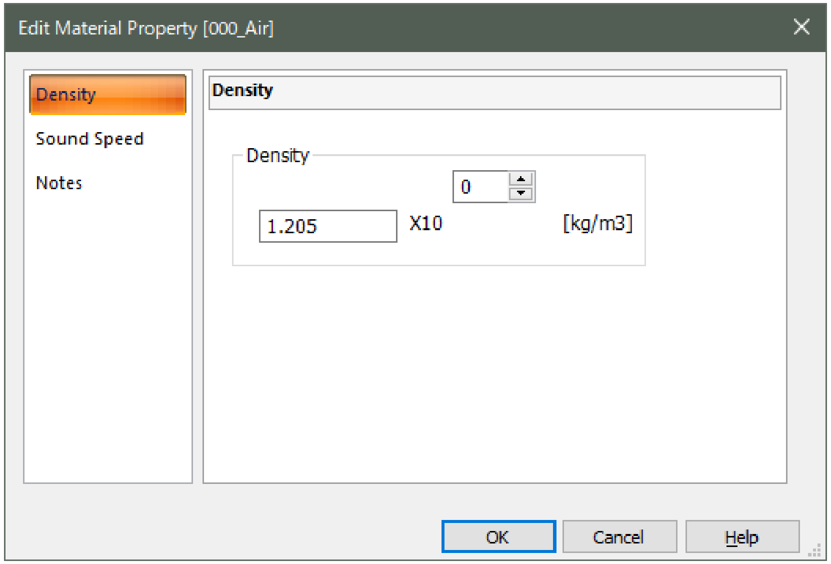
(2) Boundary Condition



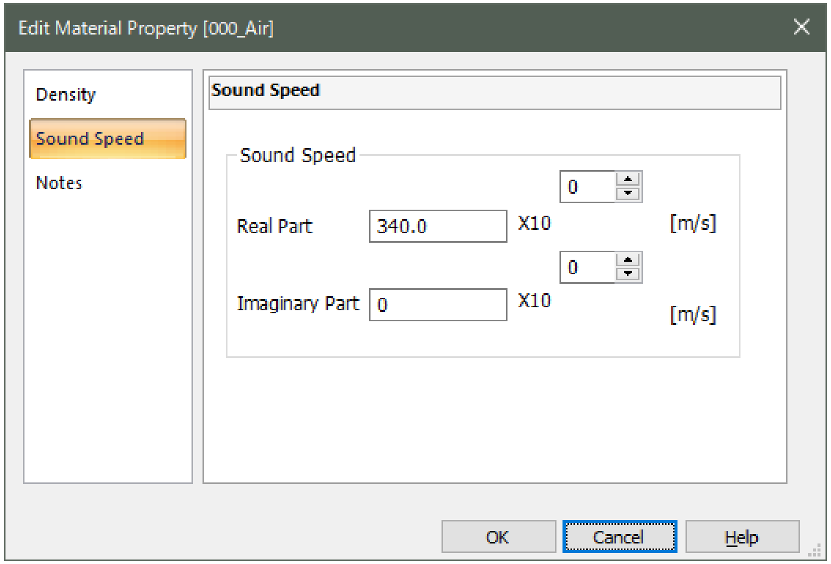


(3) Material Property

Density



Sound Speed



Damping of Sound

By setting imaginary part of the sound speed, the damping of the sound waves can be expressed.

Fig 1 shows the damping material between air.

As Fig 2 shows, the sound waves are damped in the damping material.

Fig 3 shows the level on the left side of the damping material is not uniform. It indicates the reflection is occurring.

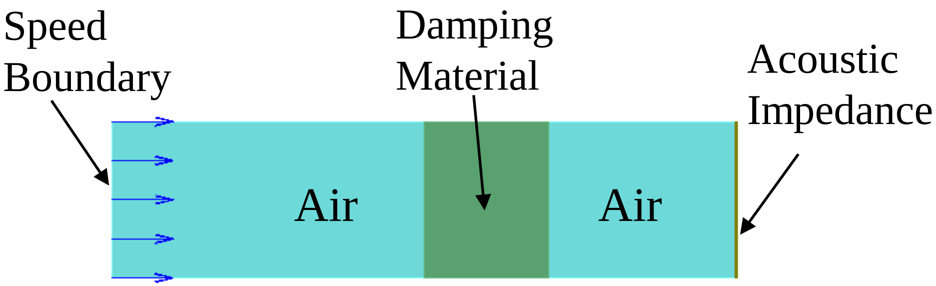


Fig 1. Sound Pressure [Pa]

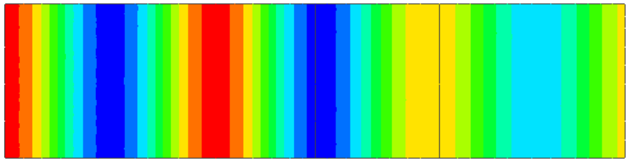


Fig 2. Sound Pressure [Pa]

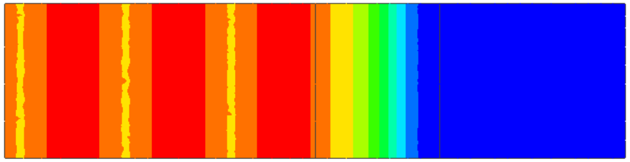
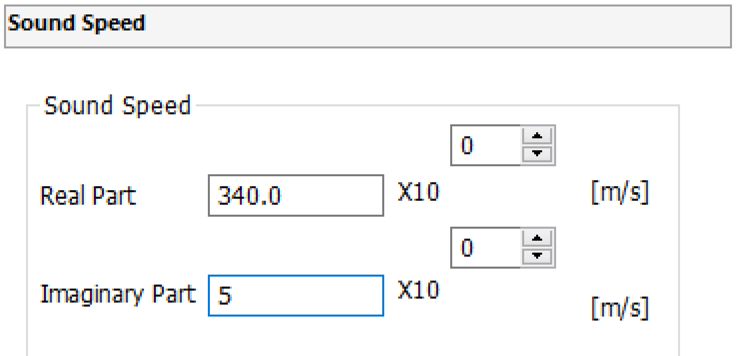


Fig 3. Sound Pressure Level [dB]

Damping of Sound

Loss of the Medium



Set the imaginary part and damping coefficient of the sound speed here.

The imaginary part indicates the attenuation, which sometimes cannot be ignored in the case of ultrasonics. Kirchhoff's equation is given below. The sound speed increases as the frequency increases.

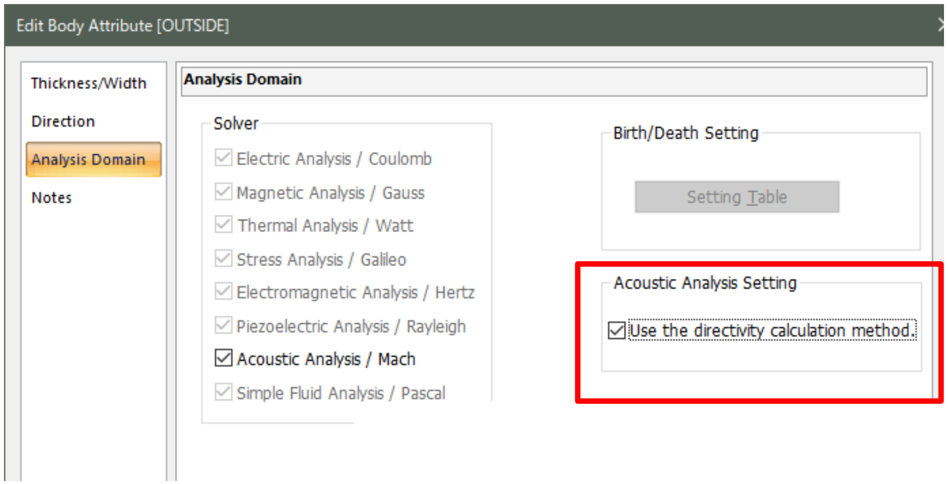
$$c\_image = \frac{\omega}{2c}\left(\frac{4}{3}\frac{\mu}{\rho} + \frac{\gamma - 1}{\gamma}\frac{\kappa}{\rho C_v}\right)$$

ω : angular frequency, c: sound speed, μ : viscosity coefficient, ρ : density
γ : heat capacity ratio, κ : thermal conductivity, Cv: specific heat at constant volume

It is $2.7\text{x}10^{-7} f$ in the air, and $2.8\text{x}10^{-9} f$ in the water,
where f is the frequency.

