Murata Software

Femtet Seminar

Understanding Magnetic Analysis

202009

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Solvers of Electromagnetic Fields

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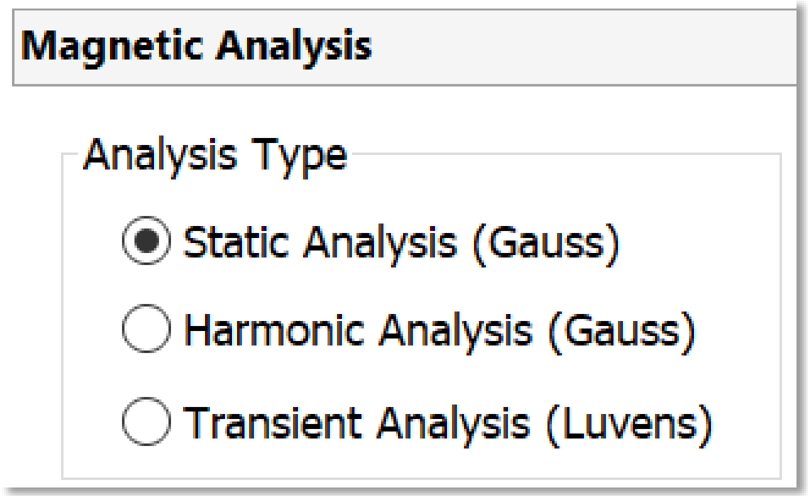
3 types of solvers are available

Solver Type	Frequencies to Solve
Electric	Constant Current, Voltage Low Frequencies (~1MHz)
Magnetic	
Electromagnetic	High Frequencies (1MHz ～ GHz order)

Analysis Type

3 analysis types are available for magnetic analysis.



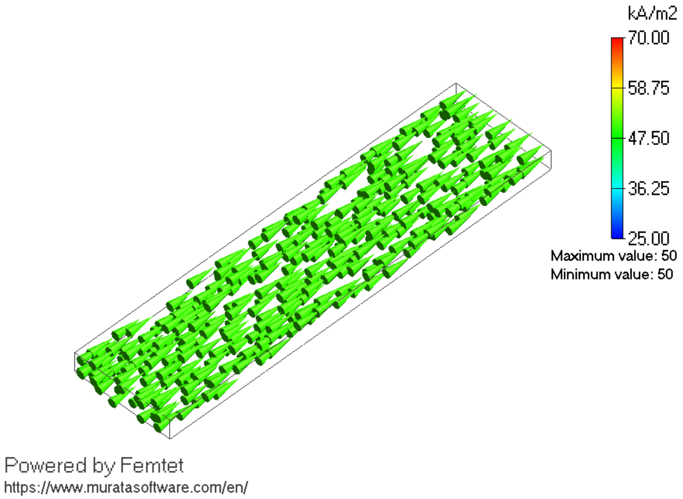
Static	Harmonic	Transient
• Static Magnetic Field Distribution • Inductance • Electromagnetic Force, etc.	• AC Magnetic Field Distribution • Inductance with Skin Effect Taken into Account • Induced Current, Induced Heat	• Magnetic Distribution on Time Axis • Induced Current • Motor

Static Analysis

The distribution of static magnetic field generated by direct current or magnet is analyzed.

The inductance and electromagnetic force are calculated as well.

The materials with nonlinear BH curve can be analyzed too.



Distribution of Current Density (Static Analysis)

Freq.=0 (DC)

$$\nabla \times \frac{1}{\mu}(\nabla \times A) = J_0$$

is solved.

A: magnetic vector potential (magnetic flux B=∇ × A)
Φ: potential   μ: permeability   σ: conductivity
J0: forced current density

Harmonic Analysis

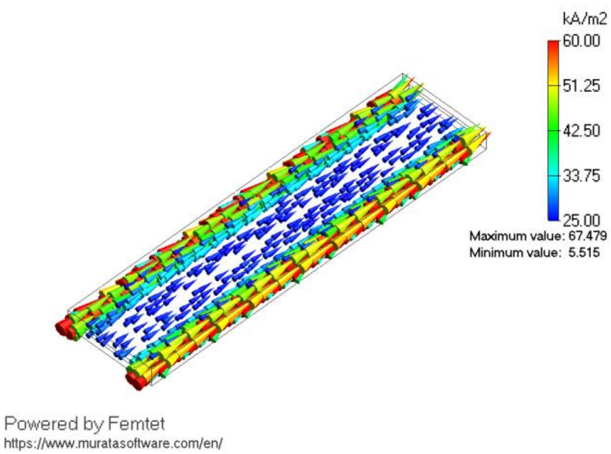
The AC magnetic field distribution (dynamic magnetic field distribution) is calculated, which is generated by alternating current.

It is possible to take the induced current and the skin effect into account.

The inductance is also calculated.

Calculation of the induction heating (IH) is also possible by coupling with thermal analysis.

It is not possible, however, to analyze the materials with nonlinear BH curves.



Current Density Distribution (10kHz)

0<Frequency (AC)

$$\nabla \times \frac{1}{\mu}\left(\nabla \times A\right) + \sigma\left(j\omega A + \nabla \phi\right) = J_0$$

is solved.

A: magnetic vector potential (magnetic flux B=∇ × A)
Φ: potential   μ: permeability   σ: conductivity
J0: forced current density

Transient Analysis

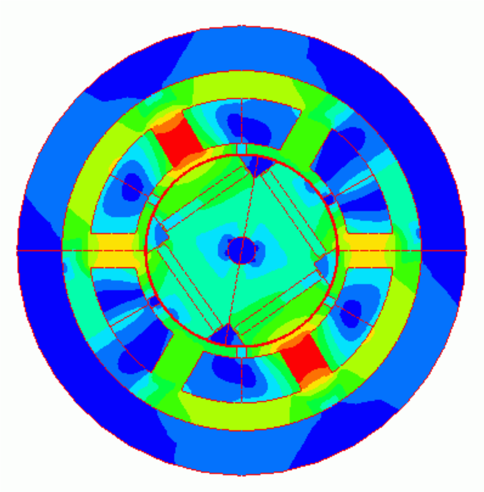
Transient analysis is optional.

The magnetic field distribution (dynamic magnetic field distribution) of time axis is calculated, which is generated by the DC/AC/arbitrary-waveform current, and magnet.

It is possible to take the induced current and the skin effect into account.

It can handle the materials with nonlinear BH curves.

Coupled analysis with an external circuit is possible, which enables the motor analysis.



Magnetic Flux Density

Analysis on Time Axis

$$\nabla \times \frac{1}{\mu}(\nabla \times A) + \sigma\left(\frac{\partial A}{\partial t} + \nabla \phi\right) = J_0$$

is solved over time steps.

A: magnetic vector potential (magnetic flux B=∇ × A)
Φ: potential μ: permeability σ: conductivity
J0: forced current density

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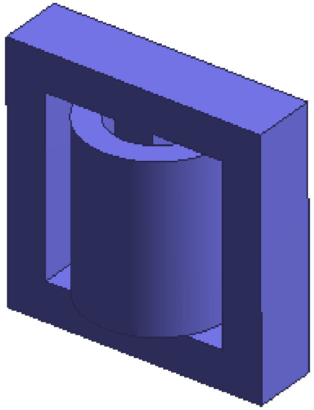
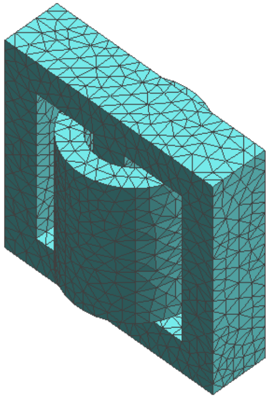
Analysis Flows

- 3D Model Creation
- Analysis Condition: Analysis type, Mesh size, etc.
- Body Attribute: Magnetization direction, etc.
- Material Property: Relative permeability, Conductivity, Iron loss, etc.
- Boundary Condition: Electric wall, Magnetic wall, Open boundary, etc.

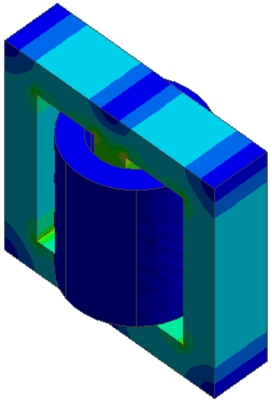


Meshing



Magnetic Filed Analysis

Results Display



Analysis Conditions: Rotating Machine

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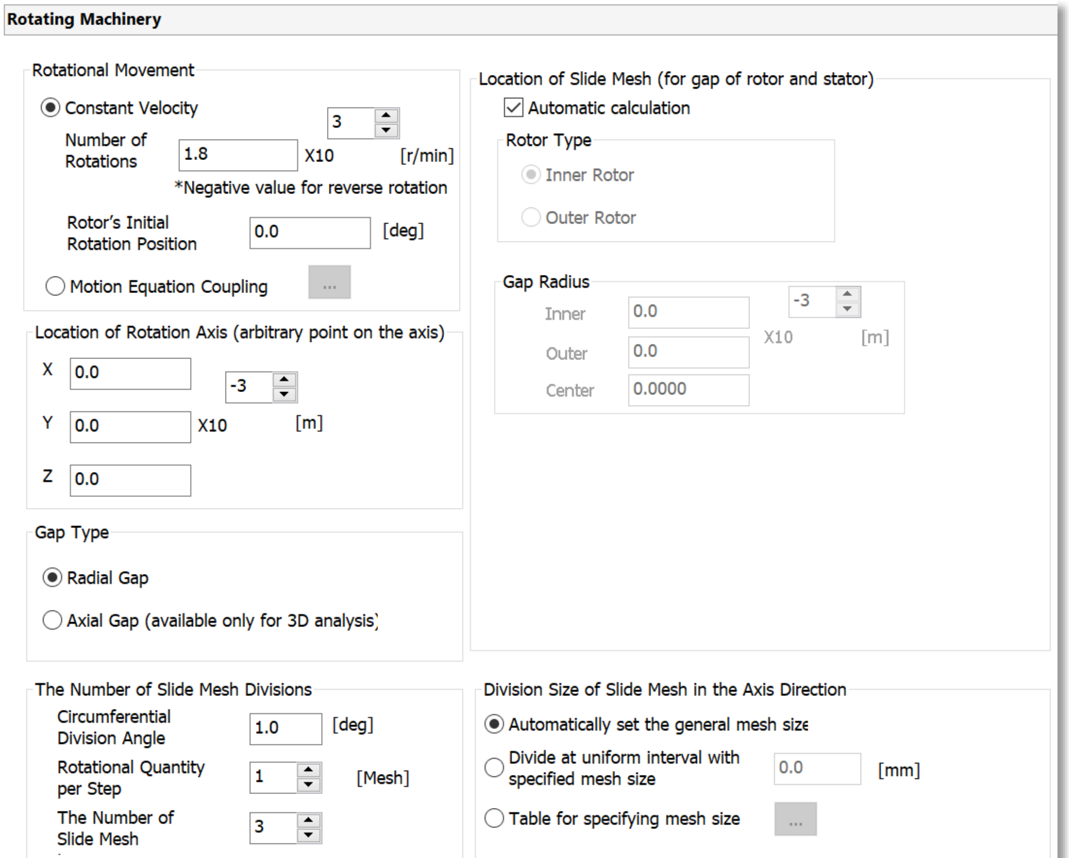
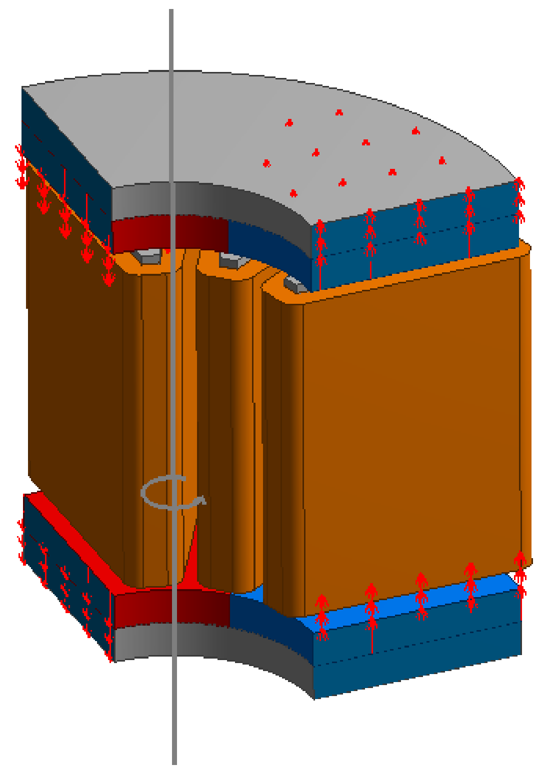
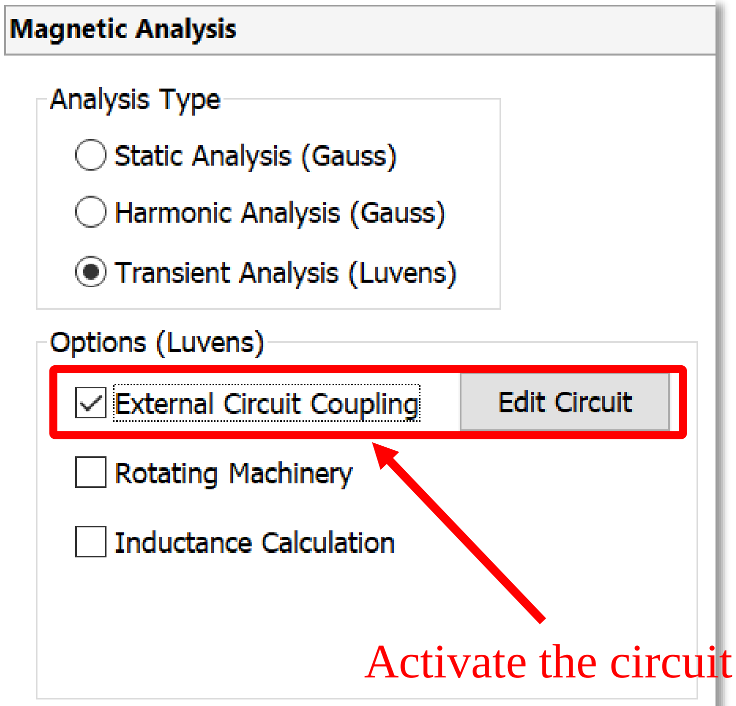
Setting of transient analysis of rotating machine.



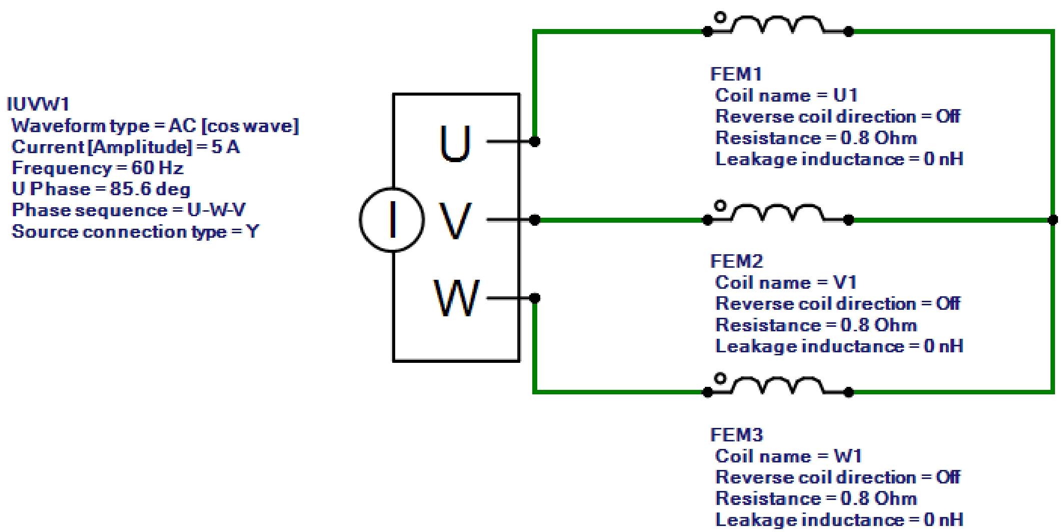


Analysis Conditions: External Circuit

Setting of coupling with an external circuit for transient analysis.



Activate the circuit editor



Analysis Conditions: External Magnetic Field

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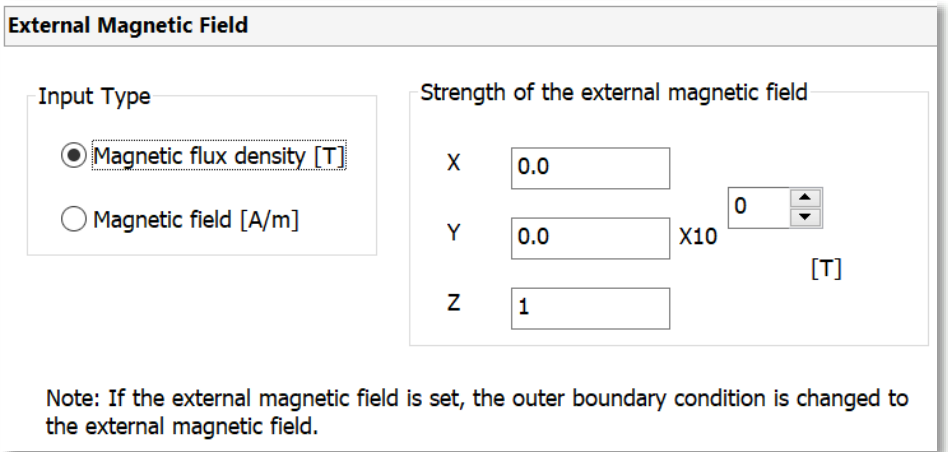
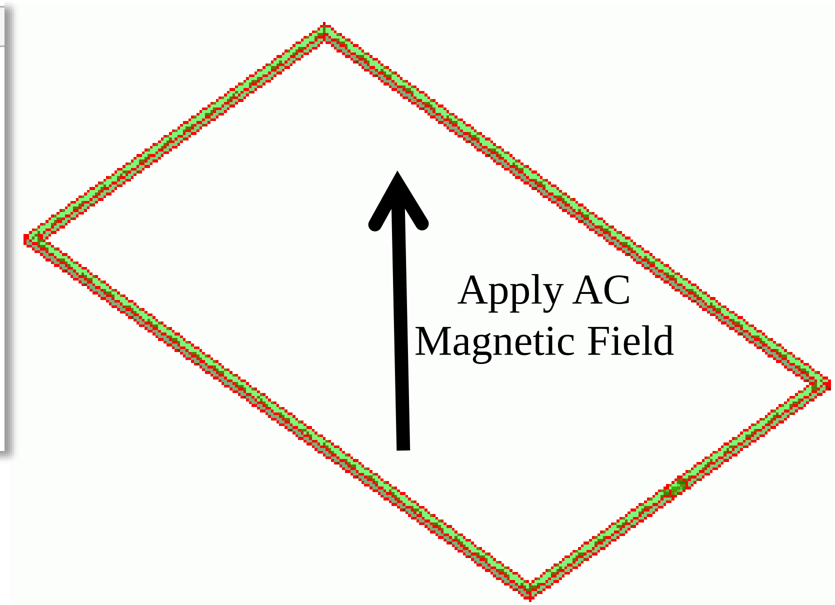
Setting to solve the external magnetic field applied to the analysis model.
In the static and transient analysis, the constant magnetic field is applied.
In the harmonic analysis, the fluctuating magnetic field is applied.





