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## Femtet Seminar

# Understanding Magnetic Analysis

202009

# Table of Contents

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1. Overview
2. Functions and Settings
3. Points to Note

## 1. Overview

- Three Solvers of Electromagnetic Fields
- Analysis Types
- Static Analysis
- Harmonic Analysis
- Transient Analysis

## 2. Functions and Settings

## 3. Points to Note

3 types of solvers are available

## Electromagnetic Field

Electric Analysis

*Coulomb*

Magnetic Analysis

*Gauss/Luvs*

Electromagnetic Analysis

*Hertz*

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

# Analysis Type

3 analysis types are available for magnetic analysis.

## Magnetic Analysis

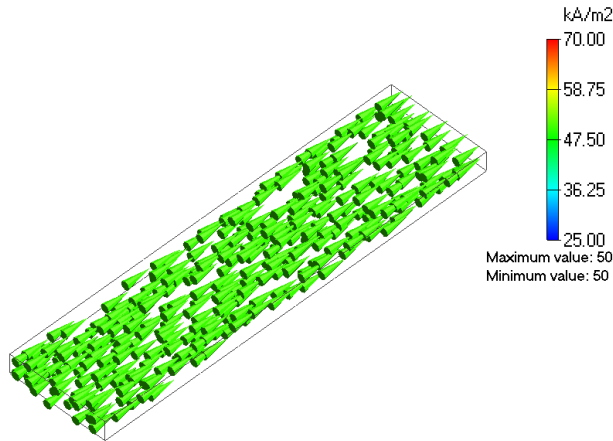
### Analysis Type

- Static Analysis (Gauss)
- Harmonic Analysis (Gauss)
- Transient Analysis (Luvens)

Static	Harmonic	Transient
<ul style="list-style-type: none"><li>• Static Magnetic Field Distribution</li><li>• Inductance</li><li>• Electromagnetic Force, etc.</li></ul>	<ul style="list-style-type: none"><li>• AC Magnetic Field Distribution</li><li>• Inductance with Skin Effect Taken into Account</li><li>• Induced Current, Induced Heat</li></ul>	<ul style="list-style-type: none"><li>• Magnetic Distribution on Time Axis</li><li>• Induced Current</li><li>• Motor</li></ul>

# 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.



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<https://www.muratasoftware.com/en/>

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  $B = \nabla \times A$ )

$\Phi$ : potential  $\mu$ : permeability  $\sigma$ : conductivity

$J_0$ : forced current density

# Harmonic Analysis

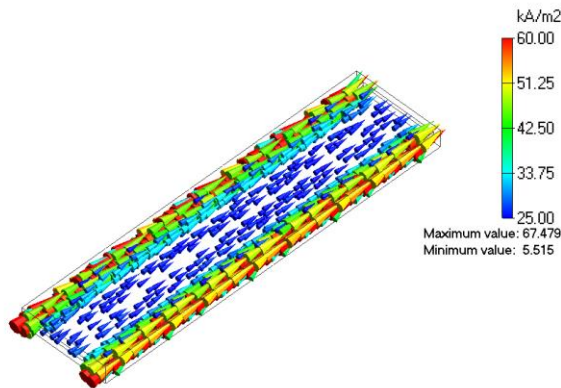
The AC magnetic field distribution (dynamic magnetic field distribution) is calculated, which is generated by alternating current.

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.



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Current Density Distribution (10kHz)

0 < Frequency (AC)

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

is solved.

A: magnetic vector potential (magnetic flux  $B = \nabla \times A$ )

$\Phi$ : potential  $\mu$ : permeability  $\sigma$ : conductivity

$J_0$ : forced current density

# Transient Analysis

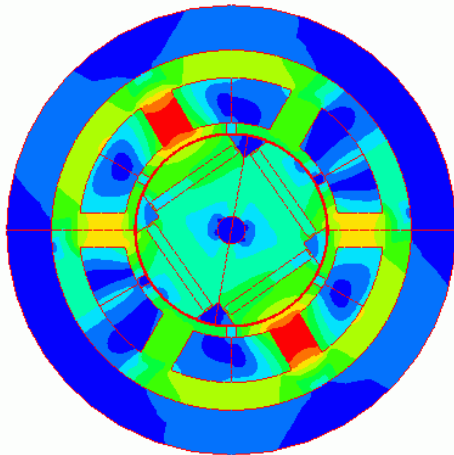
Transient analysis is optional.