(4) Body Attribute

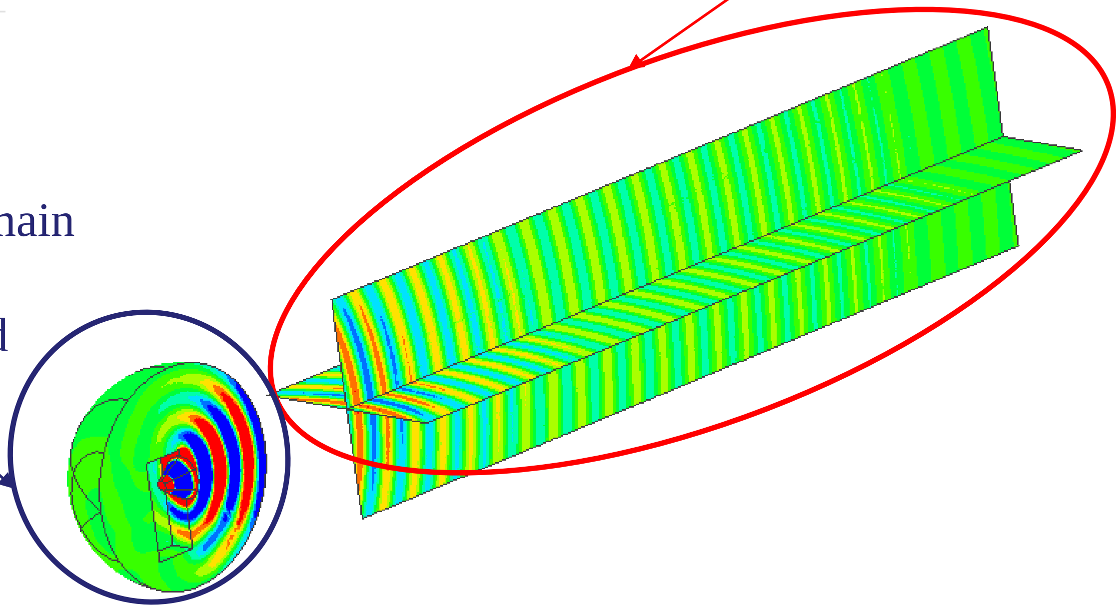
Analysis Domain



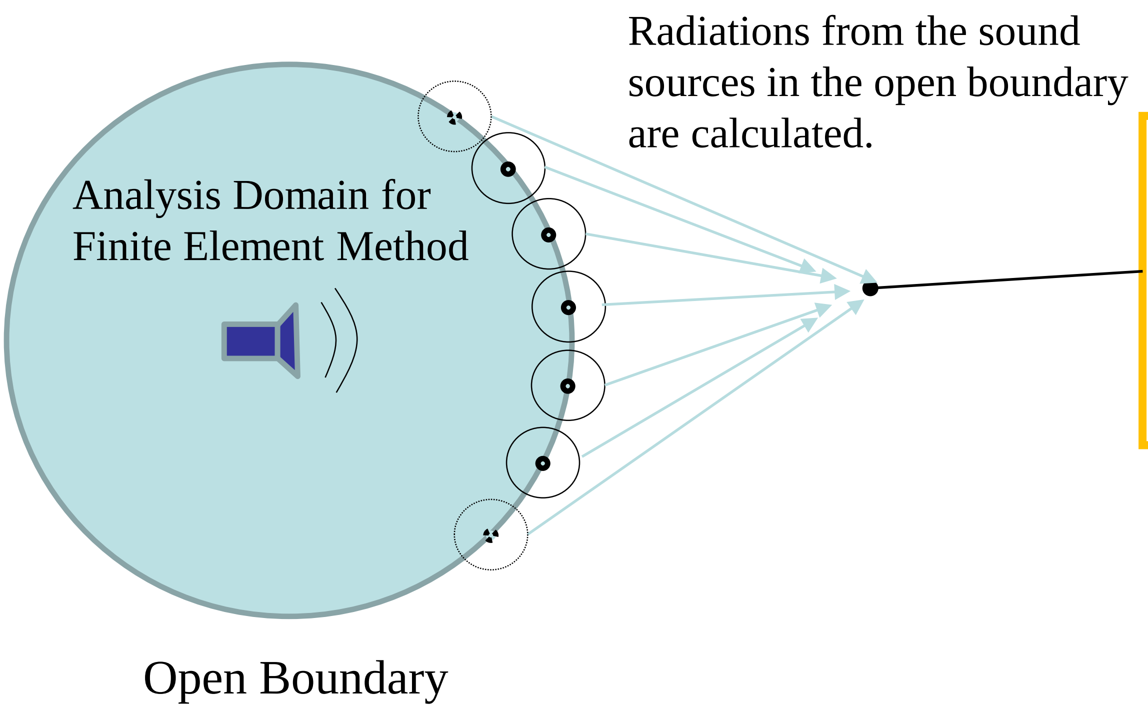
Example 8:
View by the Directivity Calculation Method

Calculated domain with the directivity calculation method

Calculation Domain for the Finite Element Method



Huygens' Principle

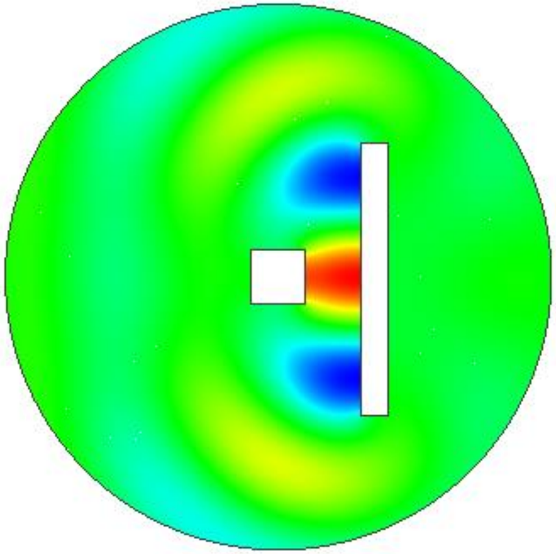


An observation point of the directivity is placed outside the analysis domain.
The outside sound waves are calculated with the Huygens' principle.

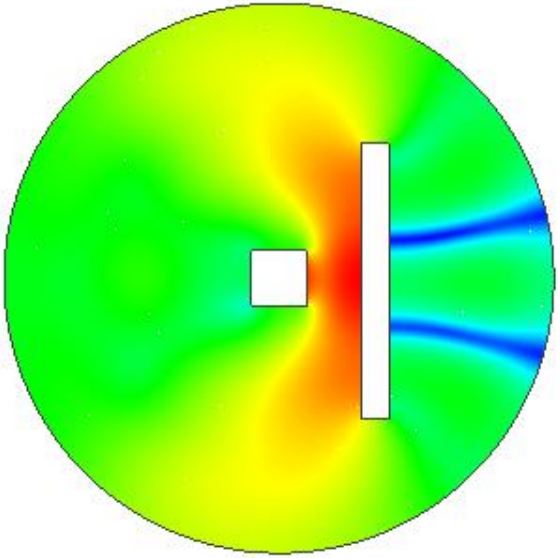
(5) Results Display - Field

Sound Pressure [Pa]
Sound Pressure Level[dB]
Particle Velocity [m/sec]
Acoustic Intensity [W/m^2]