Electromotive Force of Coil

Material Property

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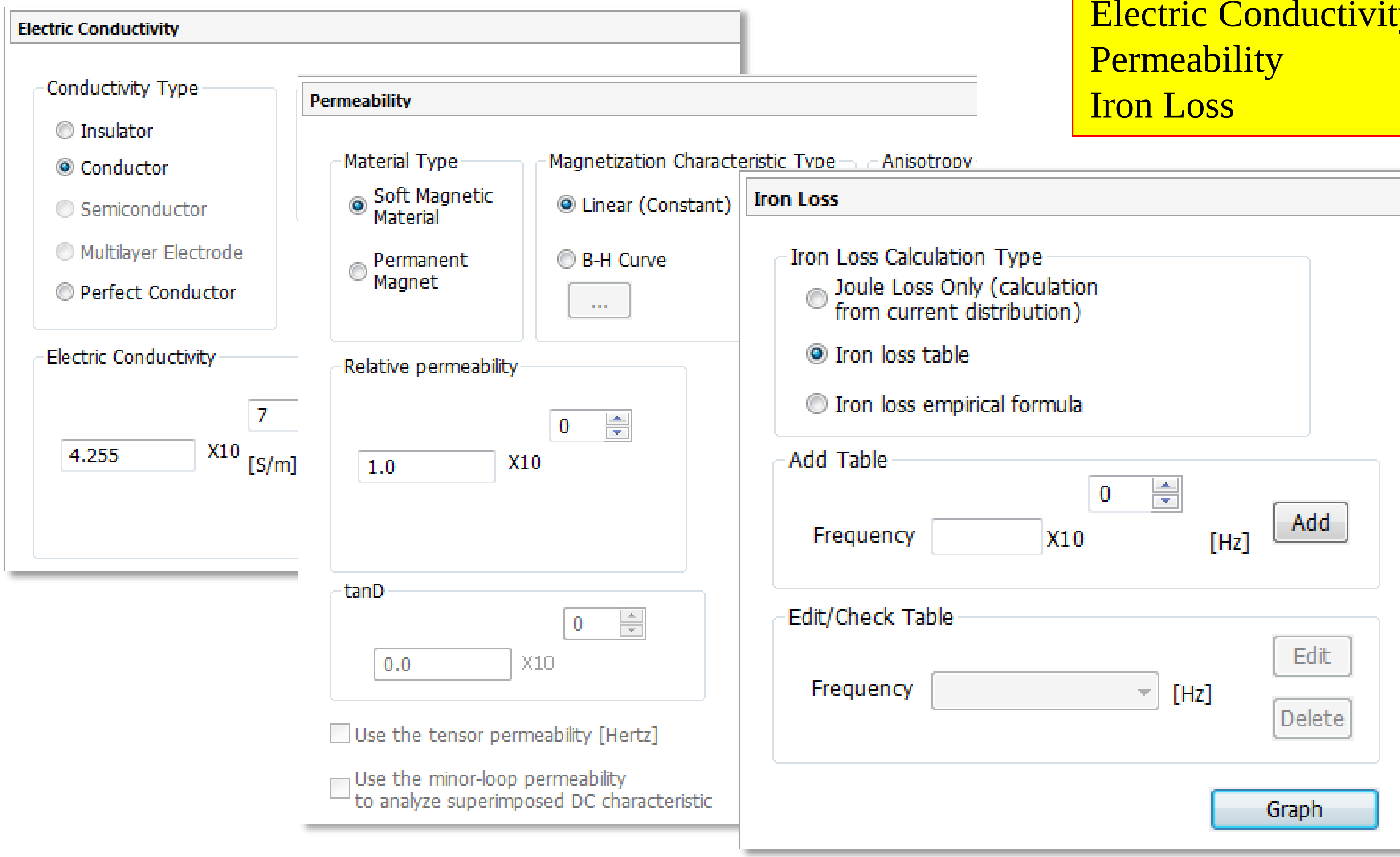
3 types of material properties are available.

Electric Conductivity
Permeability
Iron Loss

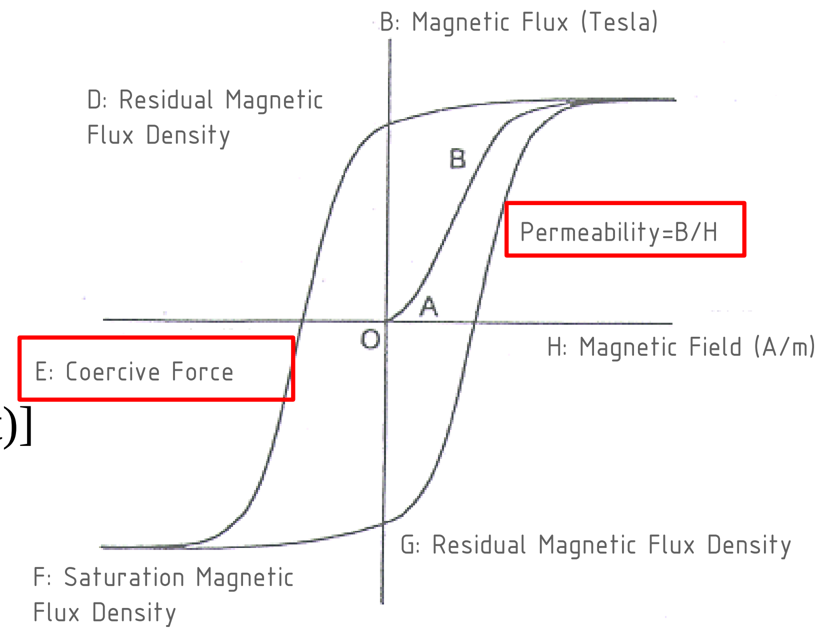


Material Property Setting for Magnetic Materials

Depending on the type of magnetic material, the setting varies.

[Soft Magnetic Material]
Having low coercive force and large permeability.
- -Iron
- -Silicon steel
- -Nickel
- -Perm alloy
- -Soft ferrite, etc.

[Hard Magnetic Material (Permanent Magnet)]
Having high coercive force.
- -Neodymium
- -Alnico
- -Ferrite (hard ferrite)
- -Samarium cobalt, etc.



B-H Curve (Magnetic Hysteresis Curve)

Material Property Setting: Soft Magnetic Material

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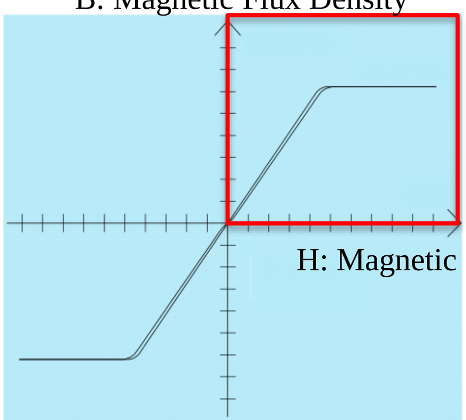
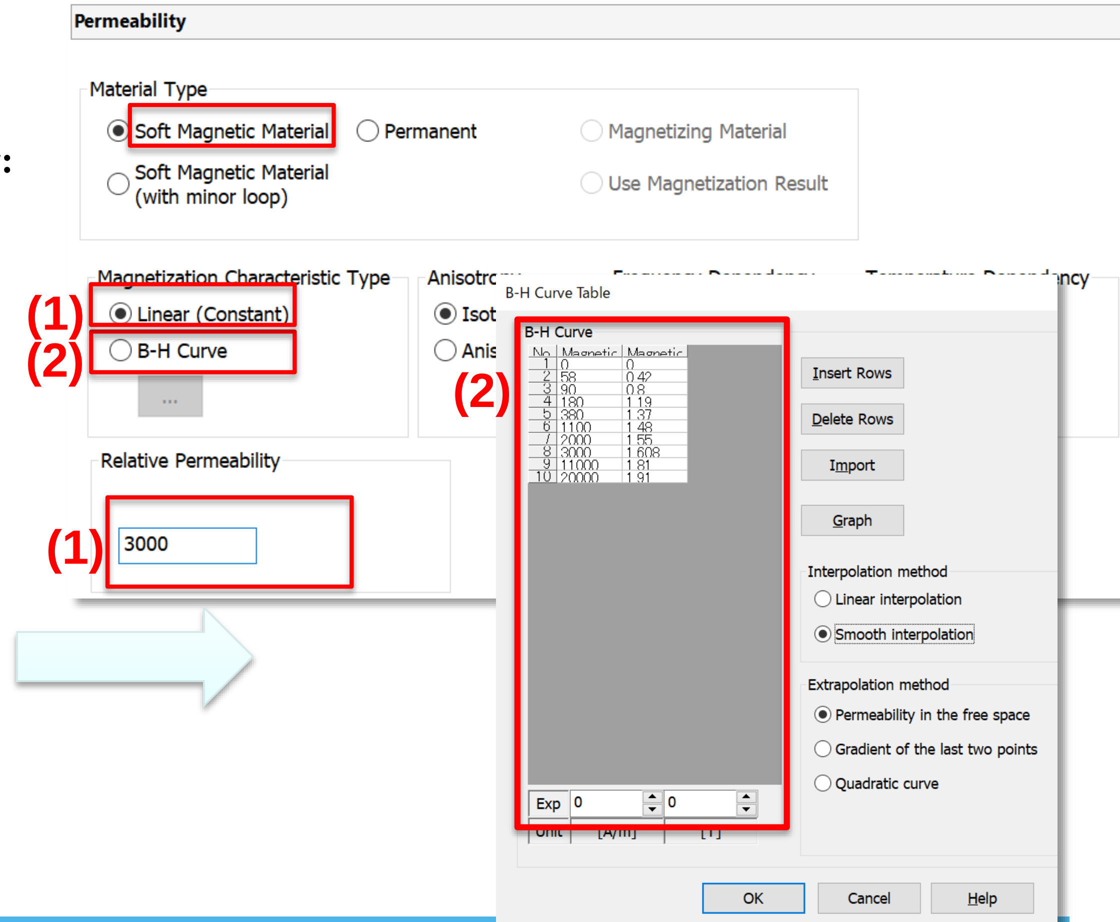
Select [Soft Magnetic Material] on the Permeability tab.
Enter either (1) or (2) below.

(1) If you want to calculate in short time:
Enter [Relative permeability].

(2) If you want to calculate with accuracy:
Enter B-H curve data (usually, of the first quadrant) in the table.
The B-H curve data can be obtained on the websites of the material suppliers.



B-H Curve of Soft Magnetic Material



Material Property Setting: Permanent Magnet

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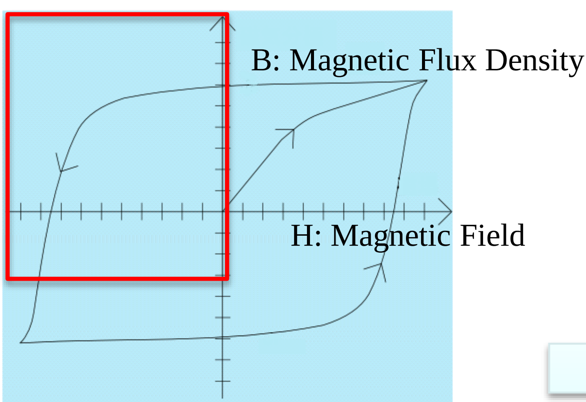
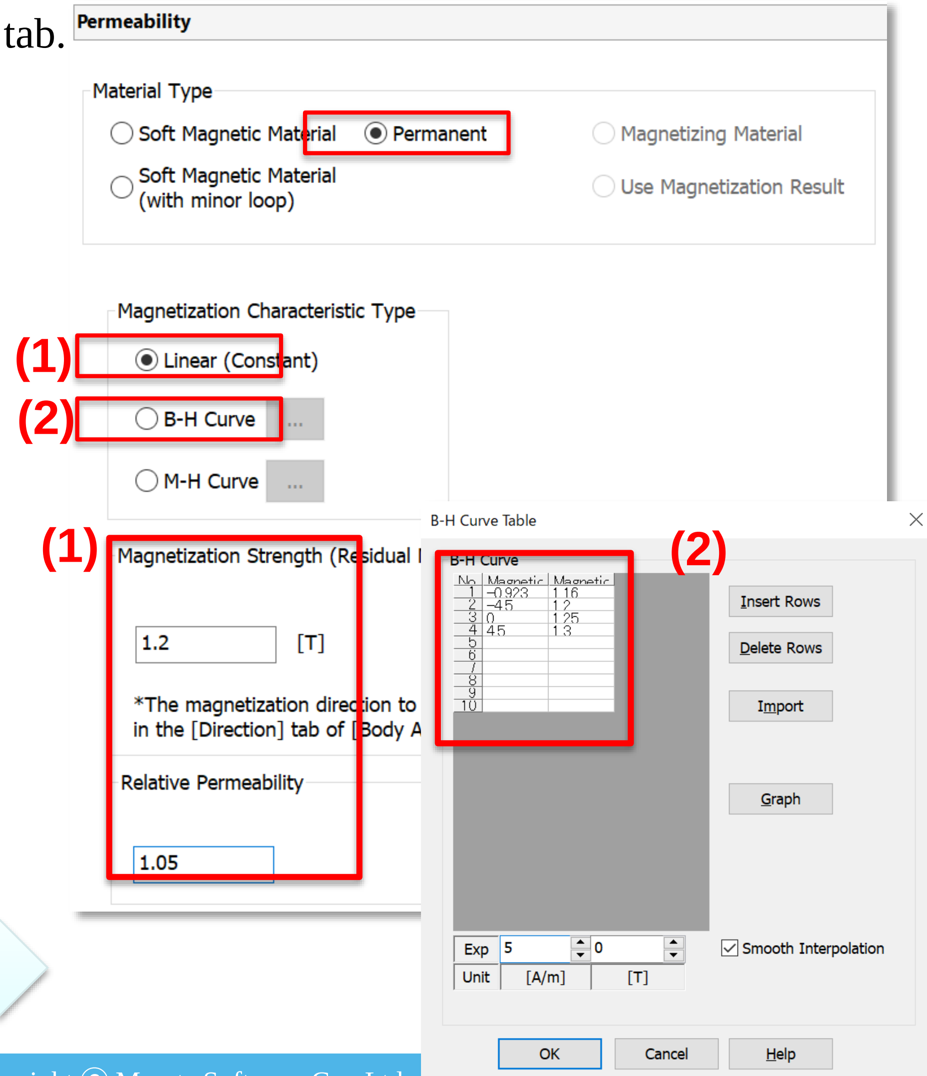
Select [Permanent magnet] on the Permeability tab.
Enter as follow on the Magnet Tab.

(1) If you want to calculate in short time:
Enter [Magnetization Strength] and [Relative Permeability].

(2) If you want to calculate in short time:
Enter B-H curve data (usually, of the second and third quadrant) in the table.
The B-H curve data can be obtained on the site of material supplier.



B-H Curve of Permanent Magnet

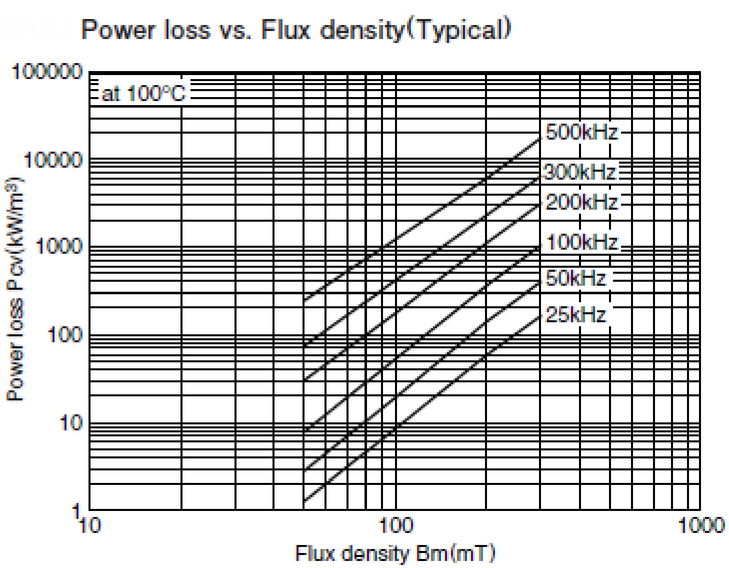


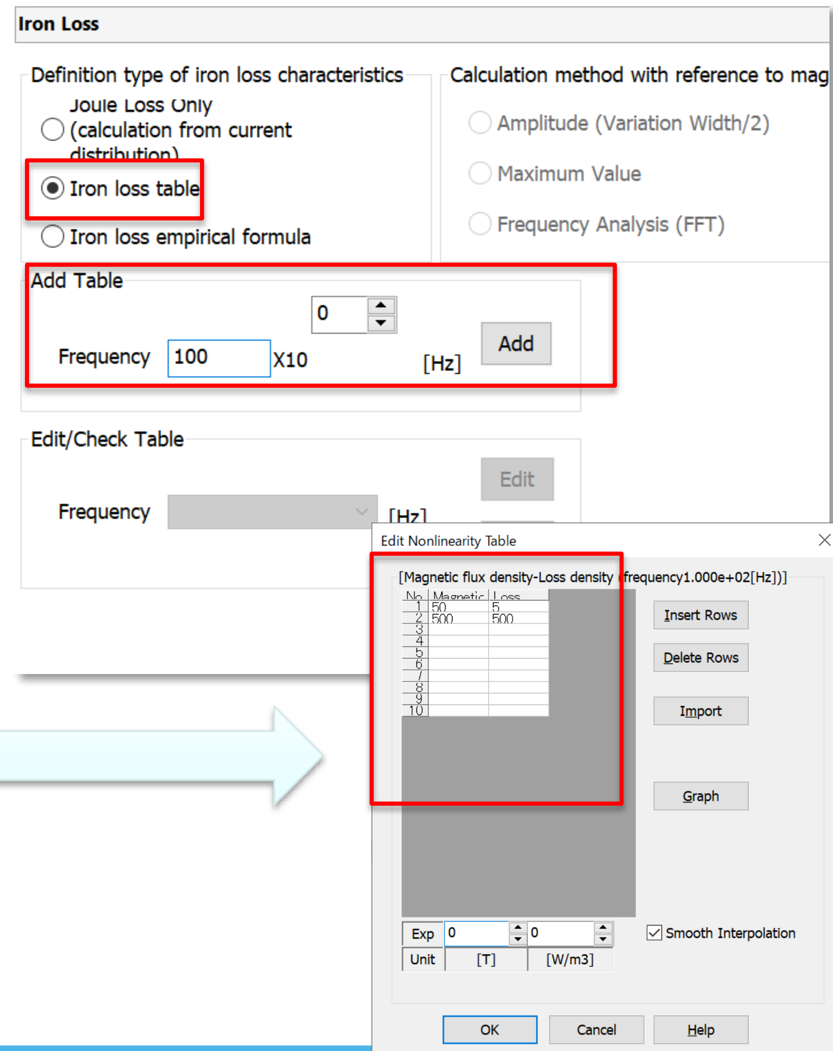
Material Property Setting: Iron Loss

There are two methods to set the iron loss.

1. Iron Loss Table

Enter the magnetic flux density and the loss density for each frequency in the table.
The data can be obtained from the material suppliers' websites.