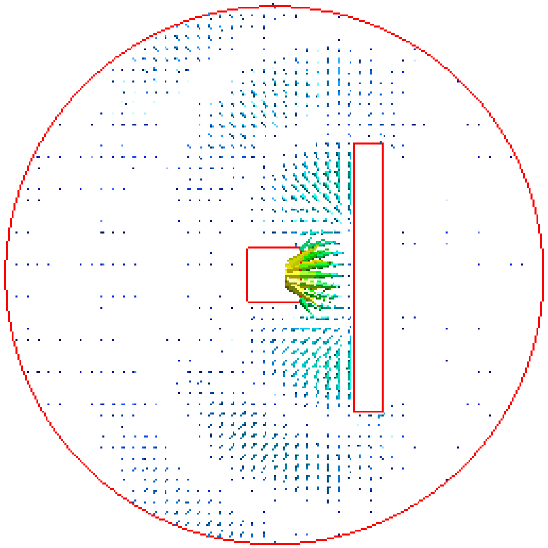
Sound Pressure



Sound Pressure Level



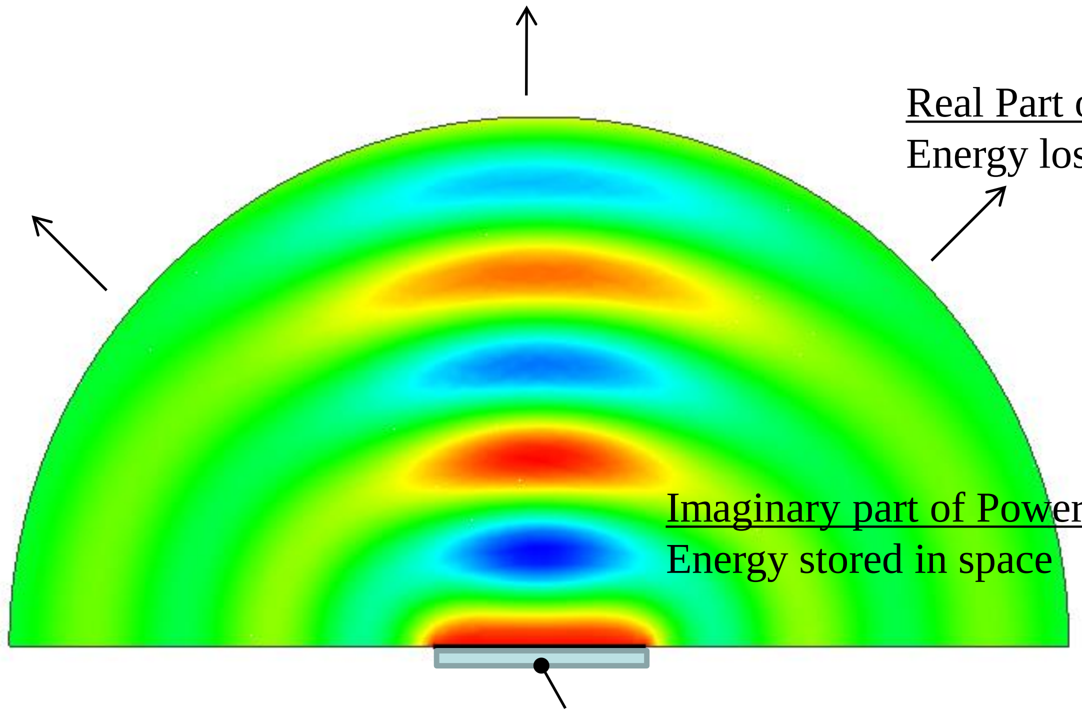
Particle Velocity



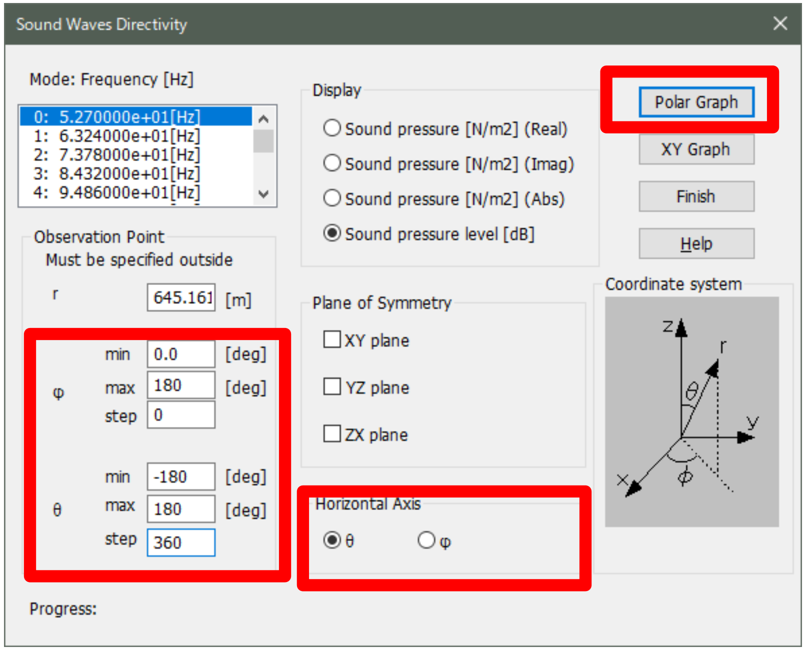
Results Display - Numerical Table

Radiation Energy : Power[W]
Radiation Impedance : Zr[Ns/m]

Example
Power [W]   = 2.60245624e-005 7.47853134e-005j
Zr   [Ns/m]   = 4.33208345e+000 1.24488632e+001j



Results Display - Graph of Directivity



Based on the Huygens' principle, the sound pressure outside the domain is calculated, where the finite element method is not applied.

[XY Plane]

Φ : min 0/max 360/step 100

θ : min 0/max 0/step 0

Horizontal axis : Φ

[XZ Plane]

Φ : min 0/max 0/step 0

Θ : min -180/max 180/step 100

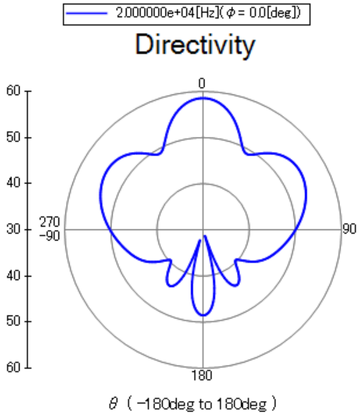
Horizontal axis: θ

[YZ Plane]

Φ : min 90/max 90/step 0

Θ : min -180/max 180/step 100

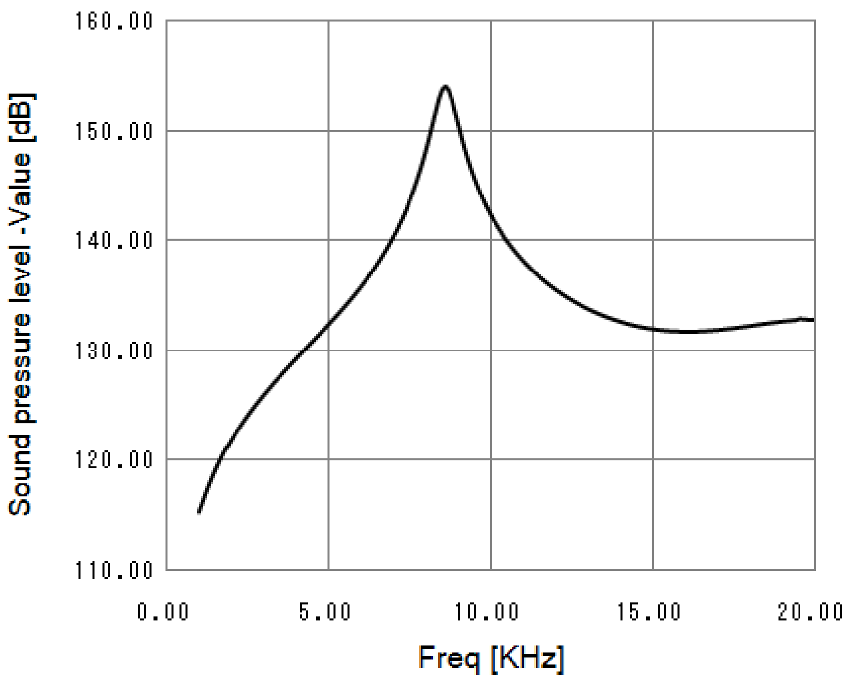
Horizontal axis: θ

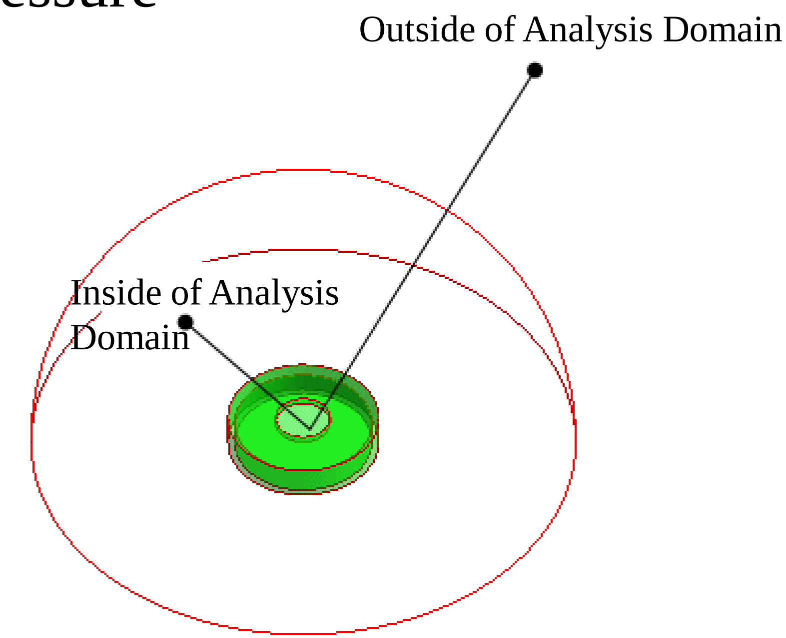


Example of Directivity of [XZ Plane]

Results Display
Graph of Frequency Response

Frequency Response of Sound Pressure





<u>Inside of Analysis Domain</u>
Use Graph function of the contour diagram.

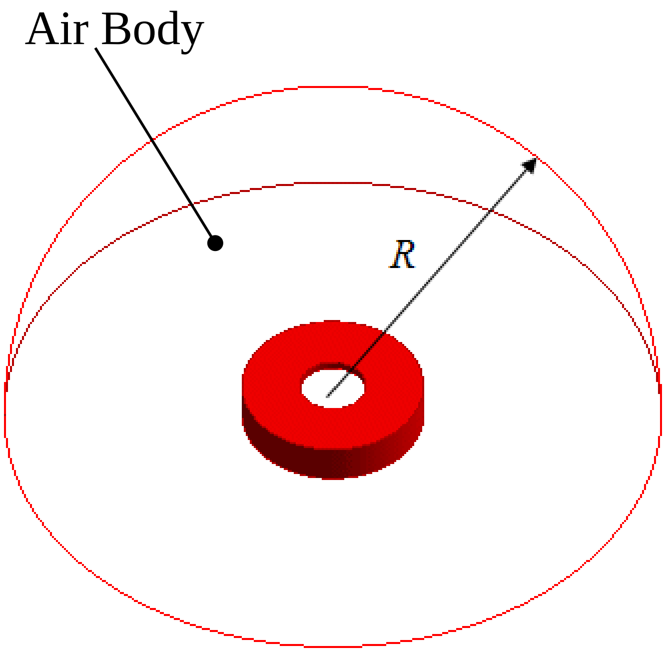
<u>Outside of Analysis Domain</u>
Refer to [Acoustic Analysis Example 8].
Or use macro in the Technical Note [Frequency Response of Sound Pressure Level].

6. Points of Acoustic Analysis

(1) Analysis Domain
(2) Mesh Size
(3) Multiple Sound Sources
(4) Frequency-dependent Sound Speed

(1) Analysis Domain

Create air body around the sound source



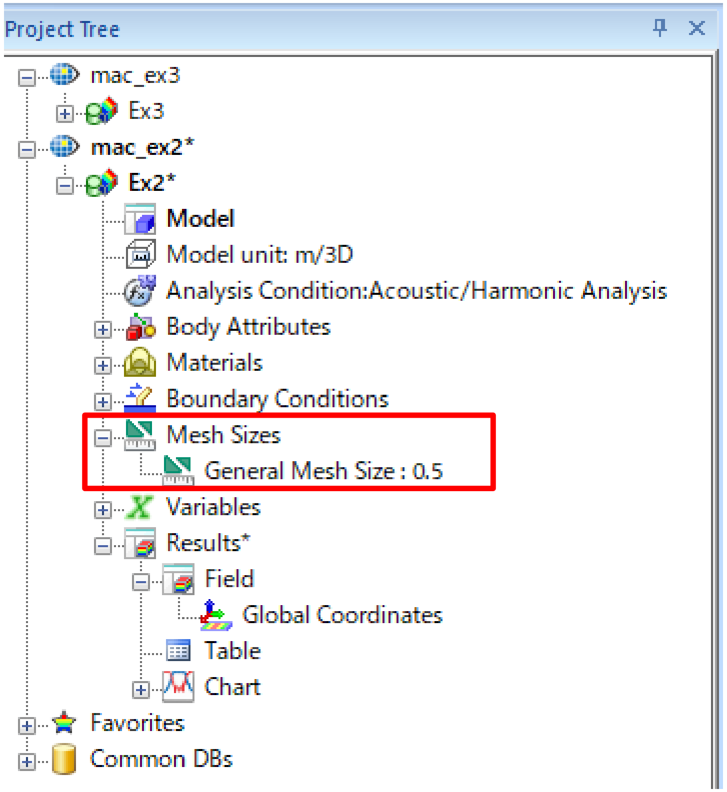
The radius of the air body is R.

R is 0.2 times the wavelength of the frequency of your interest.
If the value is small, a warning will show up as below.

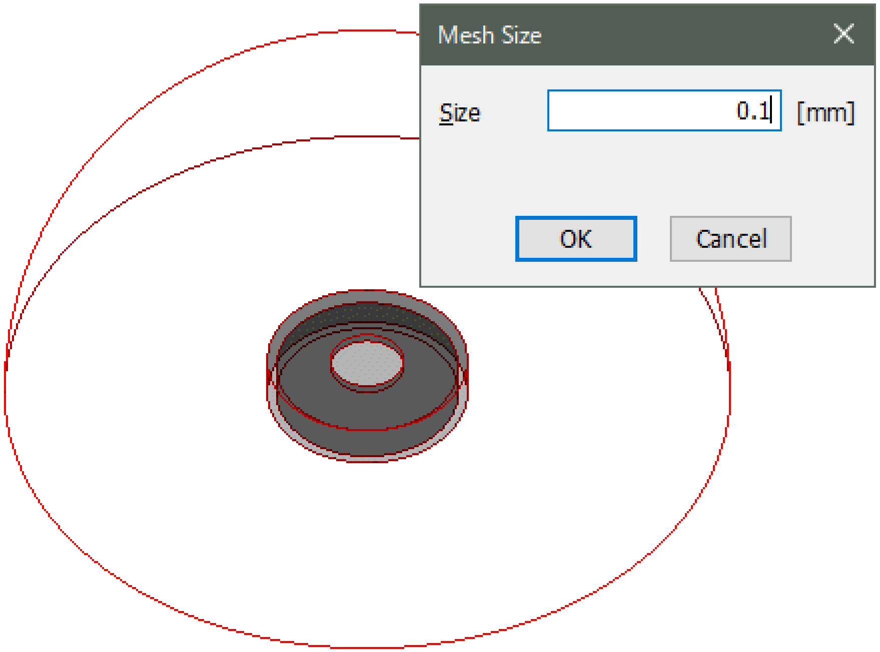
** Warning **
Distance between the wave source and the open boundary is too short. Separate them at least 0.2 wavelength.

(2) Mesh Size

Mesh size is somewhere between
a fourth and sixth of the wavelength.



Finer mesh must be applied to the
complicated form near the sound source.