Material Property Setting: Iron Loss

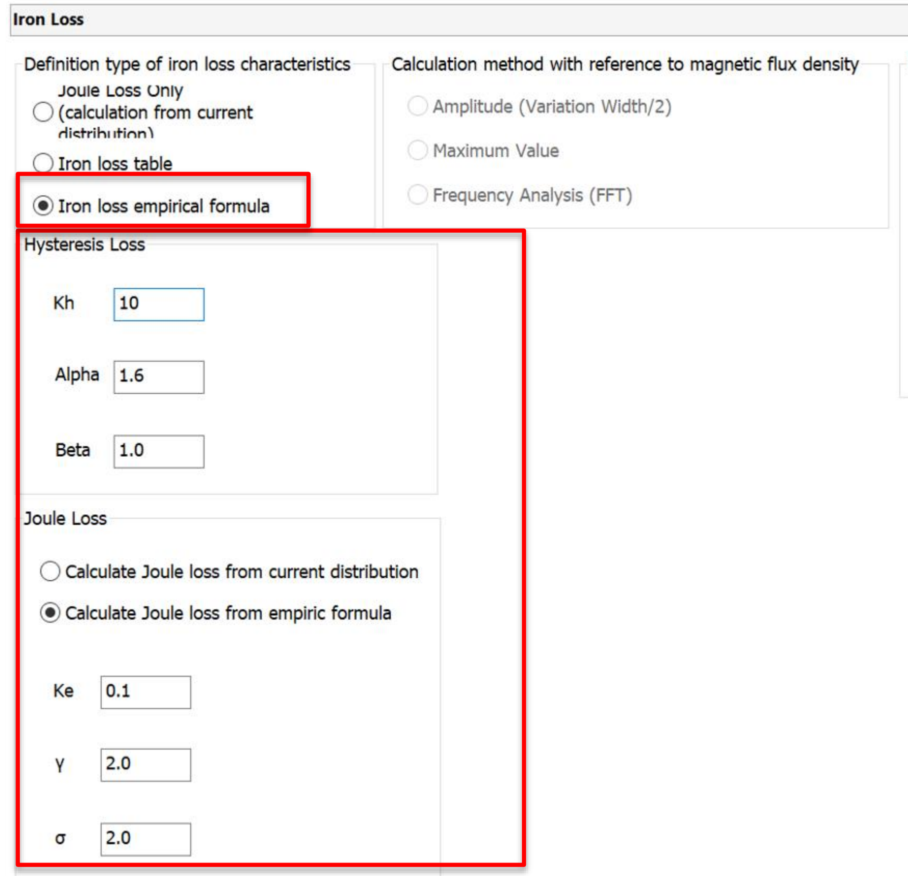
2. Iron Loss Empirical Formula

Enter the coefficients of
the iron loss empirical formula.

$$Wh = \mathrm{Kh}\,B^{\alpha}f^{\beta}$$

$$We = \mathrm{Ke}\,B^{\gamma}f^{\delta}$$

where:
Wh: Hysteresis loss density [W/m^3]
We: Joule loss density [W/m^3]
B: Magnetic flux density [T]
f: Frequency [Hz]



Material Property Setting: Iron Loss

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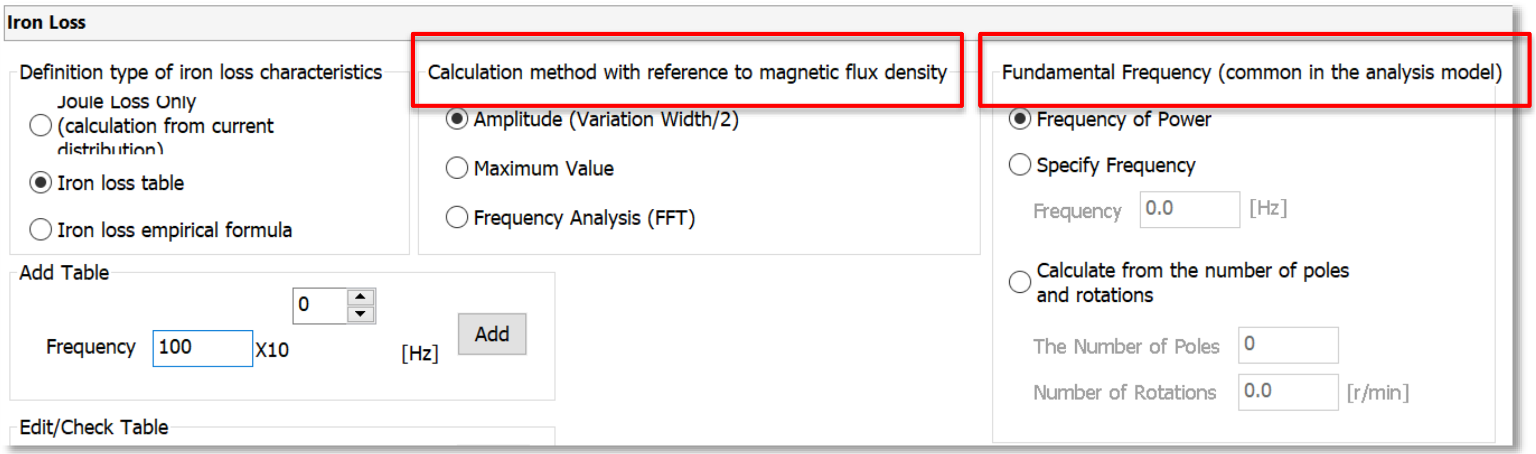
Calculation Method and Fundamental Frequency

The calculation method and the fundamental frequency are a common setting to the iron loss table and the empirical formula.



[Calculation Method of Iron Loss]
If the input current is sine wave, select [Amplitude].

If the input current is triangular or square wave, and harmonic loss is to be taken into account, select [Frequency analysis (FFT)].
*Transient analysis is required.

[Fundamental Frequency]
Basically, select [Frequency of Power].
If the waveform is arbitrary, the frequency is determined by the time range of the table.

In the case of DC power or if you want to specify the frequency yourself, select [Specify Frequency] or [Calculate from the number of poles and rotations]

Body Attribute

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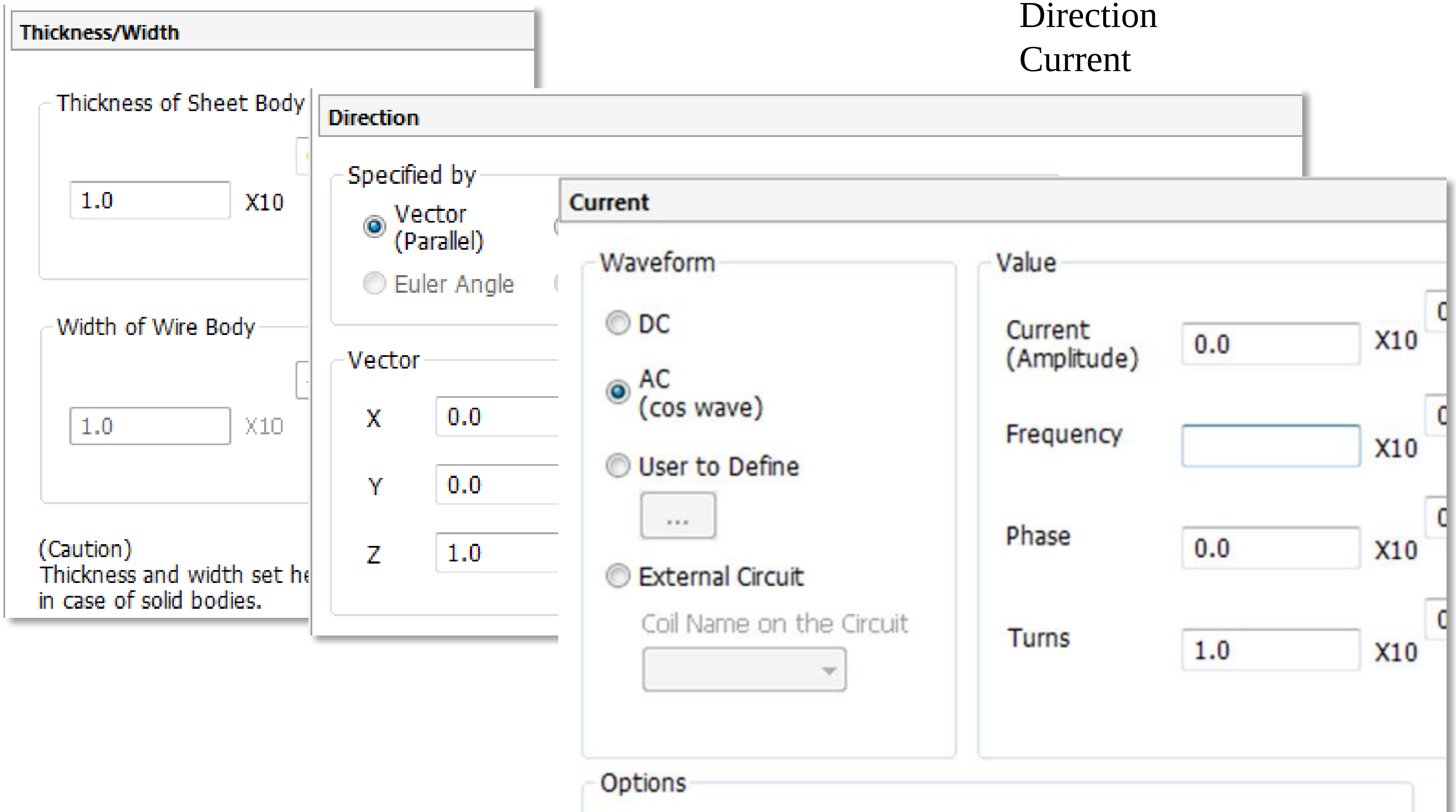
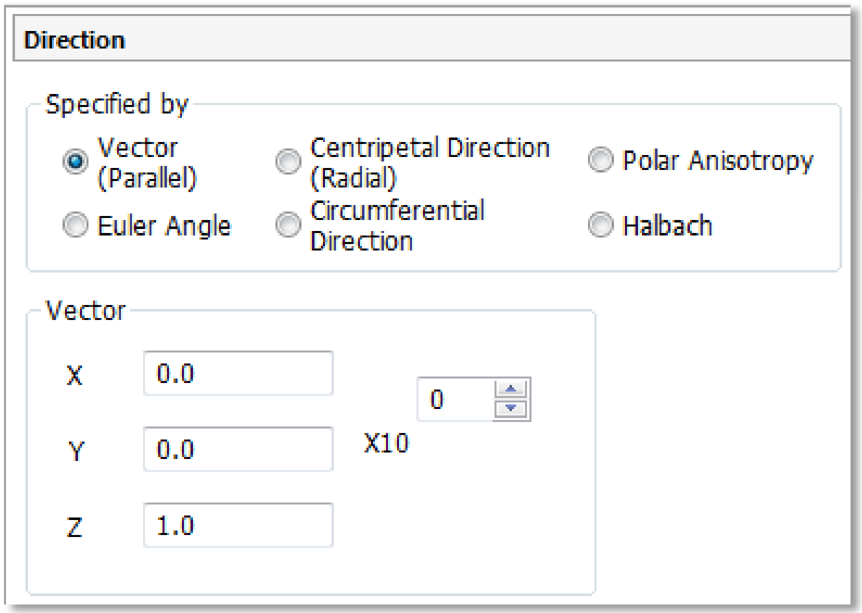
3 types of body attributes are available.

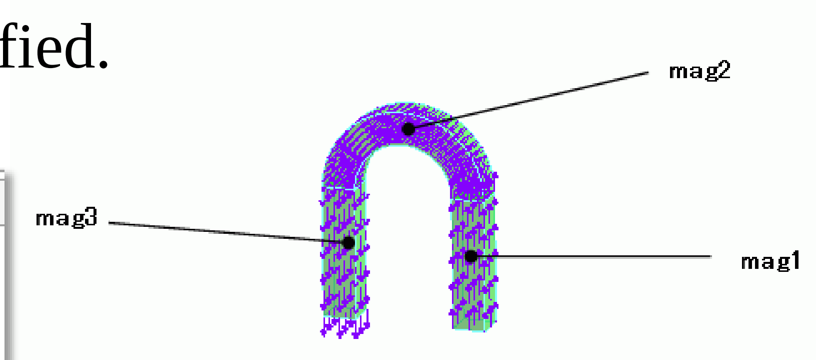
Thickness/Width
Direction
Current



Body Attribute: Direction

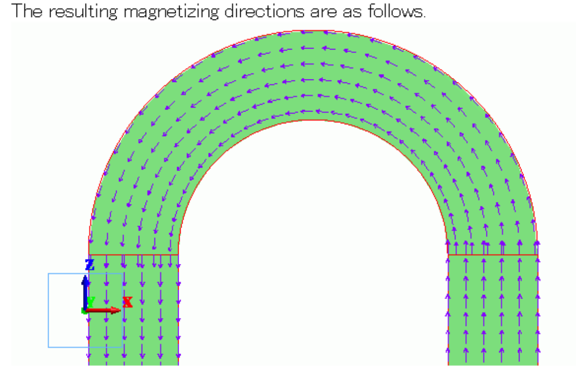
Magnetization direction is specified.





Body Attribute Name	Tab	Setting Item	Settings
mag1	Direction	Direction Type	Vector Tab
		Vector Tab	X=0, Y=0, Z=1
mag2	Direction	Direction Type	Circumferential Direction
		Coordinates on Center Axis	X=0, Y=0.005, Z=0.04
		Vectors of Center Axis	X=0, Y=1, Z=0
		Direction	Anticlockwise
mag3	Direction	Direction Type	Vector
		Vector	X=0, Y=0, Z=-1

The resulting magnetizing directions are as follows.



Horseshoe Magnet

Body Attribute: Current

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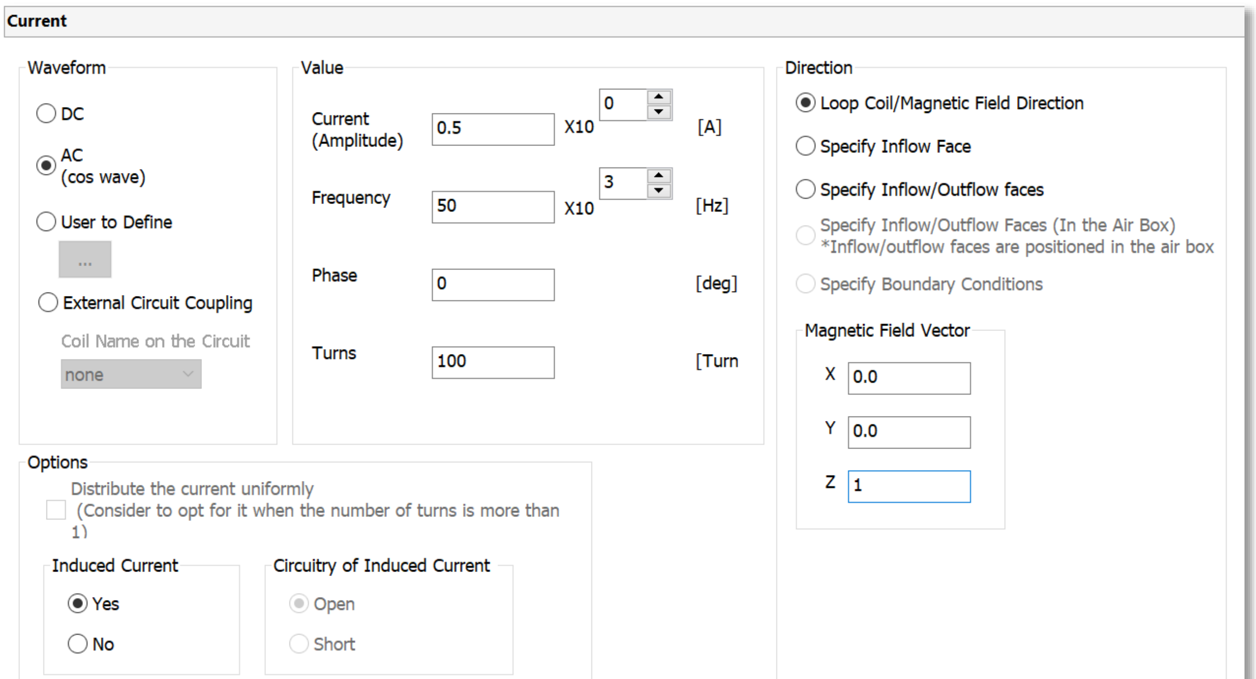
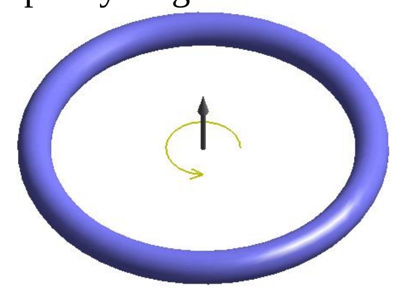
Value and direction of current are specified.

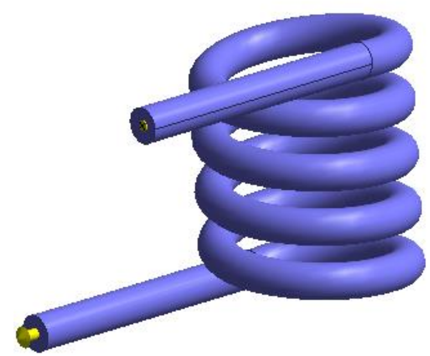


<Direction Setting>

- Loop Coil
  Specify magnetic field vector.



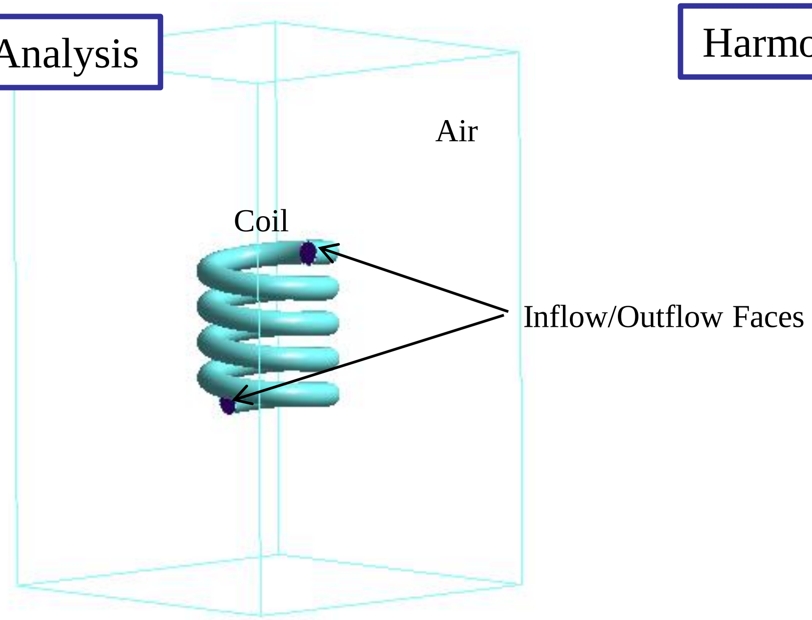
- Others
  Specify inflow/outflow faces.



Body Attribute: Current

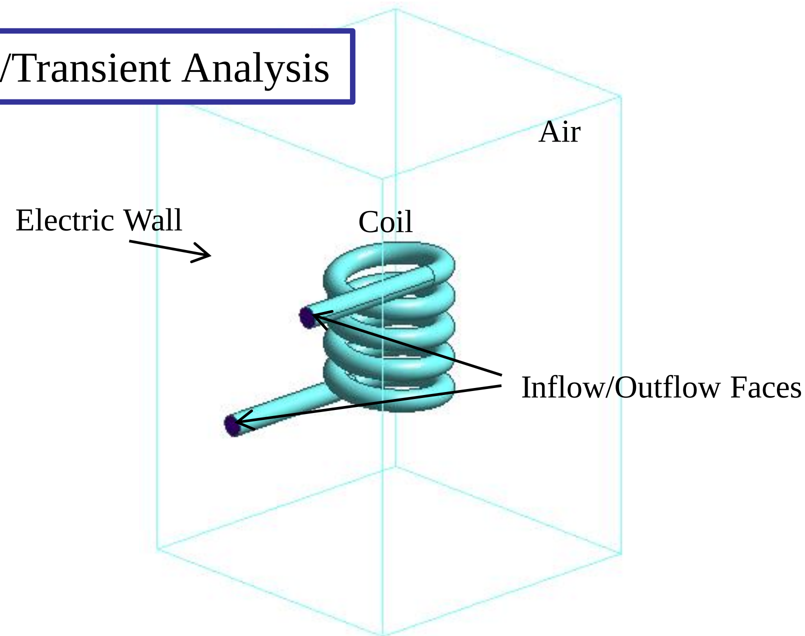
There is a setting rule for the location of inflow/outflow faces.

Static Analysis



It is allowed to place the inflow/outflow faces inside the air.

Harmonic/Transient Analysis



The inflow/outflow faces must be extended to the outside of the air body. The outer boundary condition must be electric wall. (Inflow/outflow faces are electrically connected)

*This is not the case for the loop coil.

Coil of Many Turns

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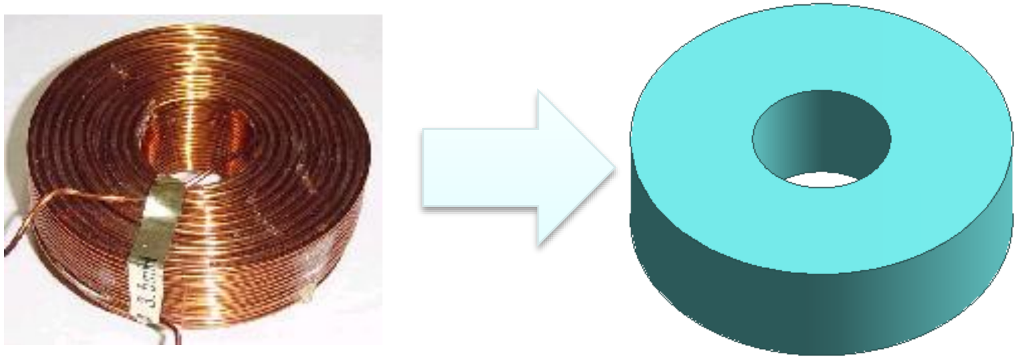
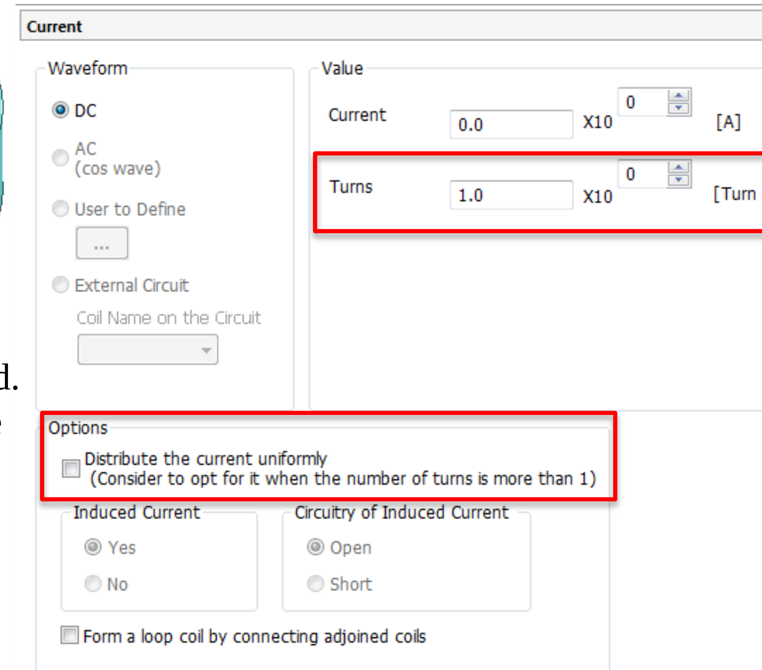
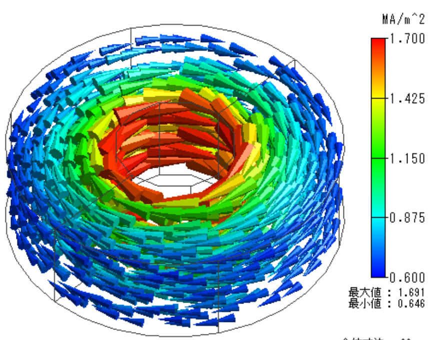
Many turns make the body form complicated and calculation time becomes longer.
Femtet has a function to make such coil a “bulk coil” where the turns are considered to be one lump.