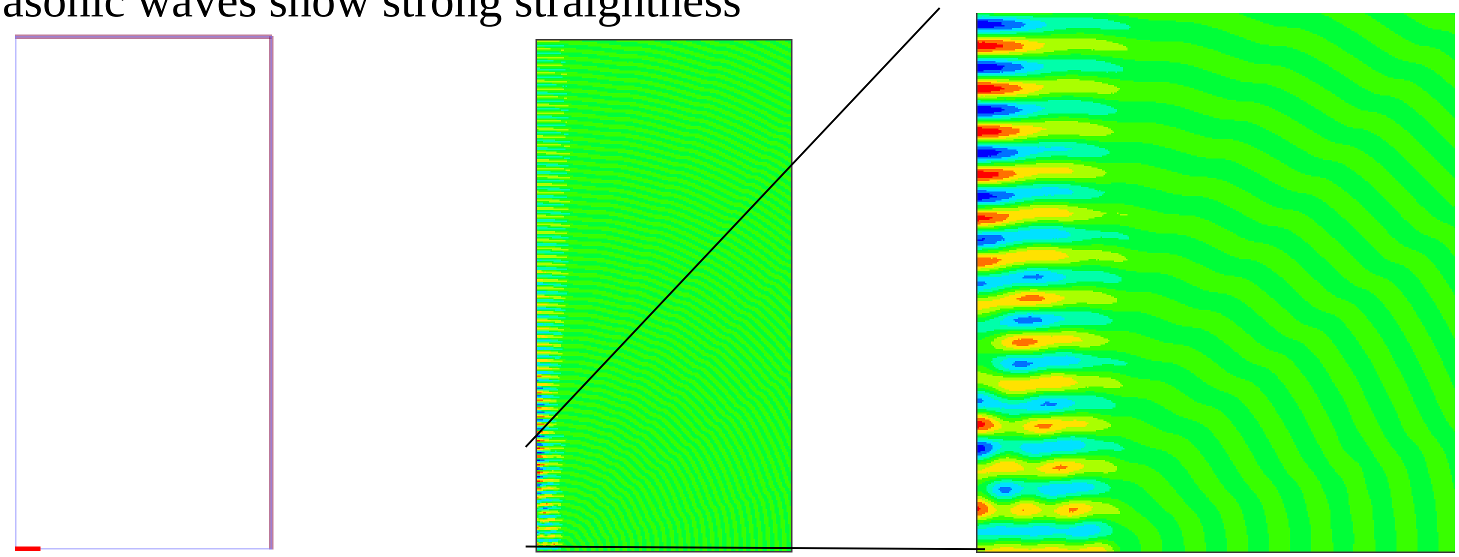


(2) Mesh Size

Ultrasonic Analysis

To prepare the mesh of a sixth of the wavelength, the number of meshes becomes large if the analysis domain is wide.
In such case, a quarter model or axisymmetric model are helpful.

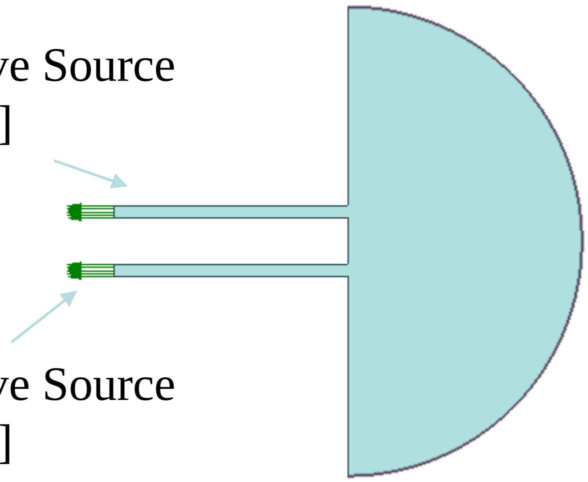
[Example]
Axisymmetric Model (1MHz)
Ultrasonic waves show strong straightness



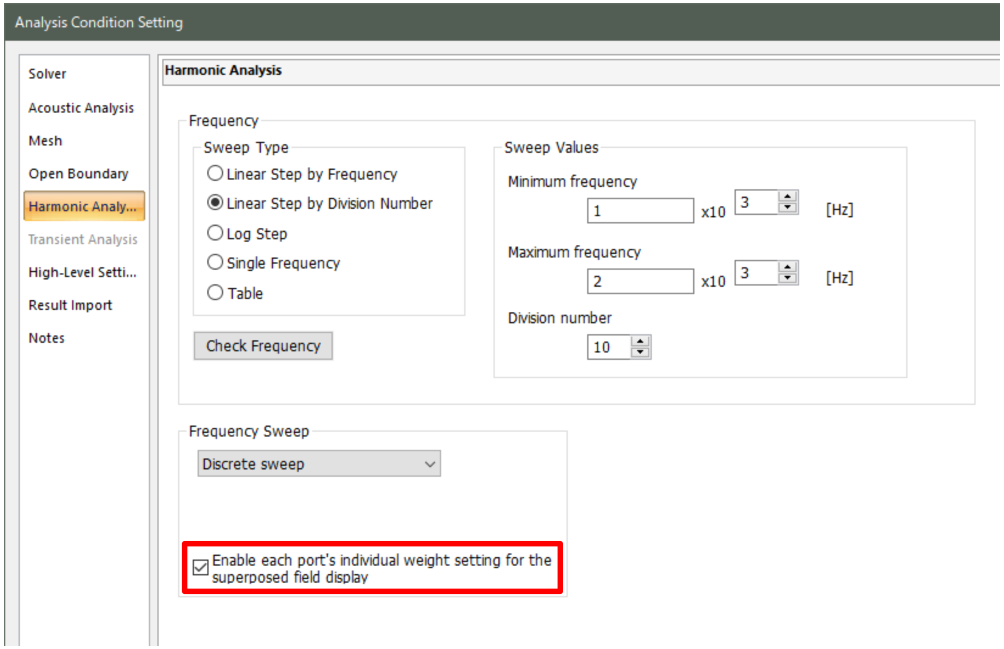
Wave Source

(3) Multiple Sound Sources

Wave Source
[V1]



Wave Source
[V2]

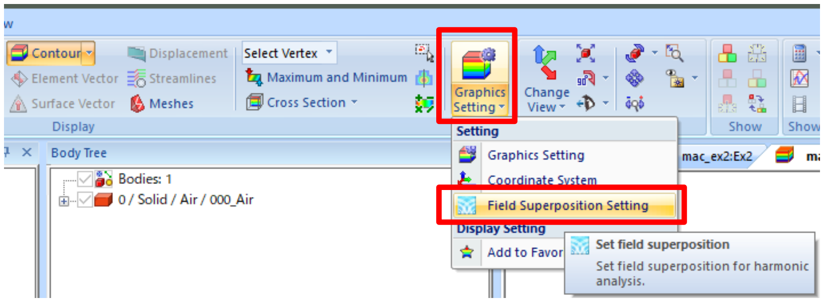


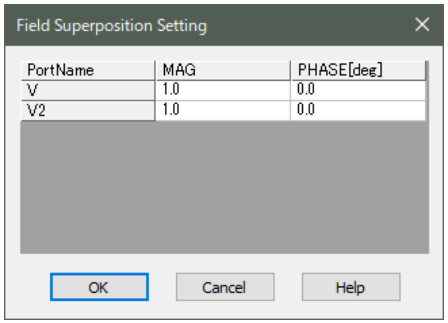
Select [Enable each port's individual weight setting for the superposed field display]

Acoustic Analysis Example 3

(3) Multiple Sound Sources

Murata Software




Field Superposition Setting

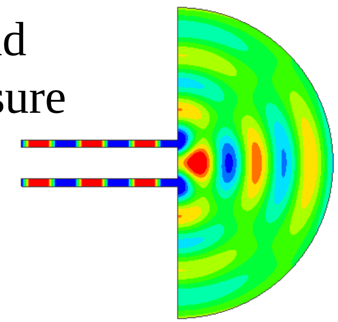
PortName	MAG	PHASE[deg]
V	1.0	0.0
V2	1.0	0.0

OK Cancel Help

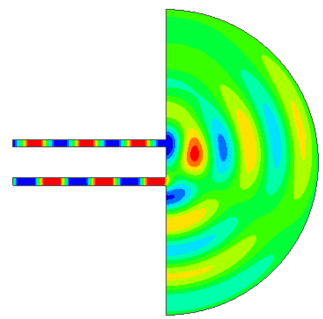
Scale factor and phase can be shifted for each boundary condition of the results.

Phase Difference: 0

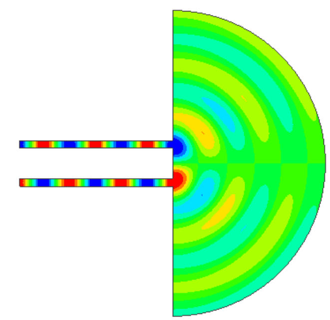
Sound Pressure



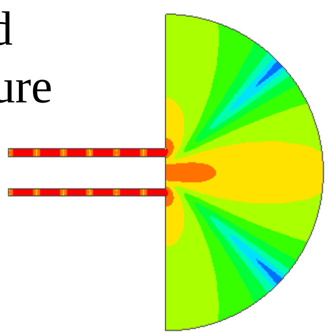
Phase Difference: 90

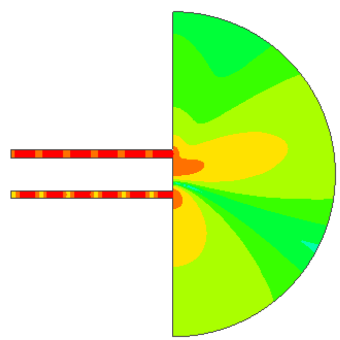


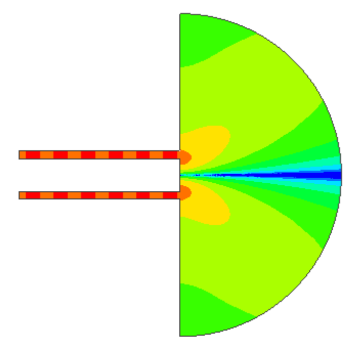
Phase Difference: 180



Sound Pressure Level



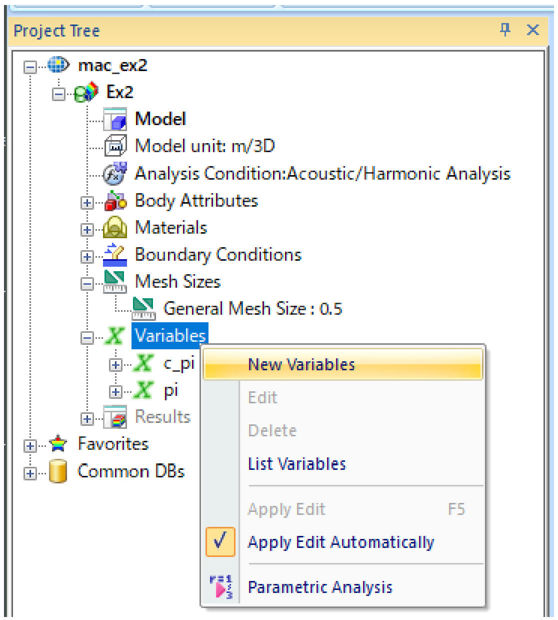


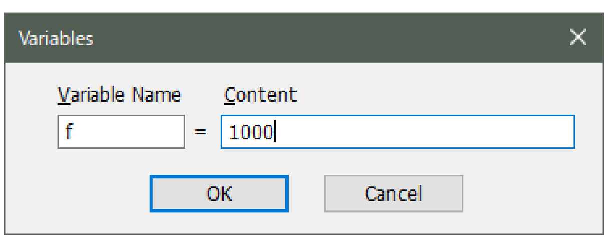


(4) Frequency-dependent Sound Speed

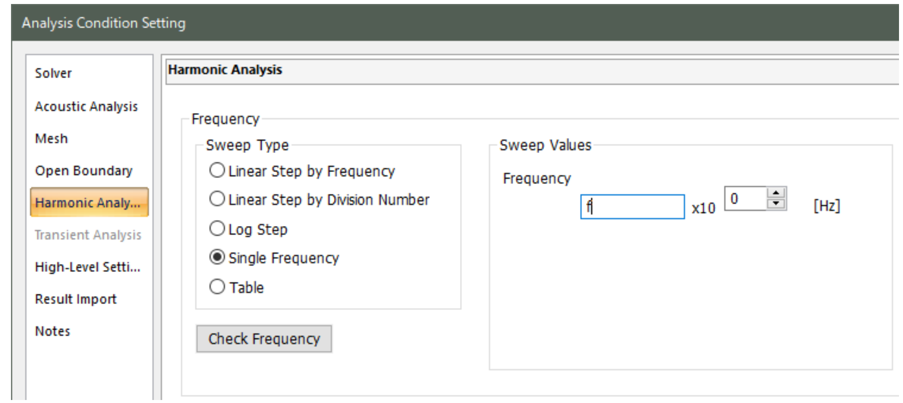
Murata Software

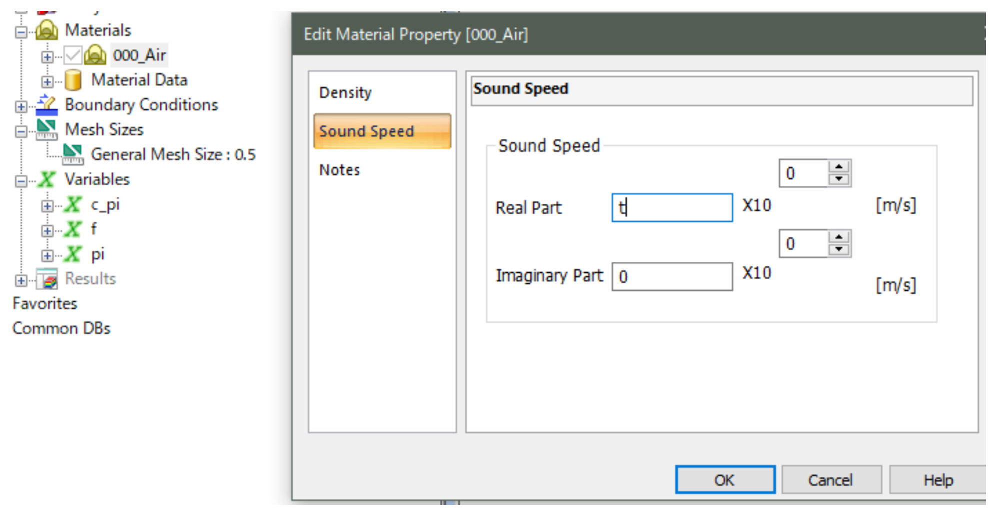
Project Tree > Right-click on Variables > Select [New Variables]





Prepare variables f and t.
Initial value can be any values.