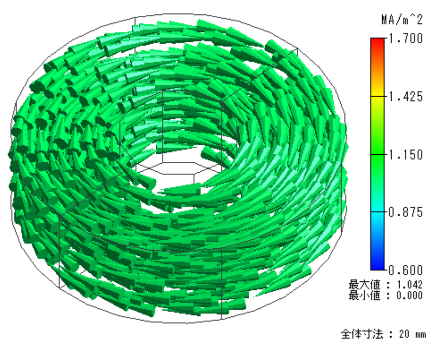




In a bulk coil, the current density distribution tends to be biased inward. For a spiral coil, select Distribute the current uniformly. It is selectable only in the harmonic analysis.



Setting OFF



Setting ON

Current Density Distribution

Boundary Conditions

Classification of Boundary Conditions

Outer Boundary Condition

It is set to the outer perimeter of the model.

Its type is selectable.

User-Defined Boundary Condition

It is applied to where needed by user.

It is given priority if it overlaps with outer boundary condition.

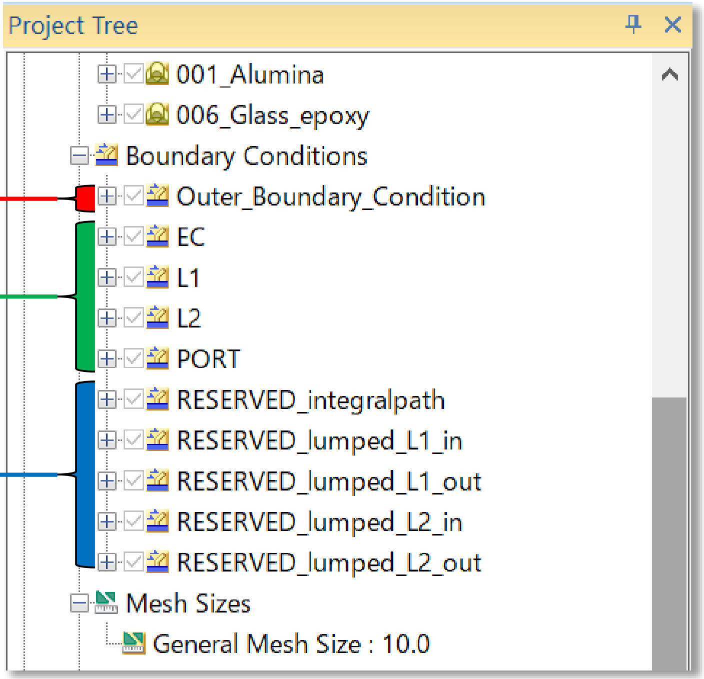
User can define the its type and name.

Boundary Condition Set by Femtet

It is automatically set by Femtet.

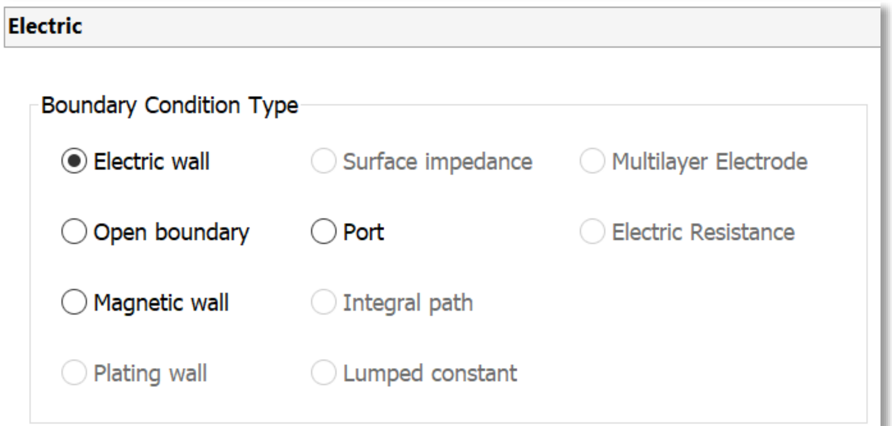
It is displayed on the results window only.

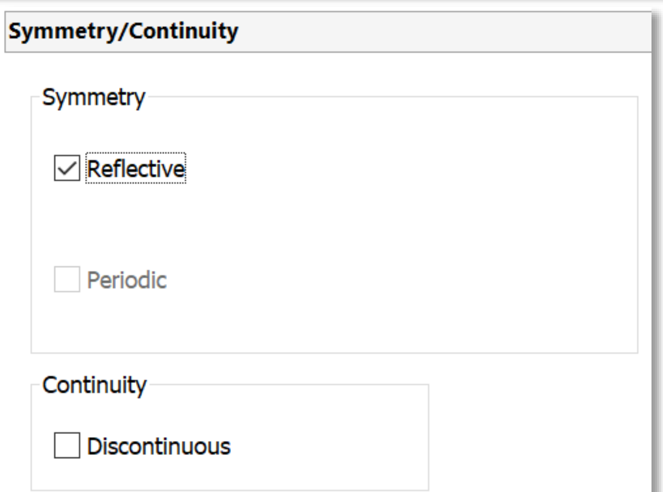
Its name begins with “RESERVED_”



Boundary Condition Types

6 types of boundary conditions are available for the magnetic analysis.





Electric Wall

Magnetic field vectors run in parallel

Open Boundary

Magnetic field expands naturally

Magnetic Wall

Magnetic field vectors cross vertically

Integral Path

Electromotive force is calculated

Reflective

Symmetric model

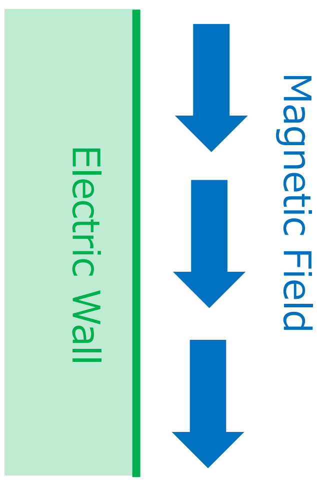
Port(*)

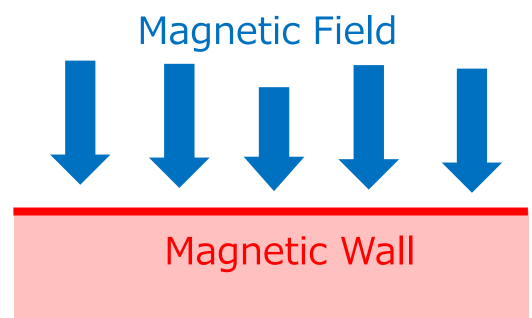
Input and output of electromagnetic waves

(*)Port is rarely used.
Conditions except Port are explained on the following pages.

Boundary Condition:
Electric Wall and Magnetic Wall

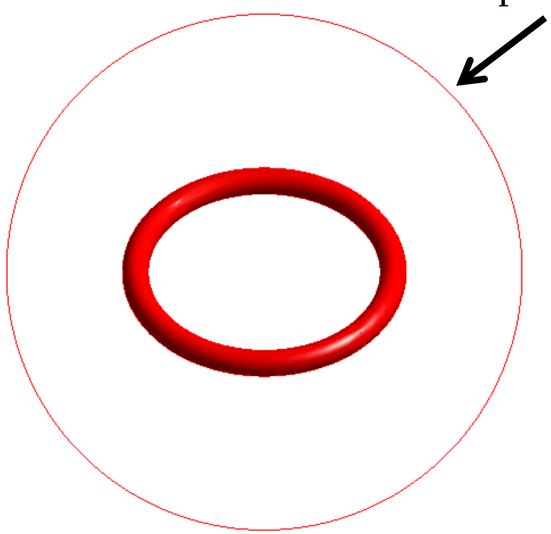
The magnetic field runs in parallel to the electric wall, and normal to the magnetic wall.
The magnetic wall is used mainly when the external magnetic field is applied.
The electric wall represents the analysis domain enclosed by conductor.
The electric wall is set by default in the magnetic analysis.



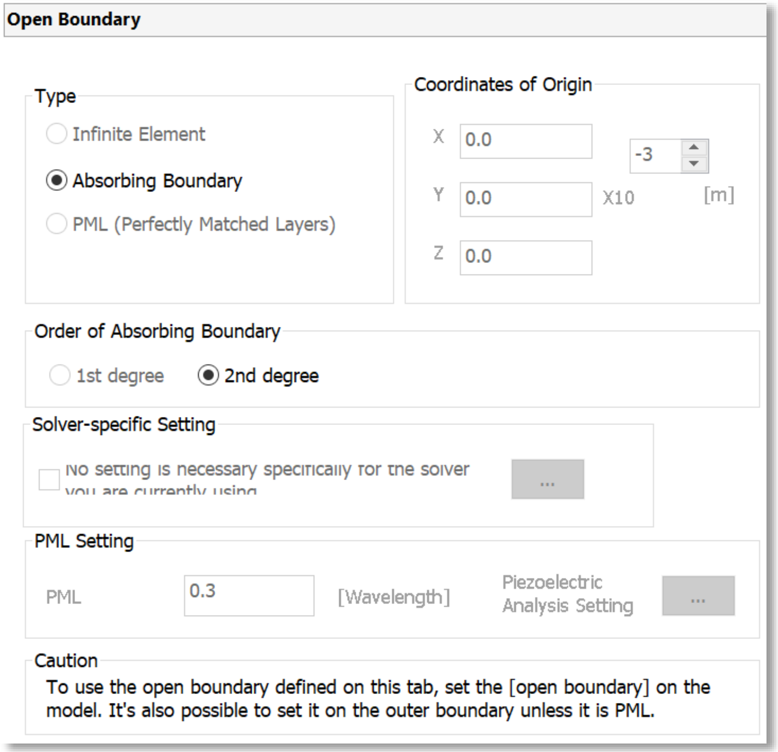


Boundary Condition: Open Boundary

The magnetic field is expanding beyond the analysis domain.
The open boundary is used for the directivity analysis.



Analysis of Magnetic Field Directivity
(near-field radiation)

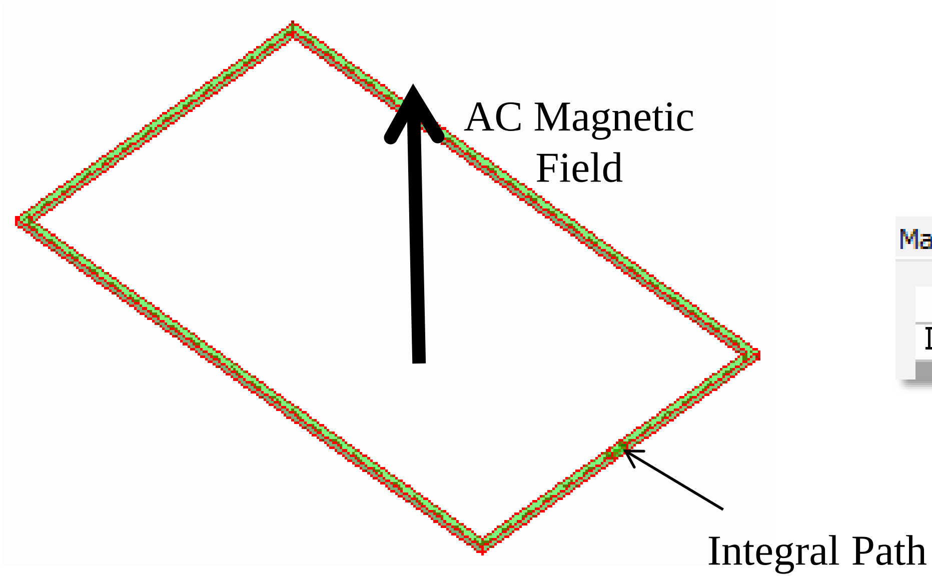


<Note>

- The coordinates of origin must be specified in the analysis condition setting.
- The open boundary can be set to spherical surface only.

Boundary Condition: Integral Path

Induced electromotive is calculated in the harmonic analysis.



Electromotive of Receiver Coil (NFC)

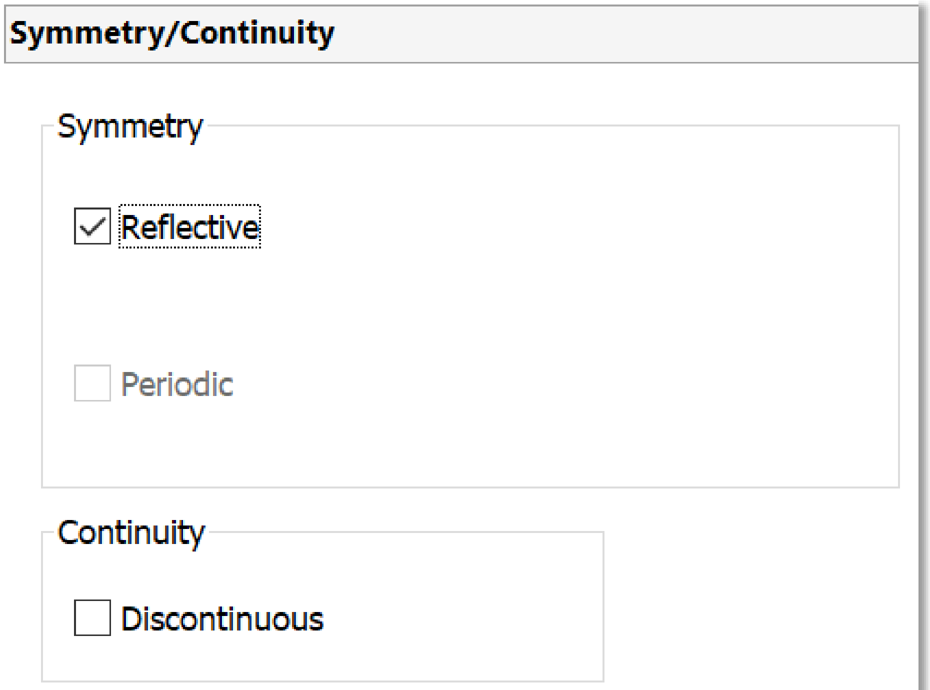
This setting is for analyzing electromotive or wireless power transmission.

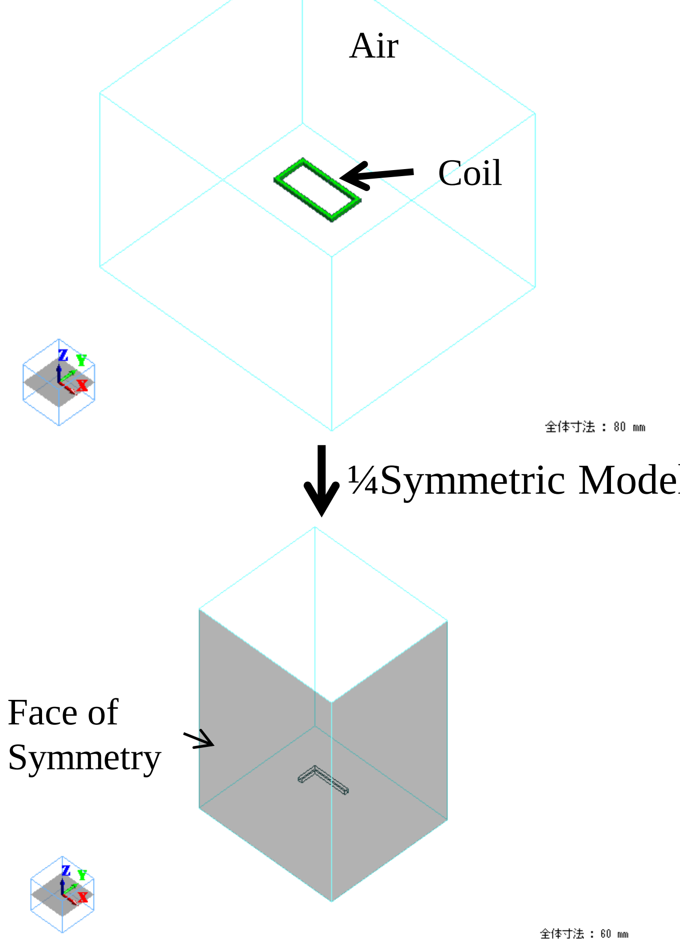
Magnetic energy [J] | Q factor | Electromotive

	Real part	Imaginary part
Integral	3.794e-5	0.335

Boundary Condition: Reflective

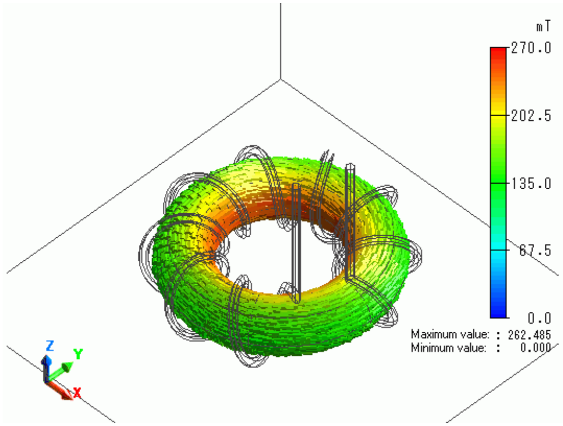
Boundary condition setting on the face of symmetry





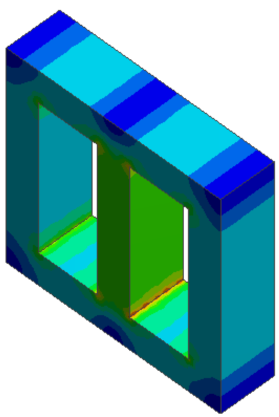
[Note]
Face of symmetry is treated as the electric wall.
Reflective can be used only when the magnetic field runs vertically.

Field shows the electromagnetic field visually.