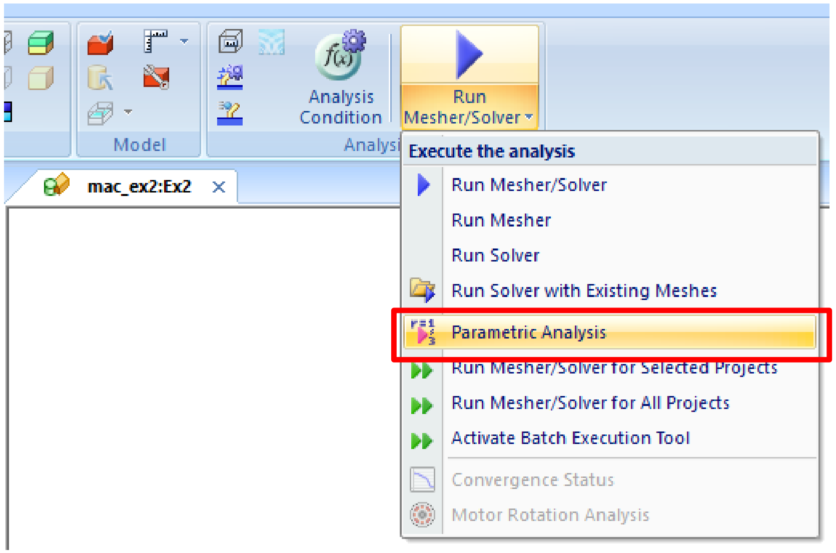


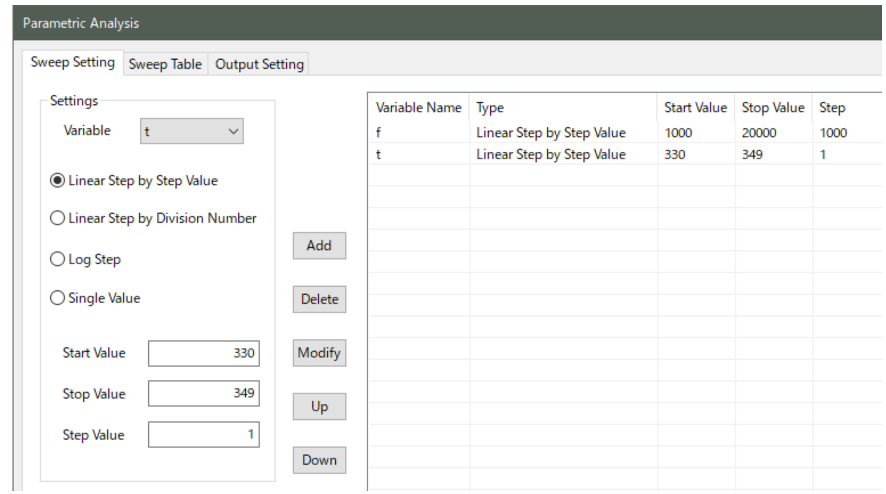
Analysis Condition Setting > Harmonic Analysis > Set f to Frequency.
Edit Material Property > Set t to Sound Speed.

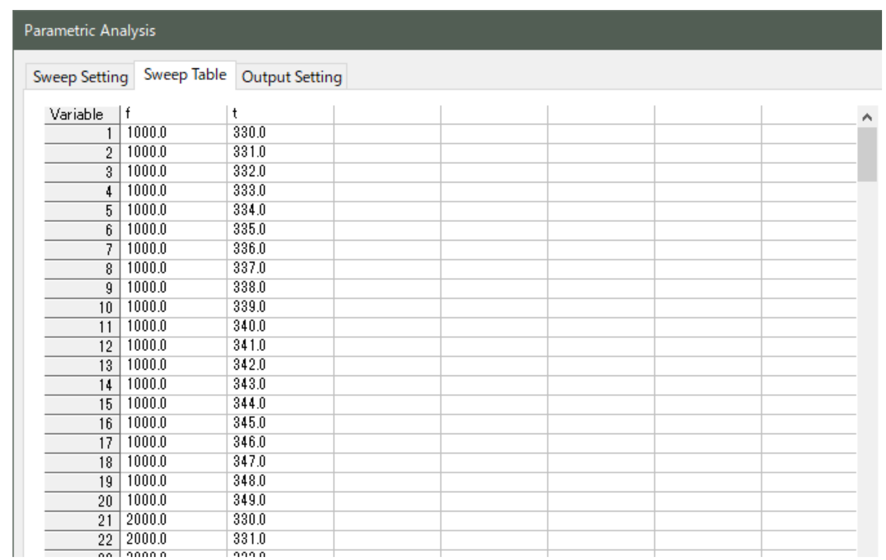
(4) Frequency-dependent Sound Speed

Murata Software

Run Mesher/Solver > Submenu > Parametric Analysis





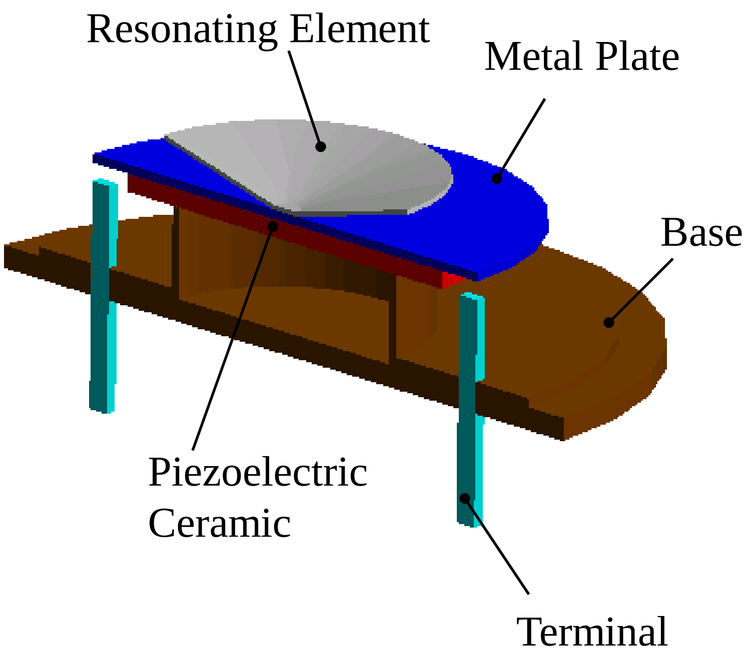


By setting in the [Sweep Table], analysis can be performed while changing frequencies (f) and sound speed (t).

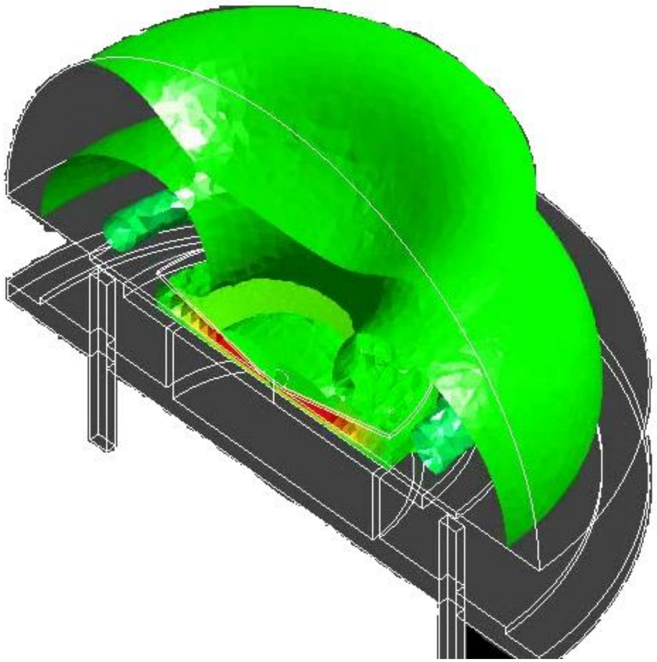
Table of Contents

Ultrasonic Sensor

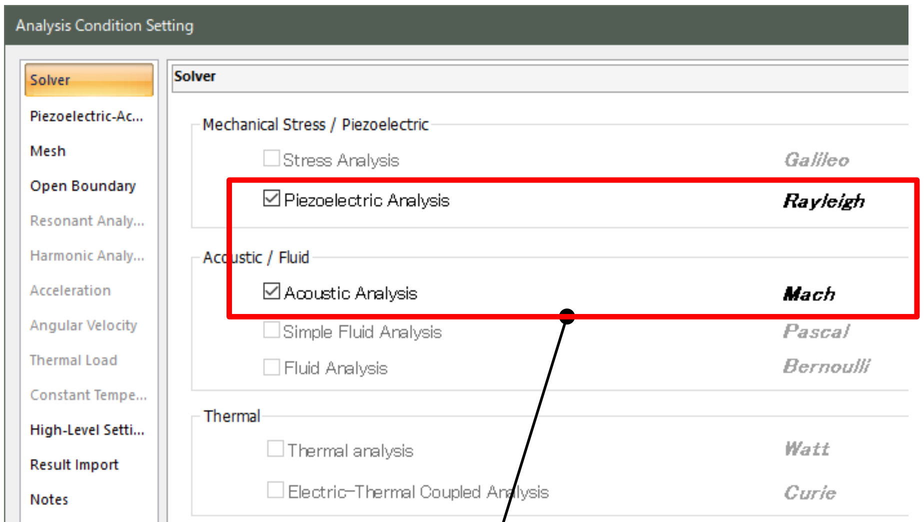
Piezoelectric Analysis

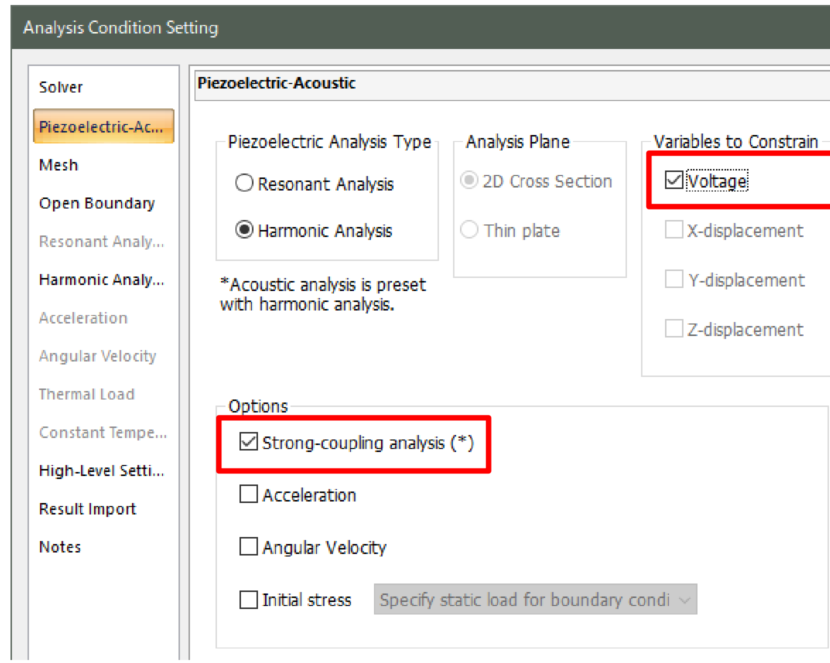


Acoustic Analysis



Analysis Condition

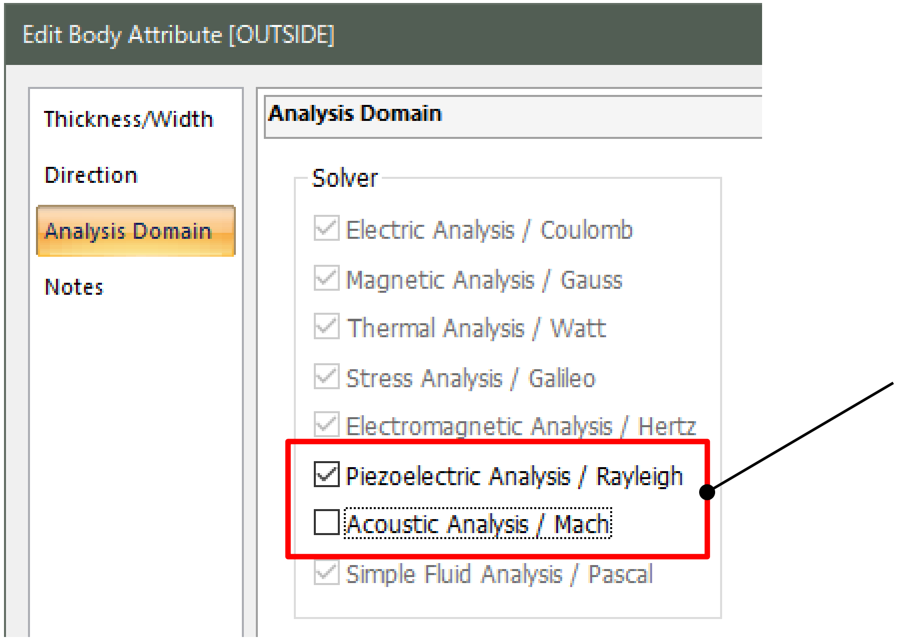




Select [Piezoelectric Analysis] and [Acoustic Analysis]

Select [Strong-coupling analysis].
Select [Voltage] if [piezoelectricity] is not taken into account.

Body Attribute



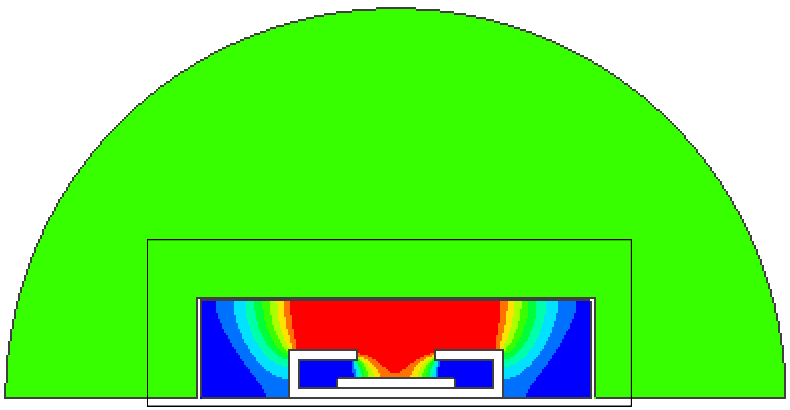
Select [Piezoelectric Analysis] for solid.
Select [Acoustic Analysis] for media.
Both cannot be selected at the same time.

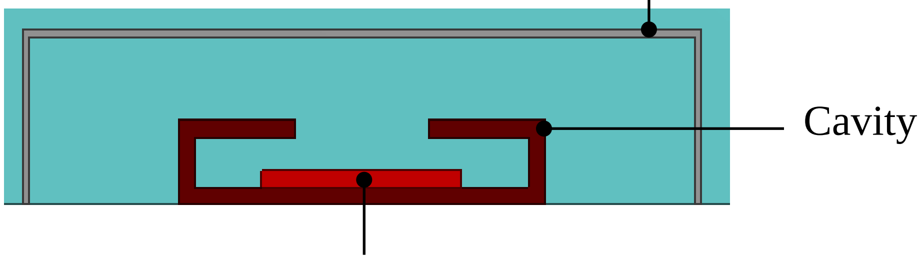
Strong-coupling Analysis

Weak-coupling Analysis

(Unidirectional from piezoelectric to acoustic)

The vibrating effect of the structure by the sound waves cannot be calculated. The sound waves outside the shielding plate cannot be calculated either.

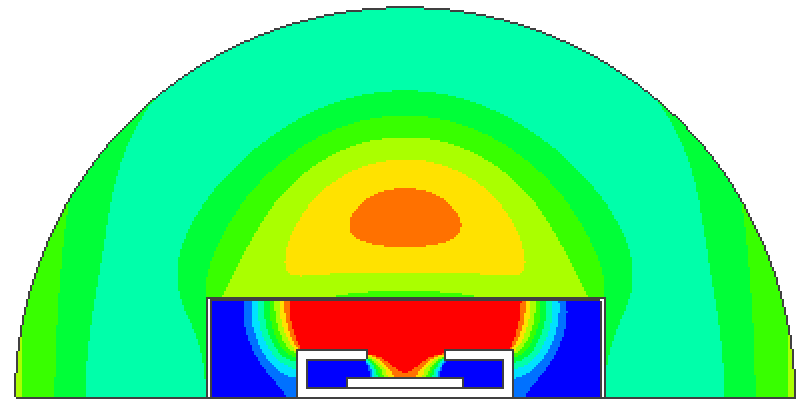


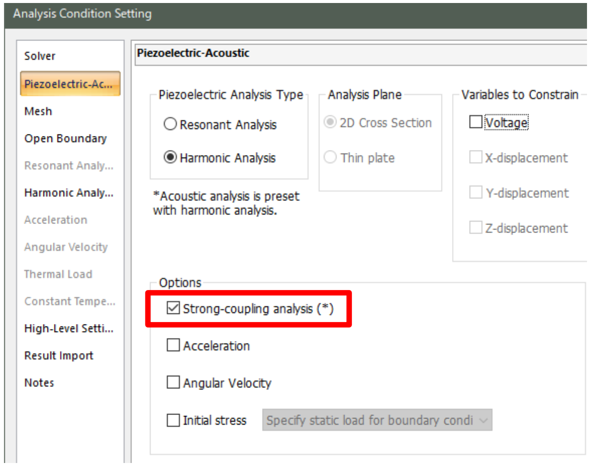


Strong-coupling Analysis

(Bidirectional between piezoelectric and acoustic)

The vibrating effect of the structure by the sound waves can be calculated and the sound waves outside the shielding plate can be calculated as well. However the calculation time is long.





Thank You