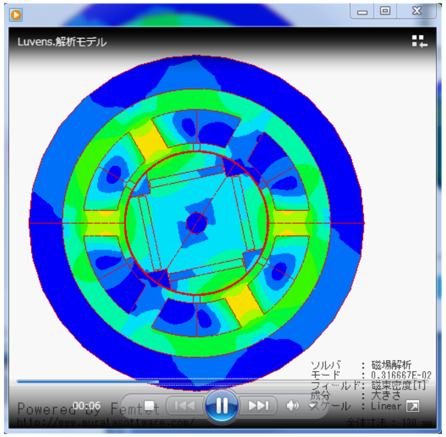


Vectors of Magnetic Flux Density

-Vector display of magnetic field, magnetic flux density, and current density
-Contour display of scalar and vector quantities of, such as, loss density
-Graph
-Animation



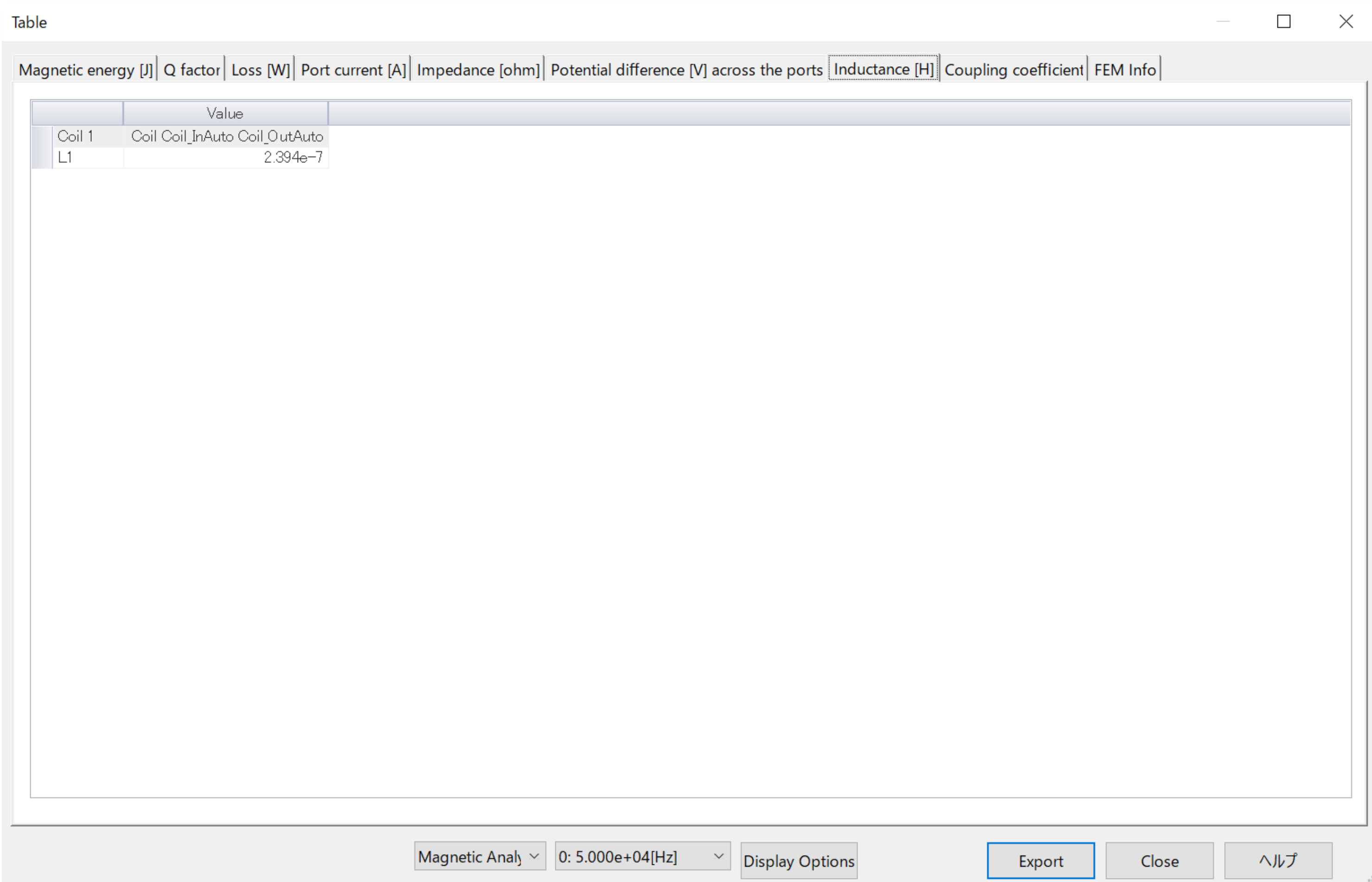
Contour Diagram of Loss Density



Animation

Results:
Table

Numerical results are displayed on the table.



Results: Directivity

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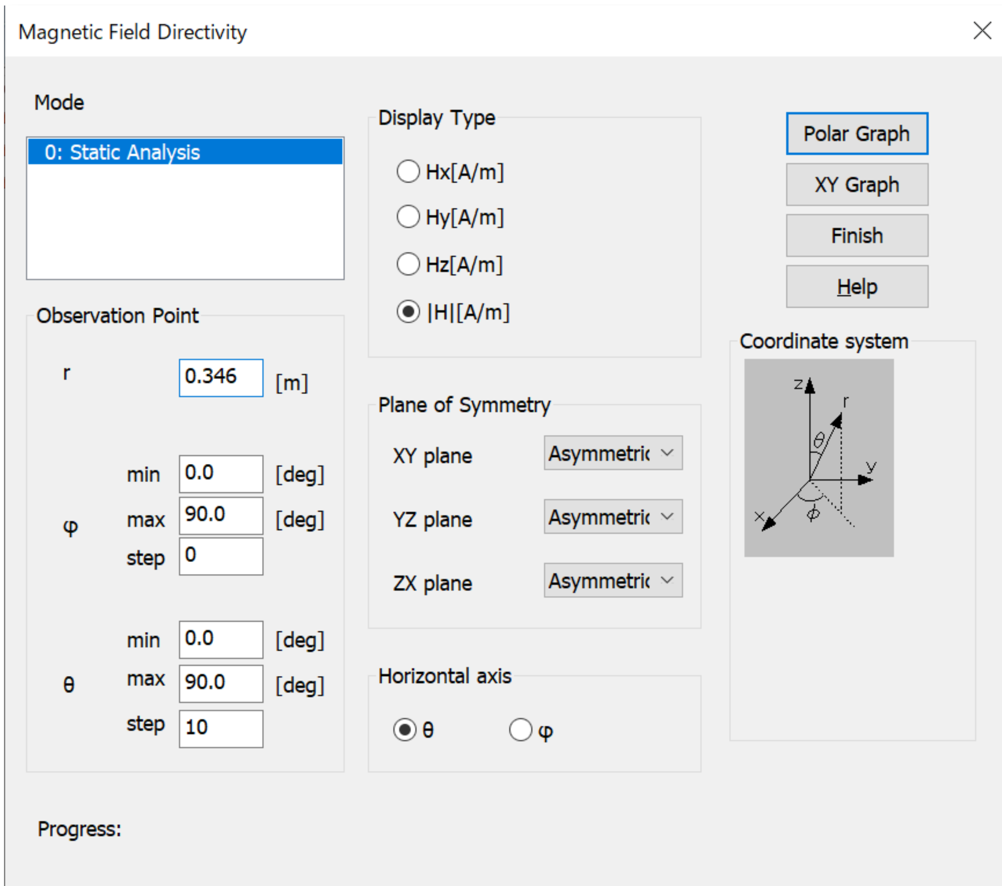
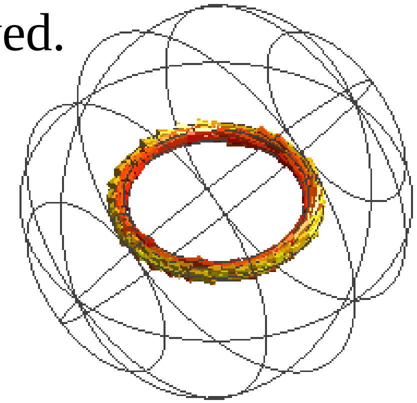
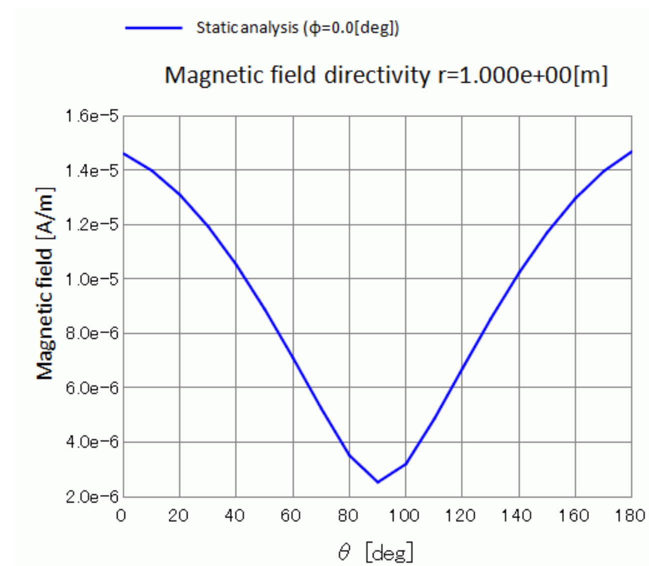
Magnetic directivity in the specified distance is displayed.







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Calculation Accuracy and Speed

Murata Software

Mesh

Air Size

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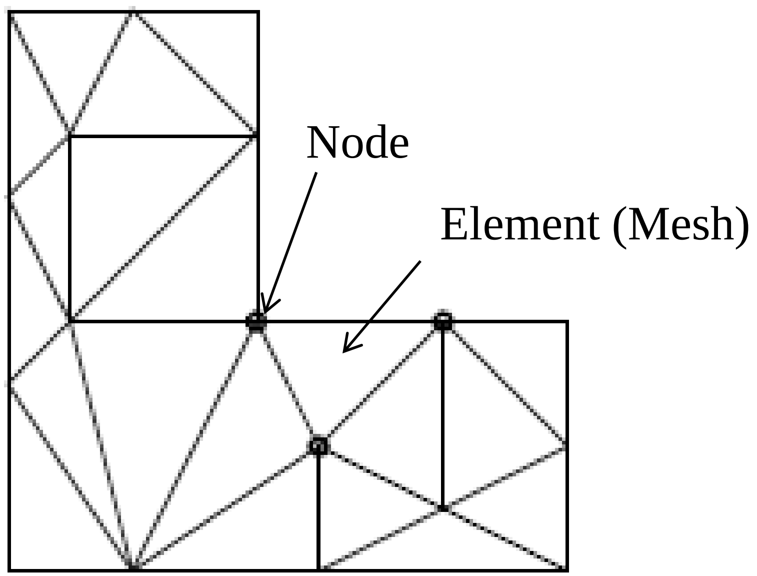
Finite Element Method

Finite element method is one of the prominent numerical methods used in a wide range of fields such as structural analysis, electromagnetic field analysis, and fluid analysis.
It subdivides an analysis domain into smaller parts called finite elements.

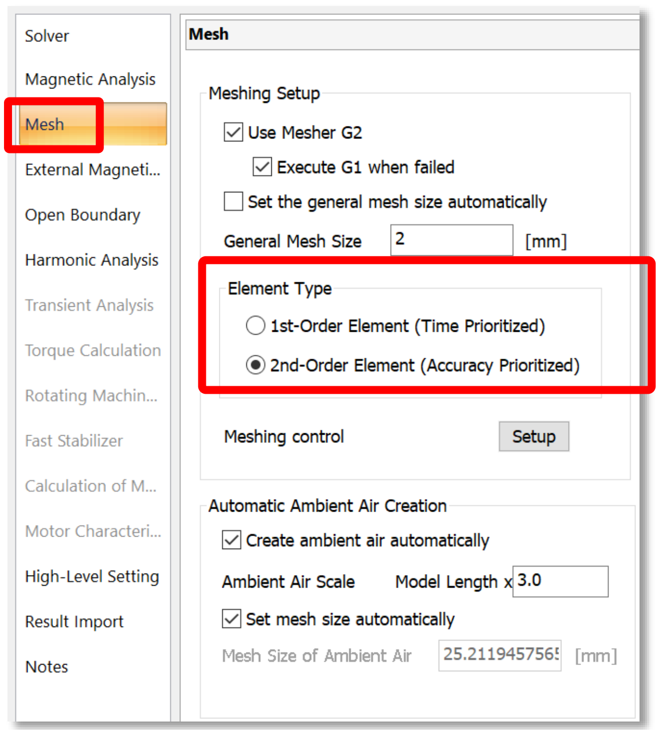


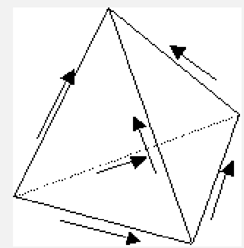
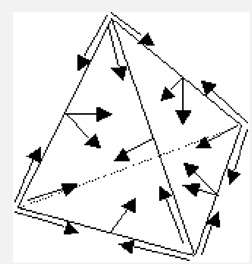
Subdivision of Analysis Domain

Element Type

Murata Software

The 1st-order and 2nd-order elements are selectable on the Mesh tab.

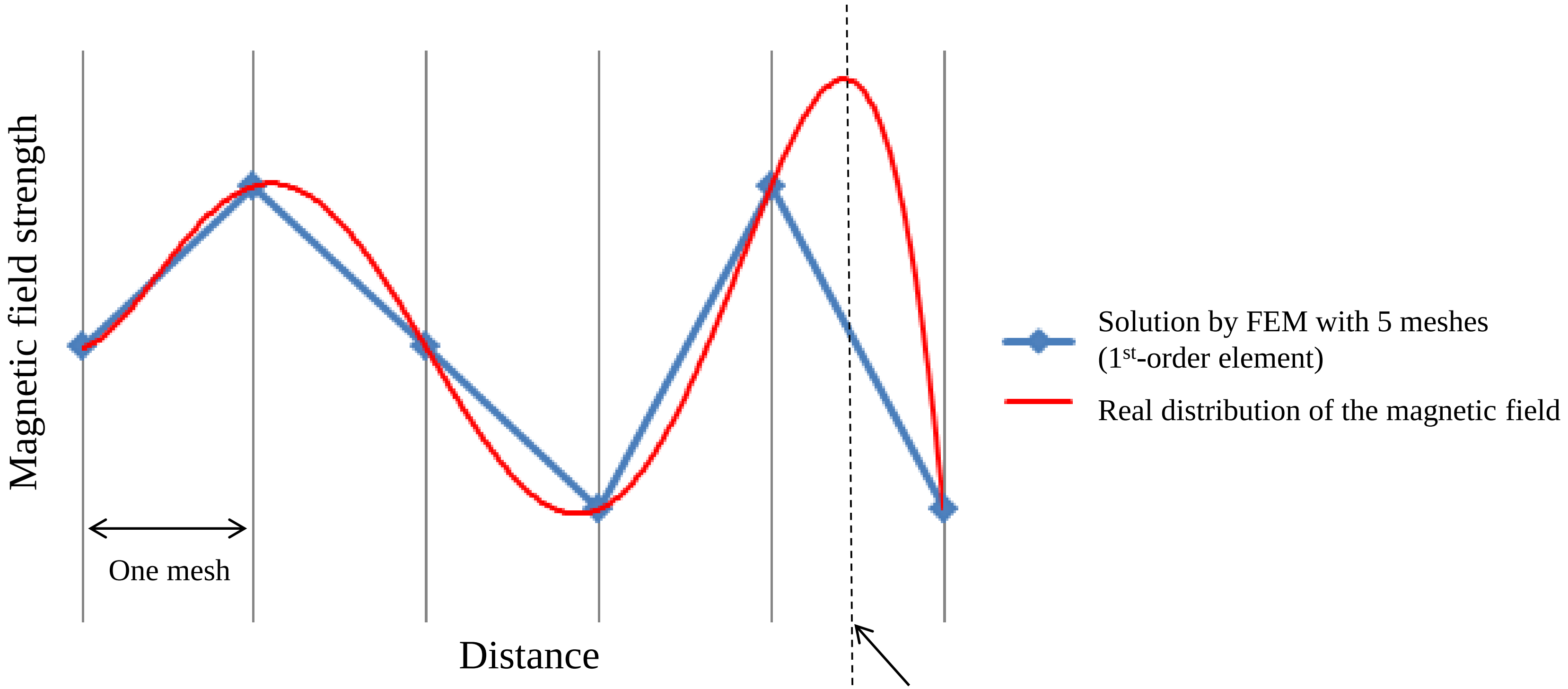


Element Type	Locations of Unknown Numbers	Calculation Time	Calculation Accuracy
1st-order Element		Short	Low
2nd-order Element		Long	High

↖ (Unknown Number)

Mesh Size

By applying the finer meshes, the calculation will be more accurate and gradually approaches the true value. The finer meshes are needed for where the magnetic field changes drastically. For where the magnetic field changes mildly, the less-fine meshes reduce the calculation time.

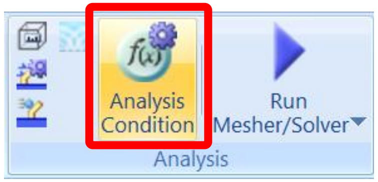


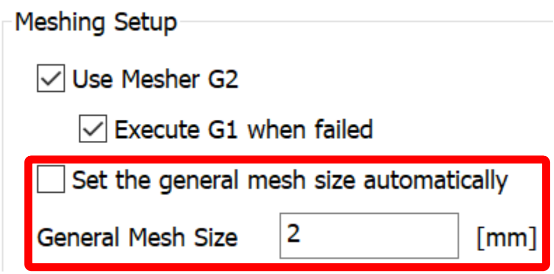
Example of the 1st-order Element

Mesh Size Setting

Murata Software

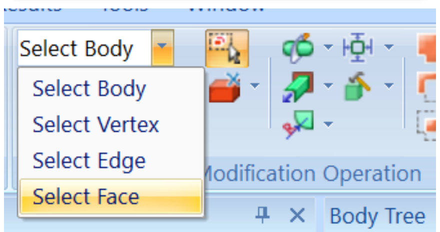
General Mesh Size



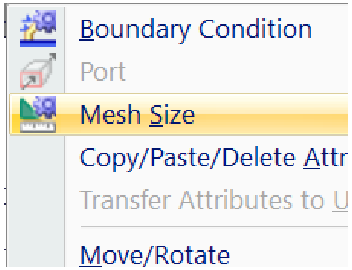


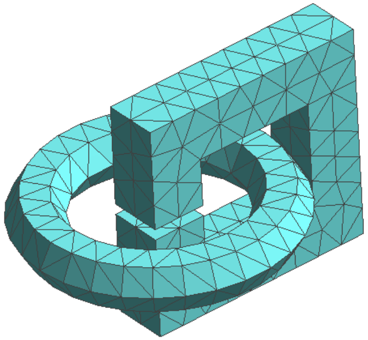
Partial Mesh Size Setting on the Arbitrary Bodies, Face, Edges, Vertices

① Select mode



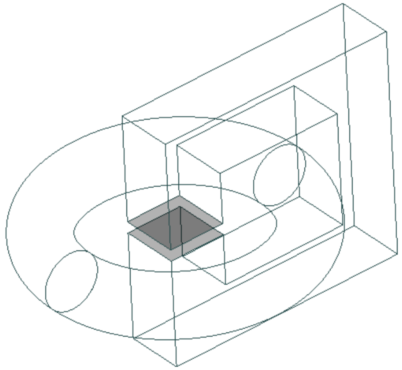
③ Right click



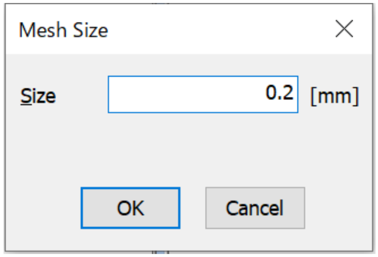


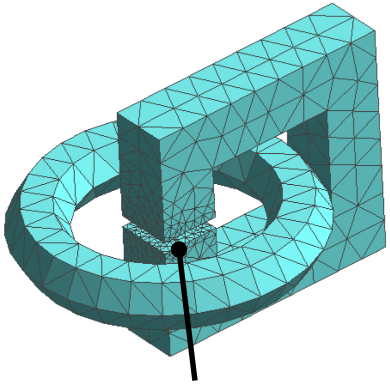
Original Meshes

② Select target



④ Enter mesh size





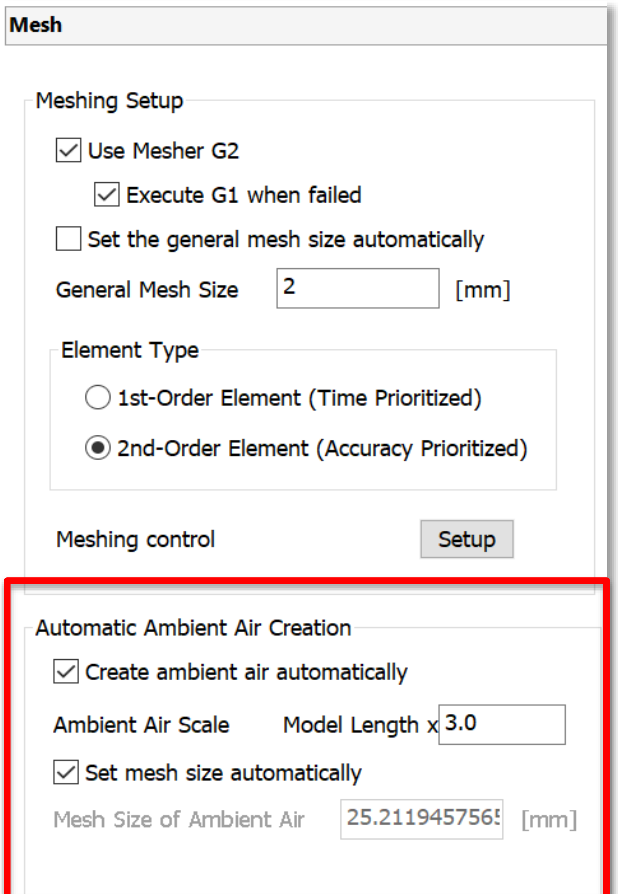
Finer Meshes on the Selected Area

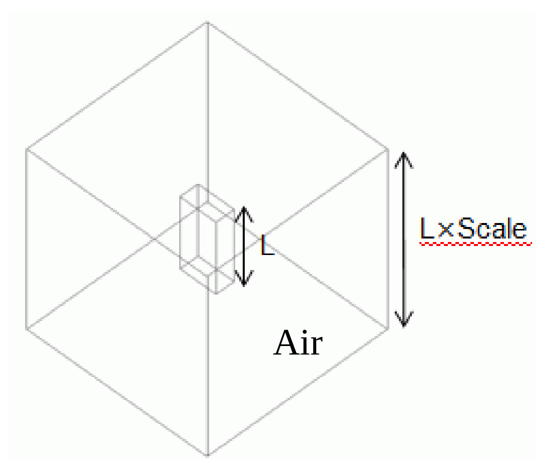
Air Size

Murata Software

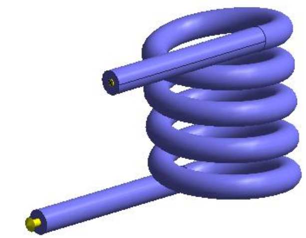
Air body must be present even where the magnetic field is sufficiently small.

Automatic ambient air is created is ON by default (scale of 3)

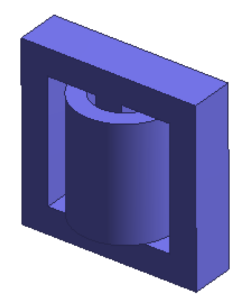




Open Magnetic Circuit
The scale of 2 or more is necessary.



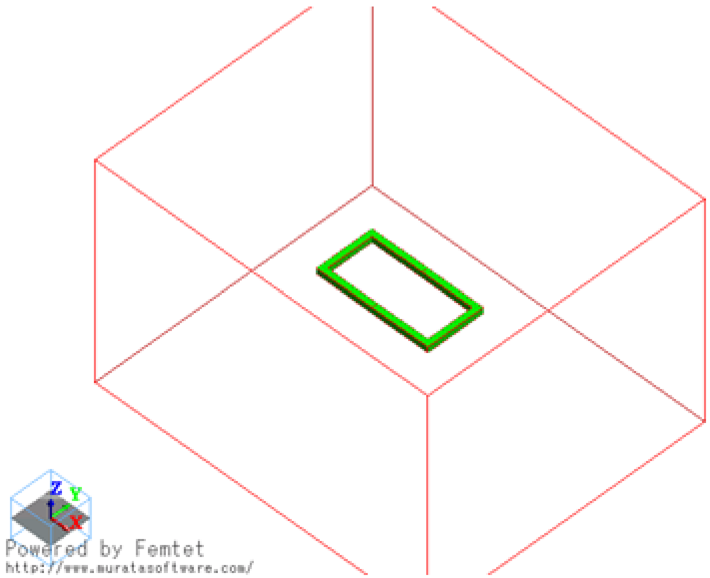
Closed Magnetic Circuit
The scale of 1.2 is enough



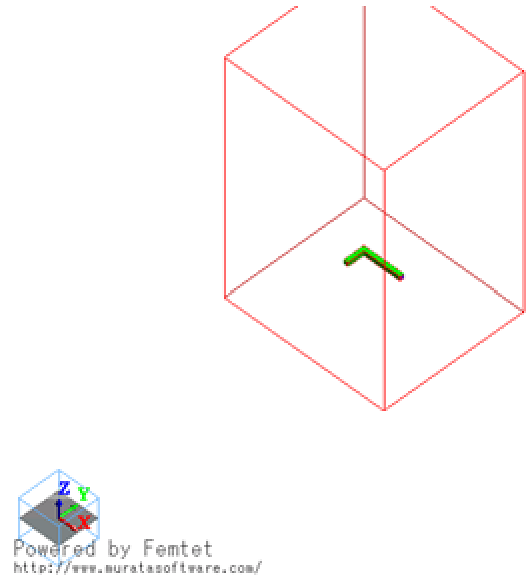
Symmetric Model

Murata Software

If the analysis model has symmetricity in its form or attributes, the model can be segmented on the face of symmetry for analysis.



Full Model



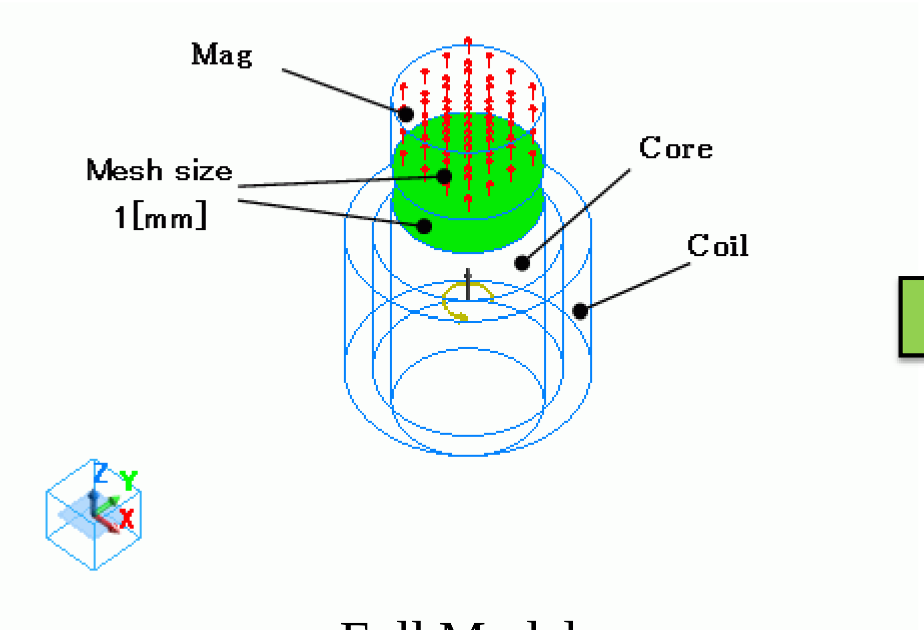
Symmetric Model

Symmetric model reduces the number of elements, calculation time, and memory consumption.

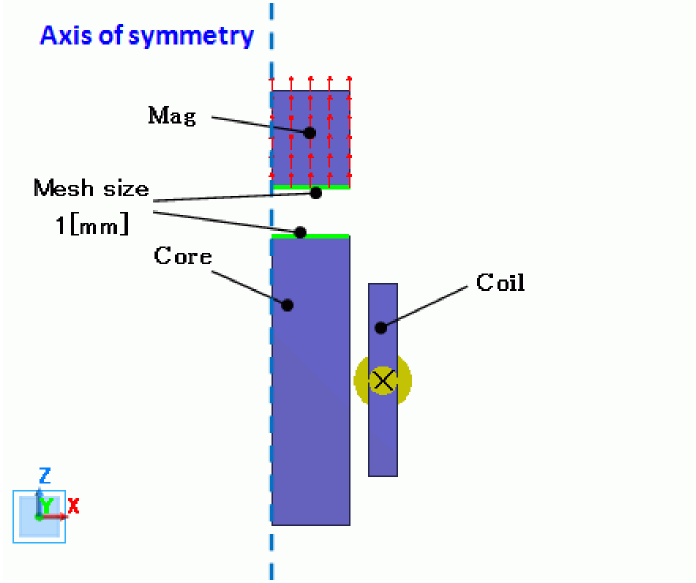
2D Axisymmetric Model

Murata Software

If the analysis model is axisymmetric in its form or attributes, 2D axisymmetric analysis will reduce the calculation time.



Full Model



Axisymmetric Model

Linear and Nonlinear Analysis

Linear and Nonlinear Analysis

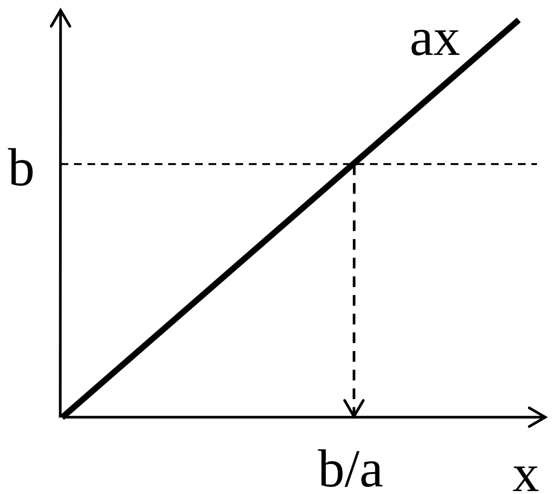
Nonlinear Magnetic Analysis

Linear and Nonlinear Analysis

Murata Software

Linear Equation

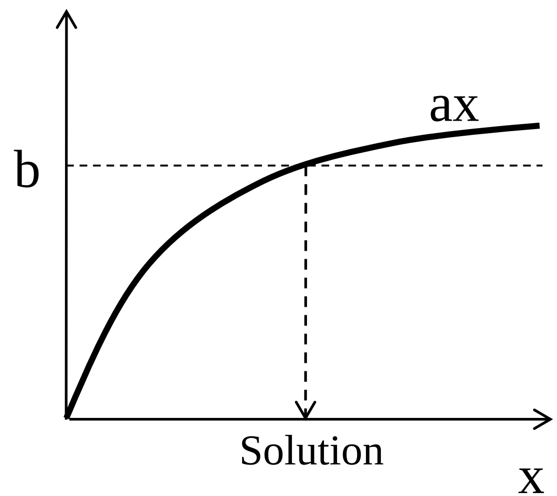
$ax = b$ a and b are constant



・Single calculation solves the equation.

Nonlinear Equation

$ax = b$ a and b are changed by x



・Iterative calculations are required.
・Newton-Raphson method solves the equation.
・Solution may not be acquired in some cases.

Calculation Load→Small

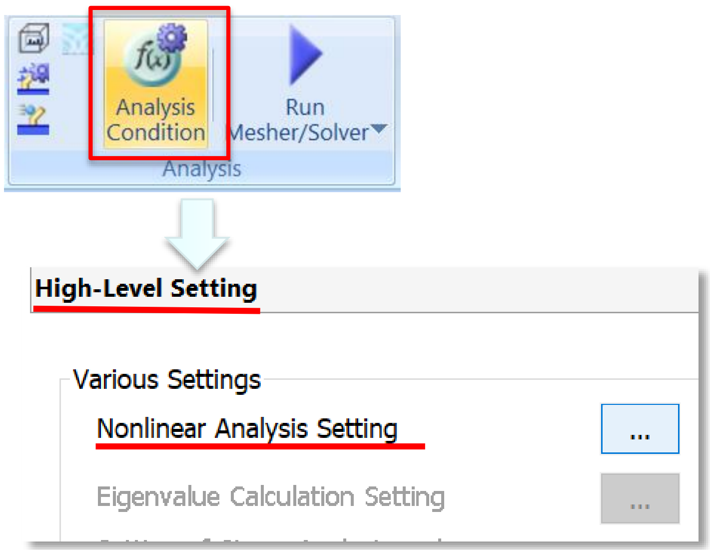
Calculation Load→Large

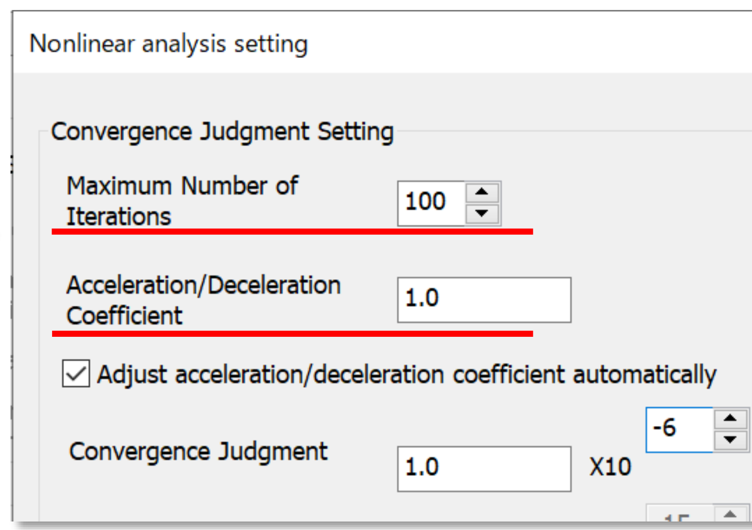
Nonlinear Magnetic Analysis

Murata Software

If the nonlinear calculation does not converge,

1. Check if a B-H curve is ragged due to the measurement error.
   Make correction to smooth the curve.
2. Go to [Analysis Condition Setting] > [High-Level Setting].
   - 2-1. Deselect [Adjust acceleration/deceleration coefficient automatically],
     Enter number smaller than 1, such as 0.5 or 0.1 in [Acceleration/Deceleration Coefficient].
   - 2-2. Increase the maximum number of iterations.





Harmonic Analysis

Frequency Range for Calculation

Inductance in the Harmonic Analysis

Skin Effect

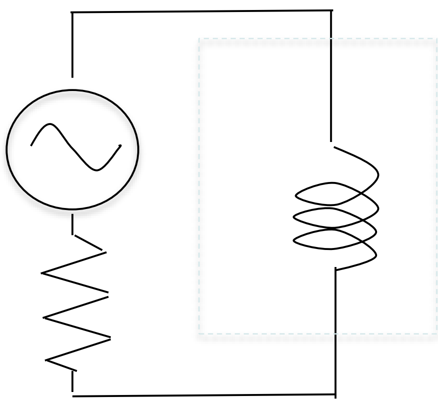
Conductor in the Harmonic Analysis

Frequency Range for Calculation

Murata Software

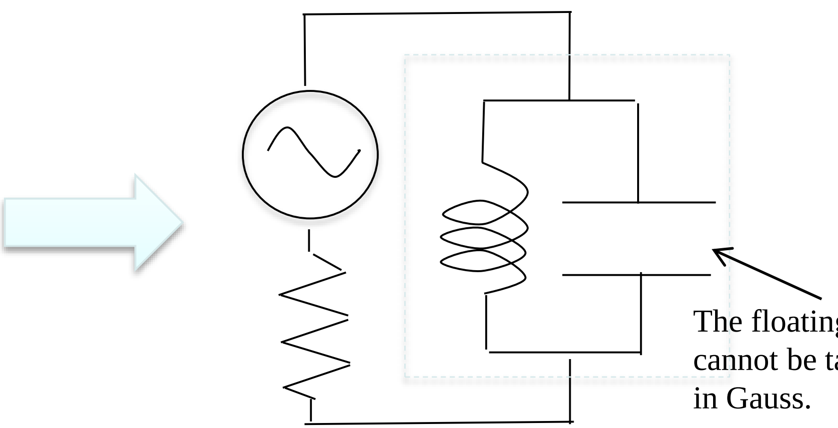
Coil

Low Frequency



Can be solved by
magnetic analysis (Gauss).

High Frequency



The floating capacitance cannot be taken into account in Gauss.

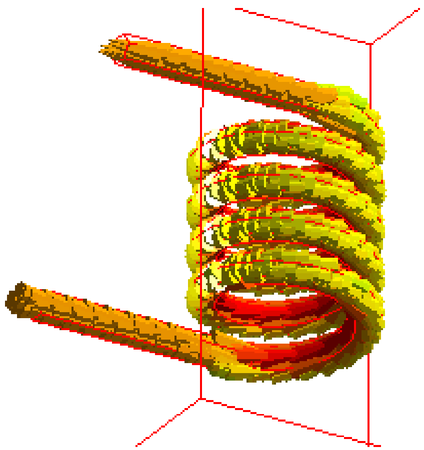
Cannot be solved by magnetic field analysis (Gauss).
Electromagnetic analysis (Hertz) is needed.

The minimum model size, which can be analyzed by the magnetic analysis (Gauss), is approx. 1/10 of a wavelength.

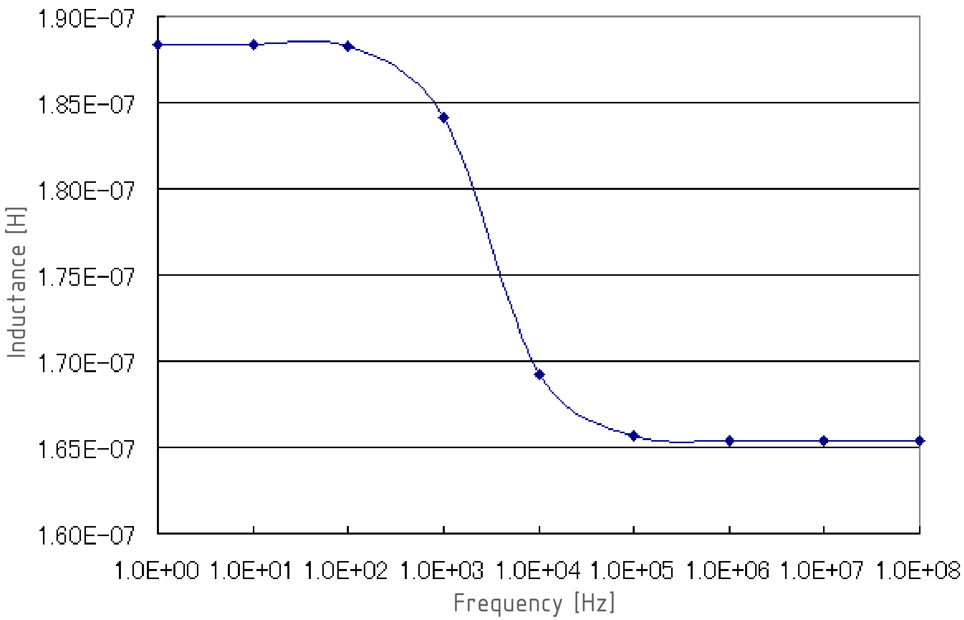
Inductance and Frequency

The inductance changes depending on the frequency.

Example of Harmonic Analysis



Diameter of section of coil: 4mm



As the frequency goes higher, the inductance becomes smaller due to the skin effect.

Skin Effect

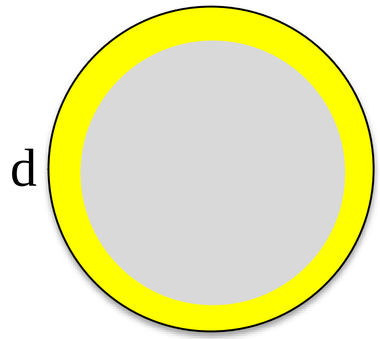
Murata Software

If the frequency increases, the magnetic field can only penetrate the surface of metal. It is called *skin effect*. Its penetration distance is called *skin depth*.

The skin depth is calculated by the equation below.

$$d = \sqrt{\frac{2}{\sigma\omega\mu}}$$

where:
σ = Conductivity
ω = Angular frequency of current=2πf
μ = Permeability



Section of Conductor
Yellow area is where the magnetic field penetrates

Ref: Skin depth of copper

1Hz	65mm
1kHz	2.1mm
1MHz	65μm
1GHz	2.1μm

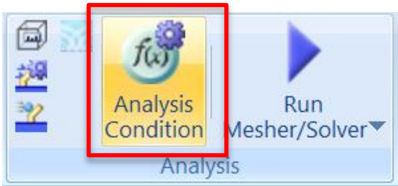
*Strictly speaking, the skin depth is a distance where the penetrating magnetic field is attenuated to 1/*e* (≒ 1/2.718 ≒ -8.7dB).

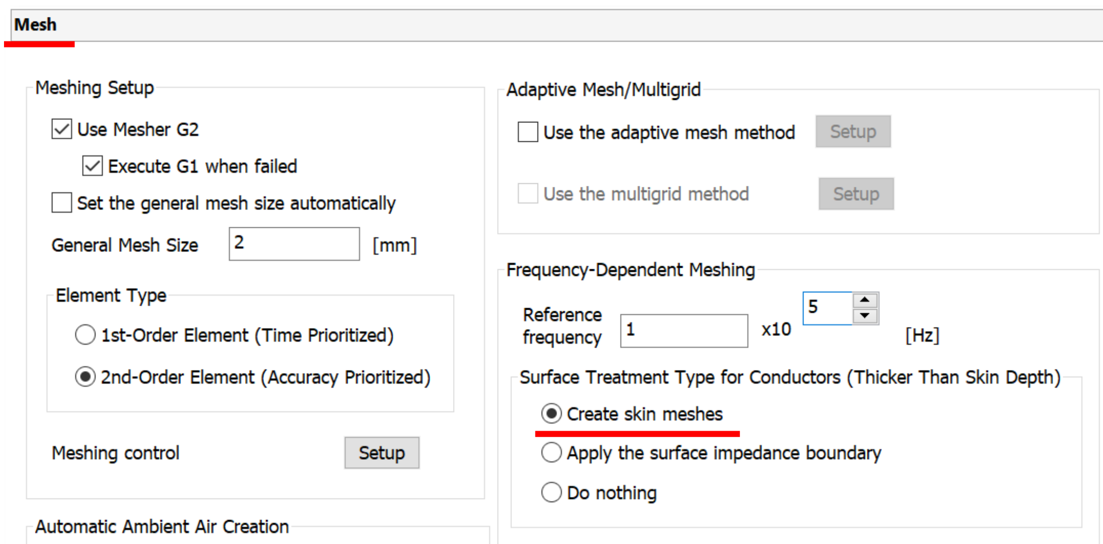
The skin effect is a phenomenon generated by the eddy current.
Because of the skin effect;
- -magnetic field in the gray area above is 0, which reduces the total magnetic field, and eventually reduces inductance.
- -the sectional area for running current is reduces, which increases resistance leading to large loss.

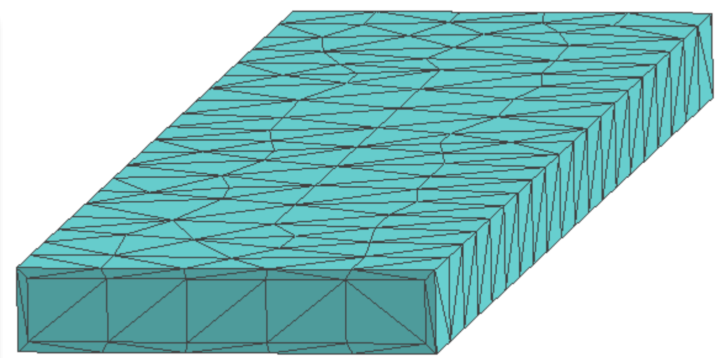
Skin Mesh

Murata Software

The skin mesh is used to calculate the skin effect with less meshes and high accuracy. This function is available for harmonic and transient analysis.







The thin meshes are created automatically on the conductor's surface.

Loss and Magnetic Field-Thermal Coupled Analysis

Loss

Magnetic Field-Thermal Coupled Analysis

Loss

The losses are:

Copper Loss: Joule loss of coil

Iron Loss: Hysteresis loss+Joule loss of core (Induced current loss)

The loss is transformed to the thermal energy.
The induction heating (IH) utilizes the heat generated by the induced current loss.

Table

Magnetic energy [J] | Q factor | Loss [W] | Port current [A] | Impedance [ohm] | Pc

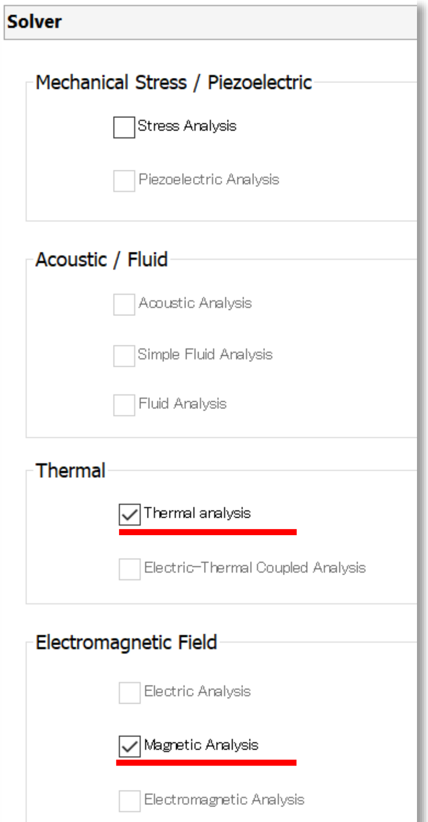
	Joule loss [W]	Iron loss [W]	Total loss [W]
Air_Auto	0.000e+0	0.000	—
Coil	4.256e-4	0.000	—
Coil_LoopAuto	4.256e-4	0.000	—
Core	0.000e+0	1.406	—
Whole	8.513e-4	1.406	1.407

調和解析の出力結果例

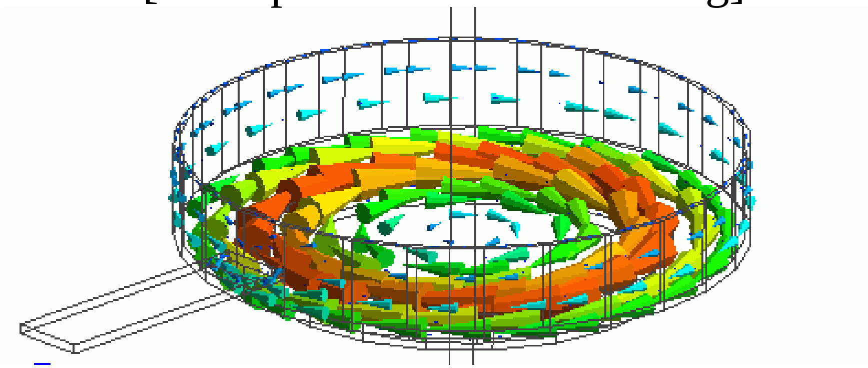
Magnetic Field-Thermal Coupled Analysis

Coupled with thermal analysis, the temperature distribution can be analyzed.
The loss, which is acquired in the magnetic field analysis, is used as the heat amount.

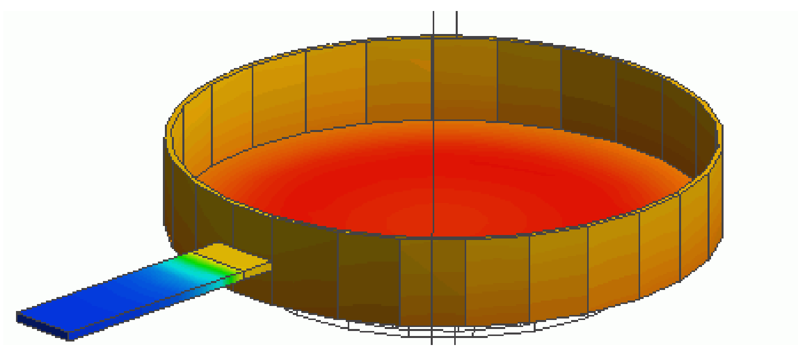
Solver Selection



[Example: Inductance Heating]



Current Density Distribution

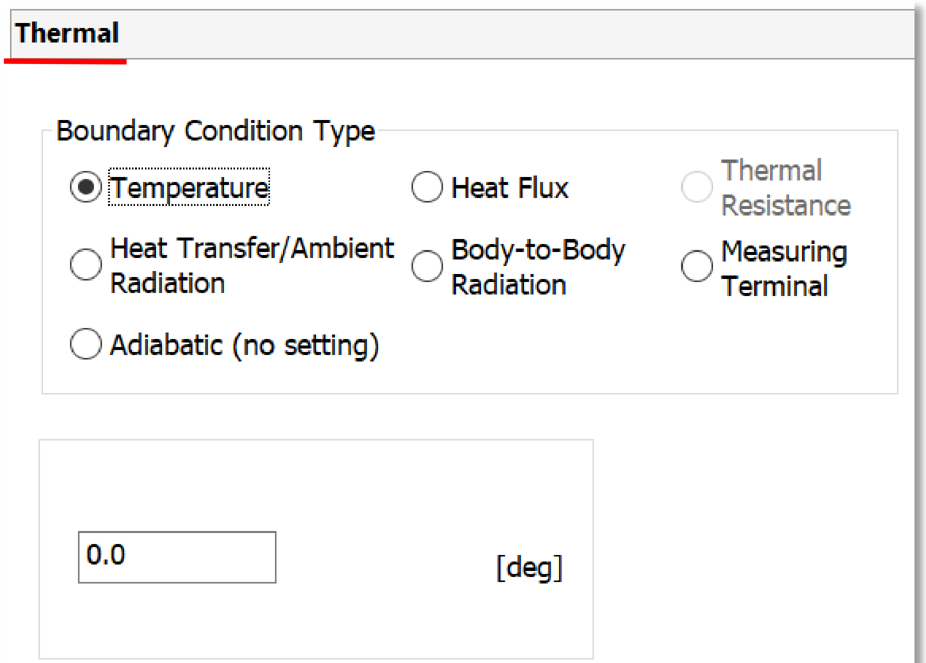


Temperature Distribution

Murata Software

Magnetic Field-Thermal Coupled Analysis

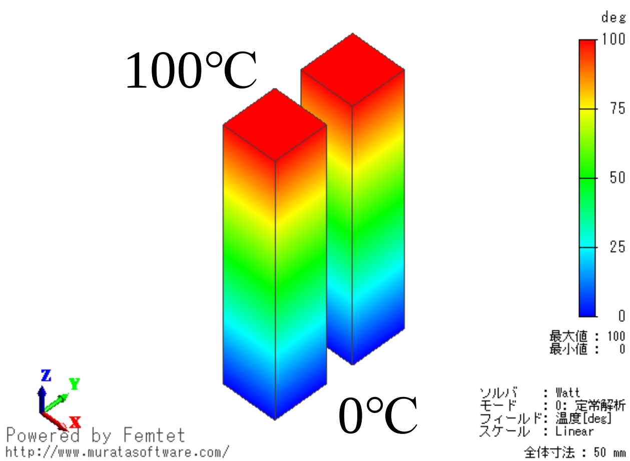
Setting of the heat radiation path (boundary condition) is the most important point.



Boundary Conditions:

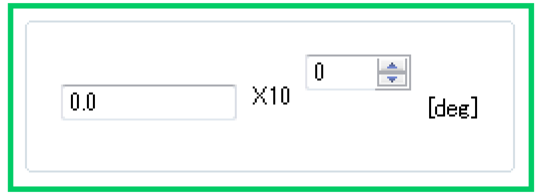
Temperature
Heat Flux
Thermal Resistance
Thermal Conductivity
Ambient Radiation
Body-to-Body Radiation
Adiabatic

Boundary Condition of Thermal Analysis



Specify the temperature

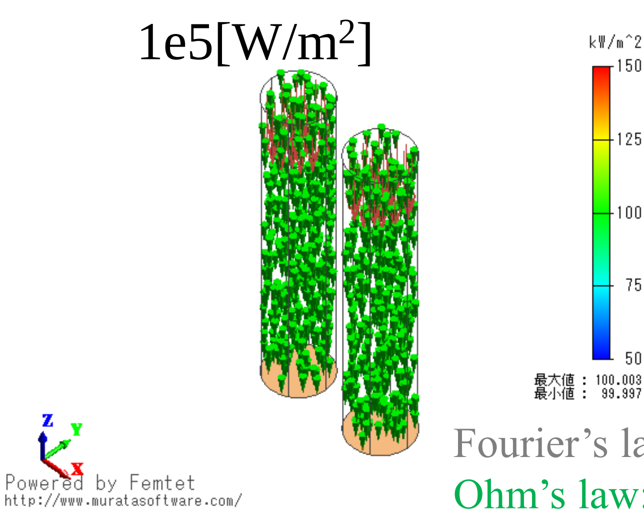
(Example 1)
Set 100°C and 0°C
at each end of the bars.



In the electric circuit, it would be:

⇨ Potential

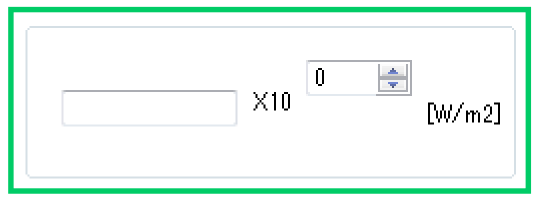
⇨ Current Density



Specify the heat flux

The inflow and outflow are defined by the signs [+] and [-] respectively.

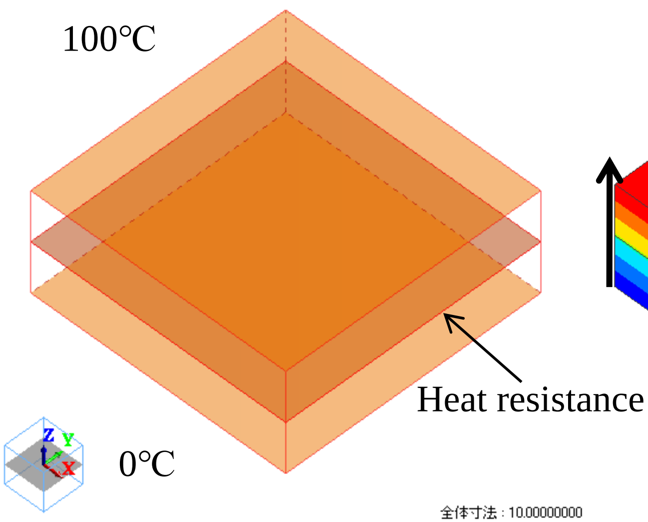
(Example 13)Set the heat flux of 1e5[W/m^2] at the tips of the bars.

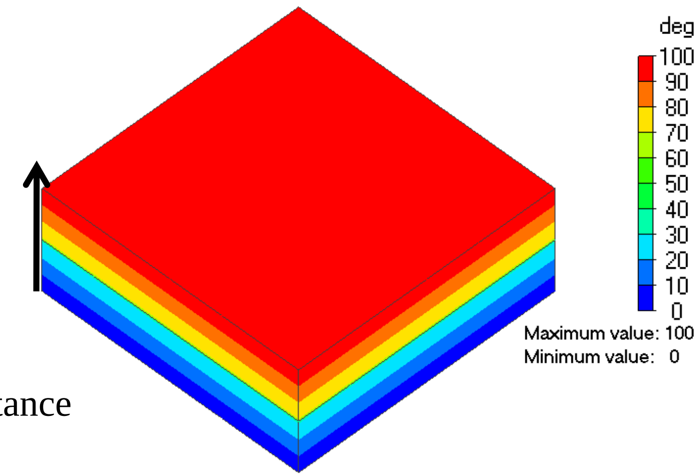


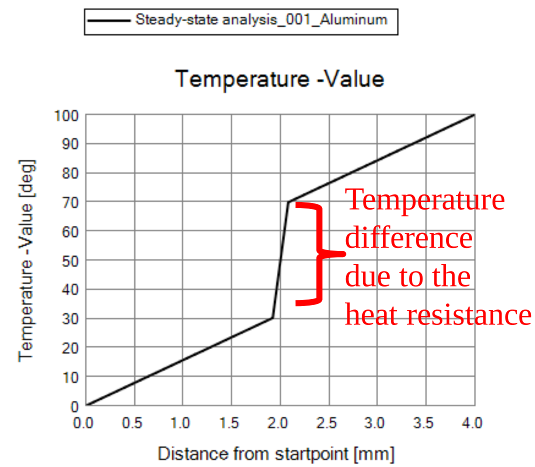
Fourier's law: The heat through a conductor creates the temperature difference

Ohm's law: The current through a conductor creates the voltage

Boundary Condition of Thermal Analysis

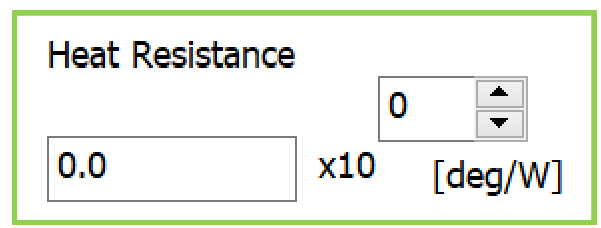




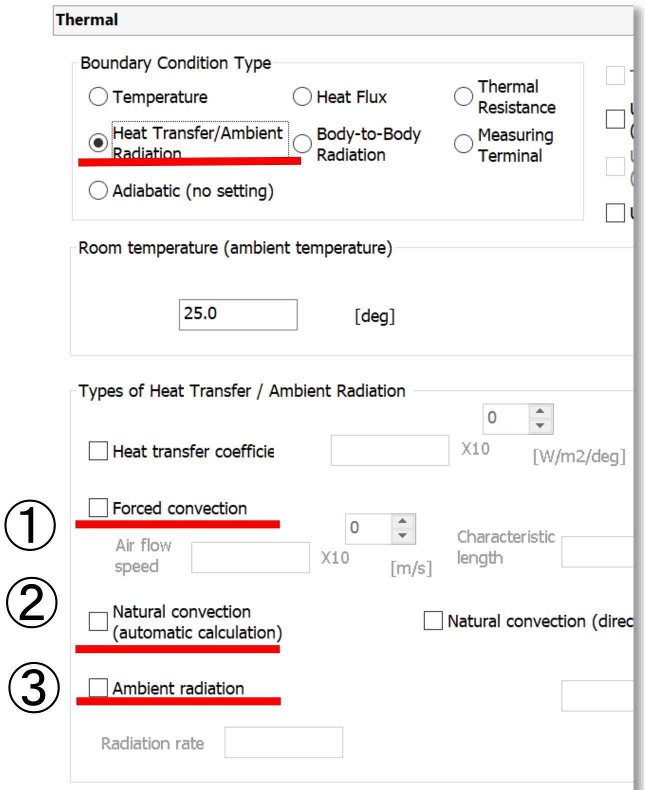


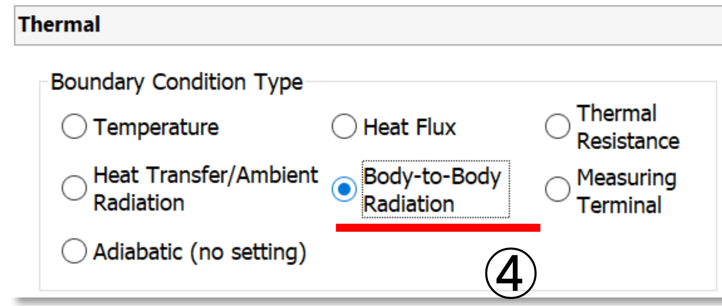
Heat resistance set on the boundary of the bodies

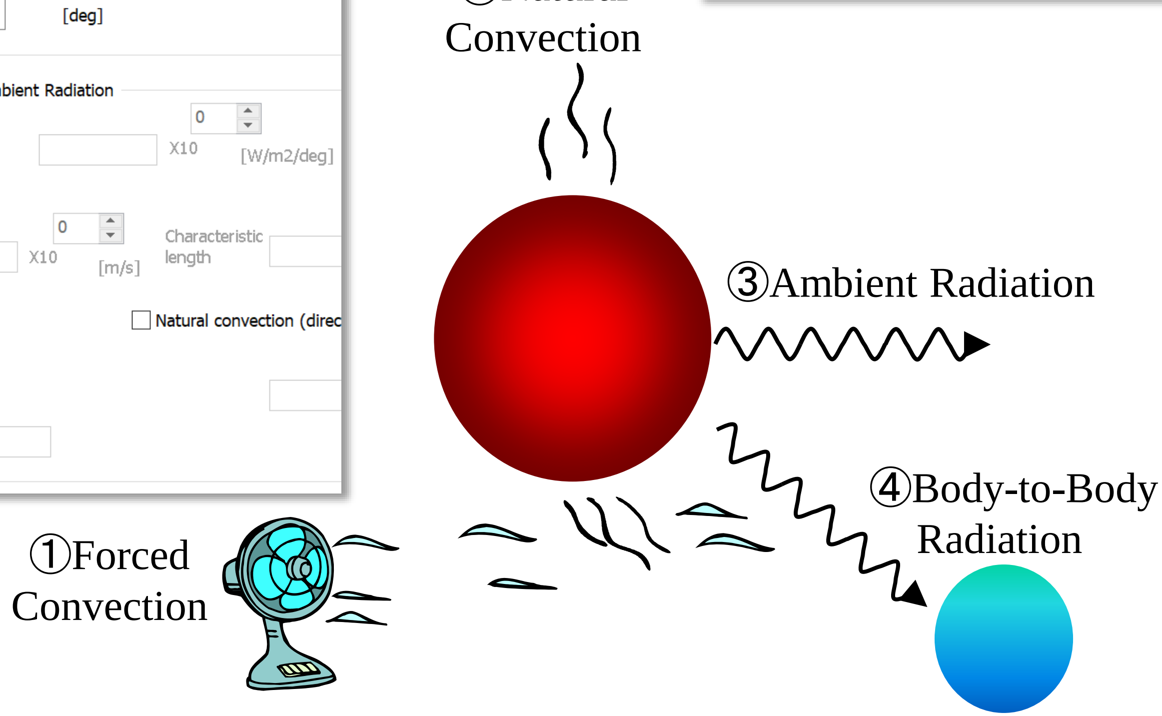
[Example 15]
The temperature changes discontinuously
at the boundary of heat resistance



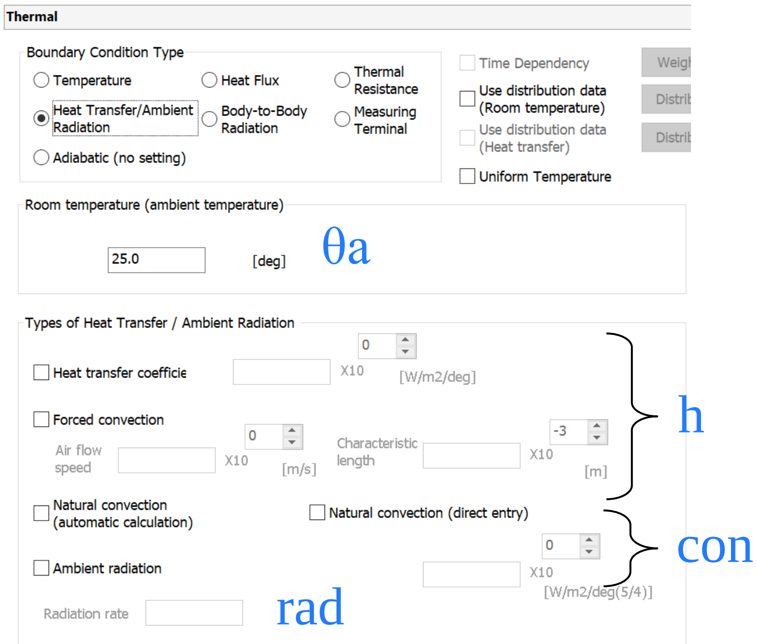
Boundary Condition of Thermal Analysis







Boundary Condition of Thermal Analysis



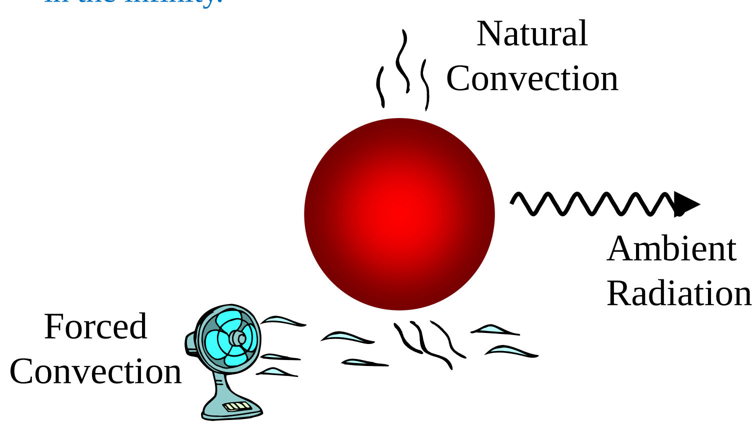
Heat Transfer and Ambient Radiation

Heat Transfer Coefficient
Specify the coefficient (h).

Forced Convection
h is calculated by the wind speed and typical length.

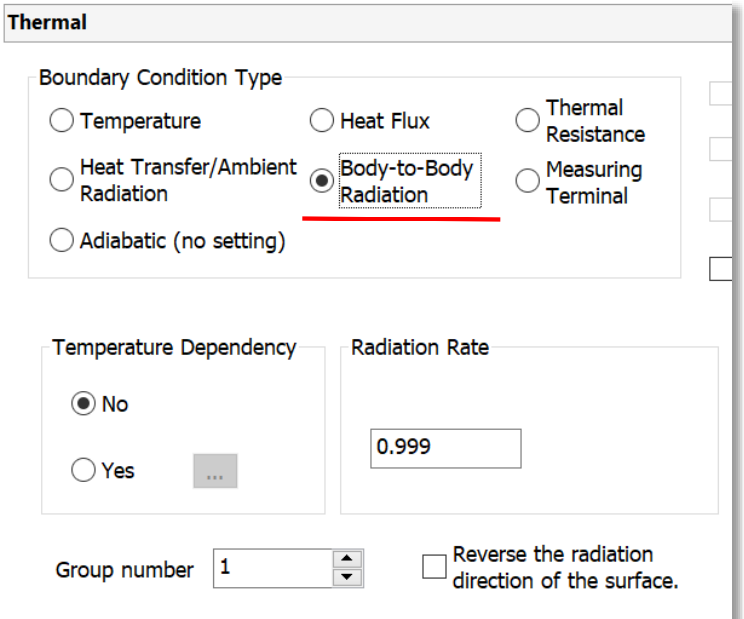
Natural Convection
Specify the coefficient (con).
Automatic calculation is possible.

Ambient Radiation
Specify the coefficient (rad) if the radiation target is in the infinity.



Murata Software

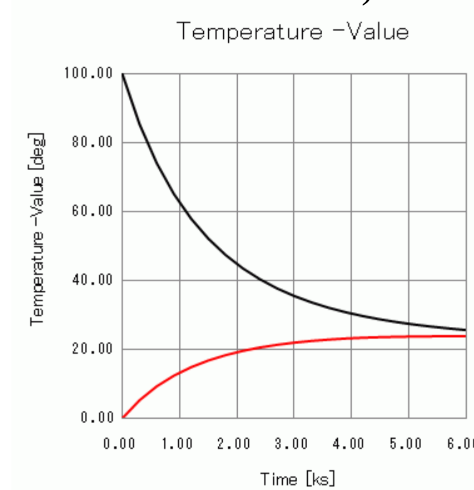
Boundary Condition of Thermal Analysis



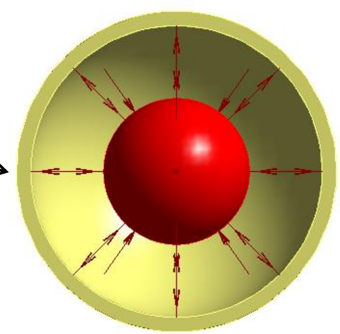
Body-to-Body Radiation

Set the emissivity between the surfaces.

(Example 9)
Transient analysis of the heat radiation between the surfaces (initial temperatures: 100°C and 0°C).



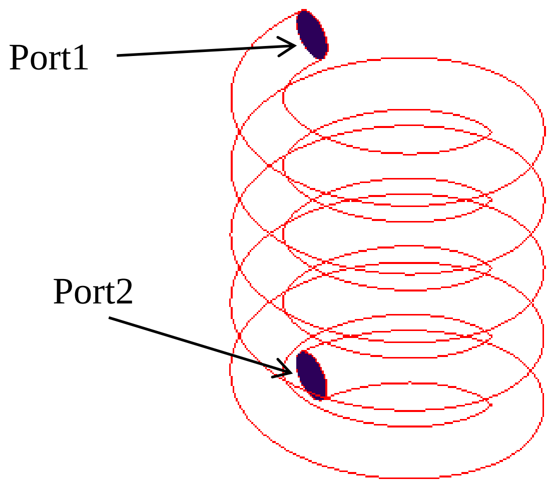
The boundary condition must be set seamlessly



*1 If there is a big gap between the body-to-body boundary conditions, the temperature drops unnaturally.
*2 If the distance to the radiation target is infinite, select [Ambient radiation].

Floating Capacitance

Floating capacitance of coil can be calculated by the electric analysis.



Table

Capacitance [F] | Electros

	Value
Electrode 1	Port1
Electrode 2	Port2
C1-2	5.24e-13

[Example 17] Inductor’s Floating Capacitance

Procedure

1. Create an analysis model.
2. Select [Electric Field Analysis (Coulomb)].
3. Set analysis condition to harmonic analysis>conductor.
4. Set the magnetic wall of the outer boundary condition.
5. Create an air body.
6. Create a coil body. Set a voltage (1V) of the boundary condition to the whole peripheral of the coil.
7. Set the port of the boundary condition to the both ends of the coil. (Port1 and Port2)
8. Set the perfect conductor for the material property.
9. Run the solver.

Murata Software

Appendix

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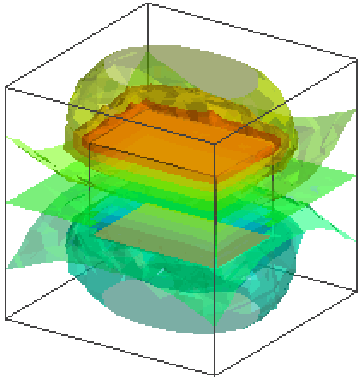
Examples

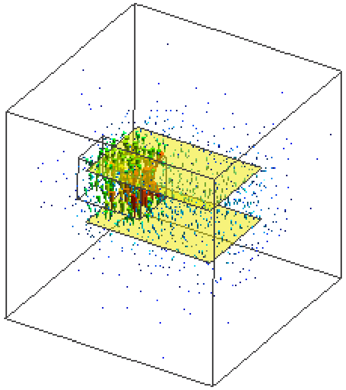
Analysis Condition

Examples

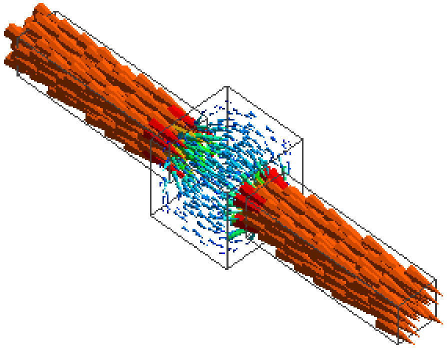
Capacitance of the Capacitor



Electrostatic Force on the Dielectric Material

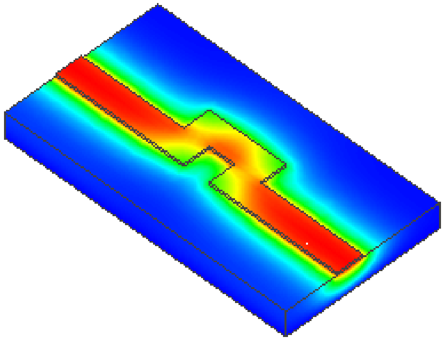


Resistance of the Conductor

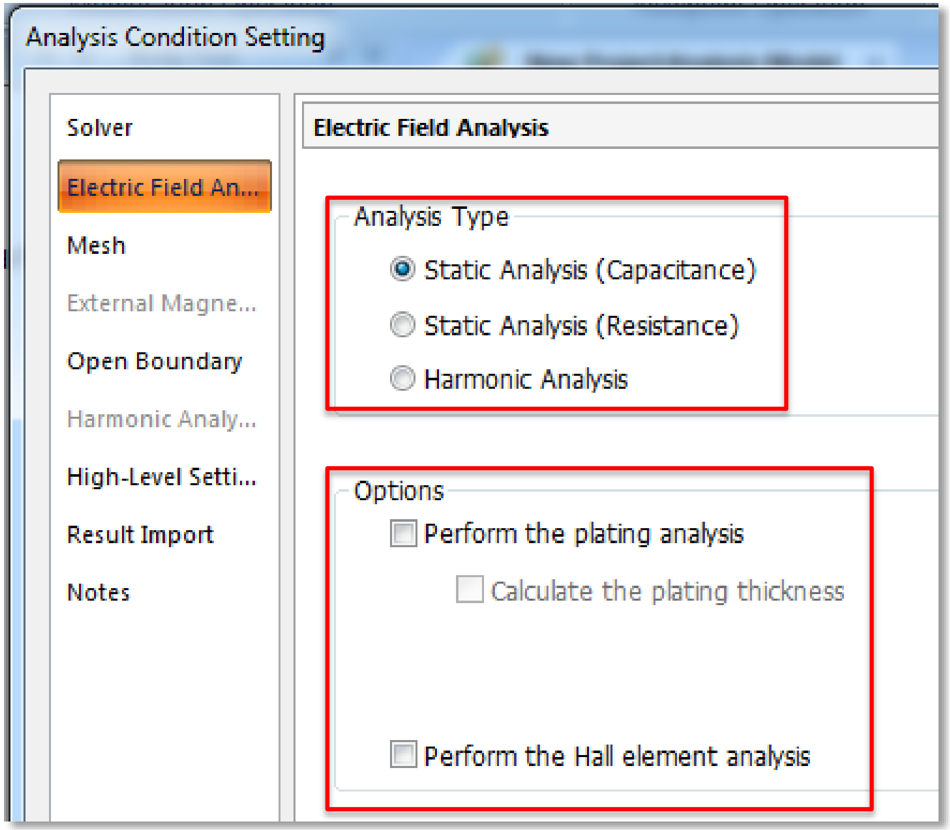


Heat of the Signal Line

(Electric Field-Thermal Analysis)



Analysis Condition



Analysis Type

- Static Analysis
- Harmonic Analysis

Options

- Plating Analysis
- Hall Element Analysis

Analysis Type

Static Analysis

Frequency=0(direct current)

Dielectric material: $-\varepsilon\nabla^2\varphi = \rho$

Conductive material: $-\sigma\nabla^2\varphi = 0$

is solved.

Harmonic Analysis

0<Frequency (alternating current)

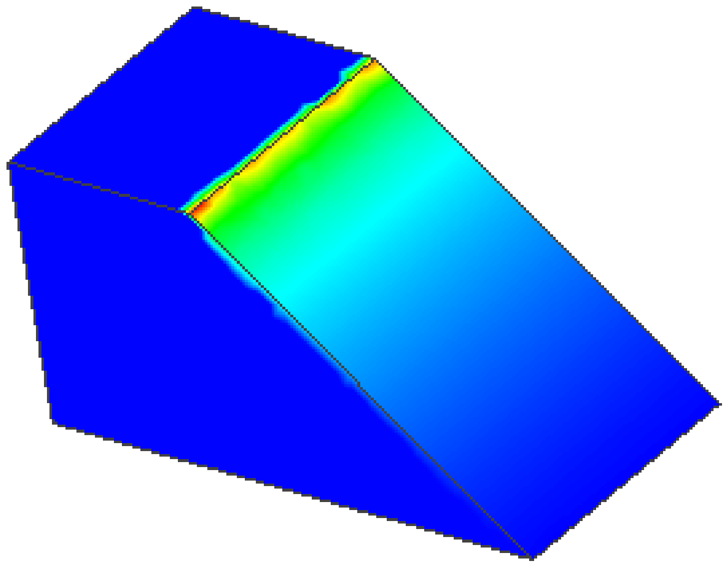
$$-\nabla\cdot(\sigma+j\omega\varepsilon)\nabla\varphi = j\omega\rho$$

where ε: permittivity
φ: potential
ρ: charge density
σ: conductivity

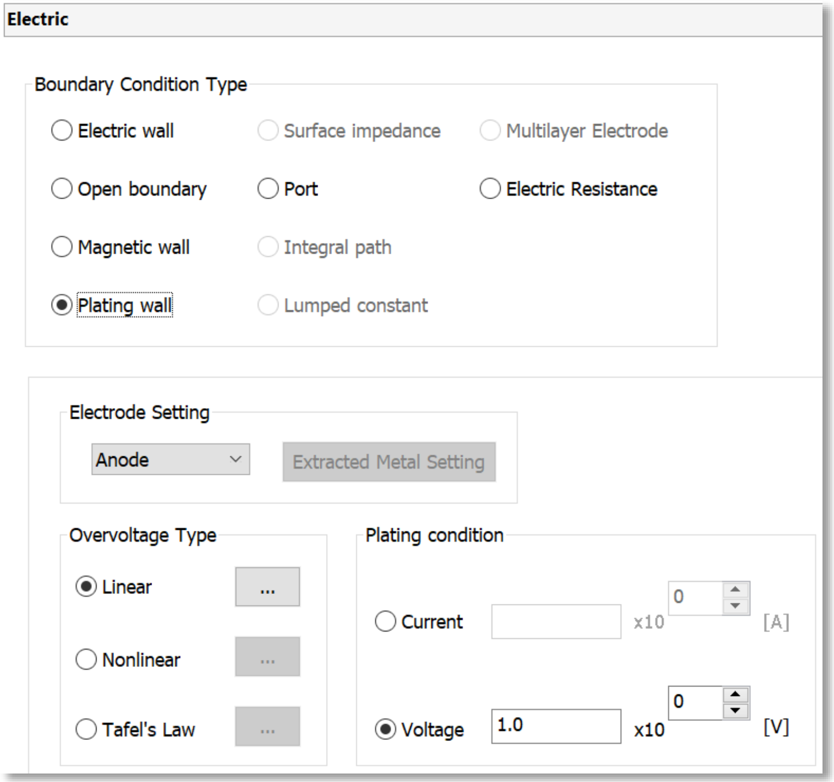
is solved.

Plating Analysis

The current density, voltage distribution, and plating thickness are solved.



Plating Bath



Analysis Condition Setting

Hall Element Analysis

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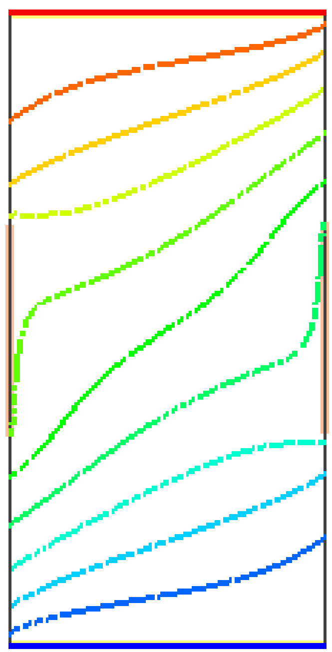
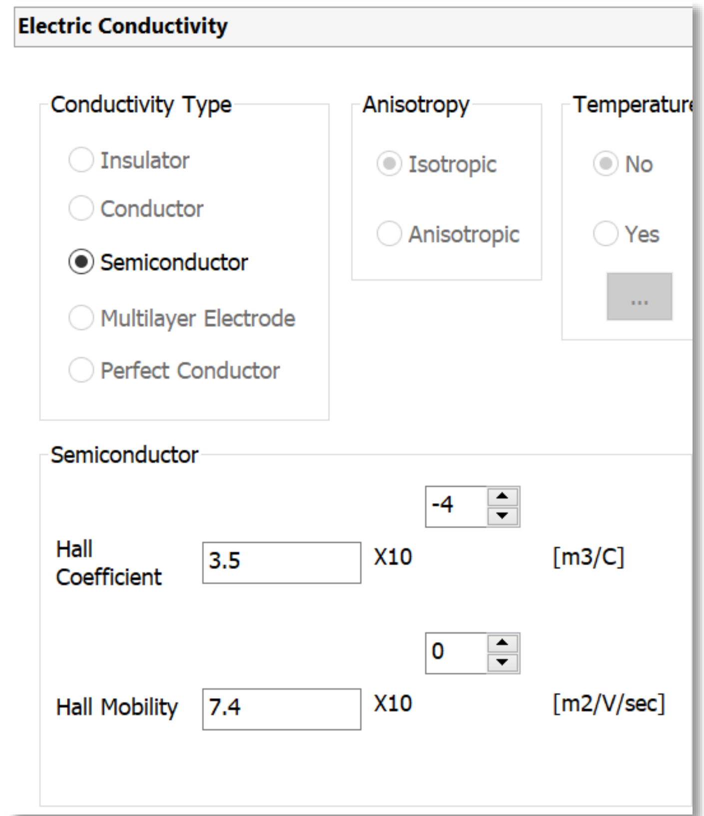
Hall voltage and resistance are solved with hall effect taken into account.



2D Hall Element



Material Property Setting

Basic Equations in Harmonic Analysis

Maxwell Equations

$$\nabla \times H = J + \delta D/\delta t \qquad (1)$$
$$\nabla \times E = - \delta B/\delta t \qquad (2)$$
$$\nabla \cdot D = \rho \qquad (3)$$
$$\nabla \cdot B = 0 \qquad (4)$$

where
H: Magnetic field strength [A/m]
J: Current density [A/m^2]
D: Current flux density [C/m^2]
E: Electric field strength [V/m]
B: Magnetic flux density [T]
ρ: Charge density [C/m^3]
J_e: Induced current density [A/m^2]
Je is an unknown current generated by the Faraday's law.

In the equation (1),
set $J = J_0 + J_e$,
$\nabla \times H = (J_0 + J_e) + \delta D/\delta t$
$= (J_0 + \sigma E) + j\omega\varepsilon E$
by approximating $j\omega\varepsilon E = 0$,
$\nabla \times H = J_0 + \sigma E$
$H = (1/\mu)$
$\nabla \times (1/\mu)B = J_0 + \sigma E$ (5) is given.

From the equation (4), the vector potential A is defined, which will give
$B = \nabla \times A$ (6)

The scalar potential φ is defined by replacing the equation (2) in (6).
$\nabla \times E = - \delta/\delta t(\nabla \times A)$
$\nabla \times (E + \delta A/\delta t) = 0$
$E = -\nabla\varphi - \delta A/\delta t$ (7)

By replacing the equations (6) and (7) in (5),
$\nabla \times (1/\mu) \nabla \times A = J0 - \sigma (\nabla\varphi + \delta A/\delta t)$ is given.

Calculation Method of Output Items

<Inductance>

Calculated by the interlinkage magnetic flux

$L = \Phi / I$

Φ: Interlinkage Magnetic Flux

I: Coil Current

<Electromagnetic Force>

Calculated by the nodal force method

$F = -\int T \cdot \nabla N dV$

T: Maxwell Stress Tensor

N: Interpolation Method

[Gauss]

[Gauss], the solver of the magnetic analysis, is named after Carl Friedrich Gauss.