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  $B = \nabla \times A$ )

$\Phi$ : potential  $\mu$ : permeability  $\sigma$ : conductivity

$J_0$ : forced current density



## 1. Overview

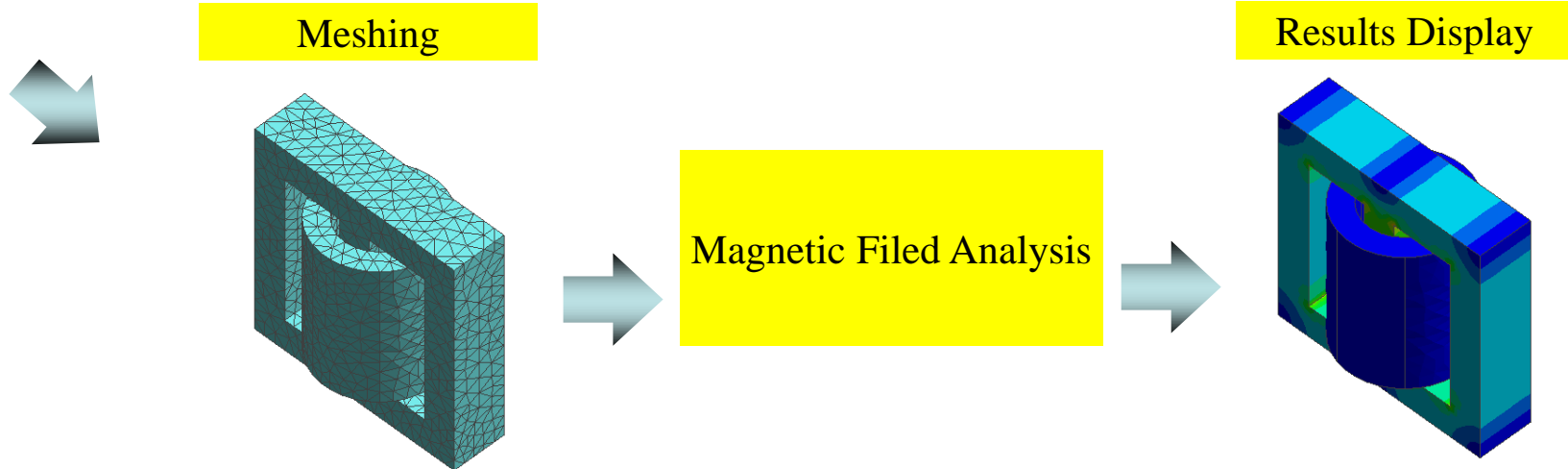
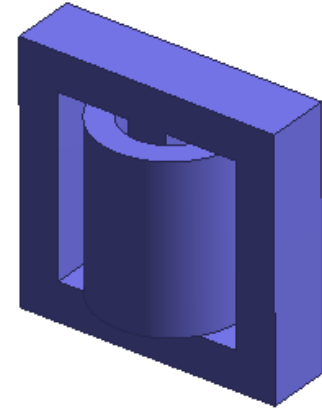
## 2. Functions and Settings

- Analysis Flow
- Analysis Condition
- Material Property
- Boundary Condition
- Results

## 3. Points to Note

# 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.



# Analysis Conditions: Rotating Machine

## Setting of transient analysis of rotating machine.

**Rotating Machinery**

**Rotational Movement**

Constant Velocity

Number of Rotations:  X10  [r/min]  
\*Negative value for reverse rotation

Rotor's Initial Rotation Position:  [deg]

Motion Equation Coupling

**Location of Rotation Axis (arbitrary point on the axis)**

X:   [m]

Y:  X10 [m]

Z:

**Gap Type**

Radial Gap

Axial Gap (available only for 3D analysis)

**The Number of Slide Mesh Divisions**

Circumferential Division Angle:  [deg]

Rotational Quantity per Step:  [Mesh]

The Number of Slide Mesh:

**Location of Slide Mesh (for gap of rotor and stator)**

Automatic calculation

**Rotor Type**

Inner Rotor

Outer Rotor

**Gap Radius**

Inner:   [m]

Outer:  X10 [m]

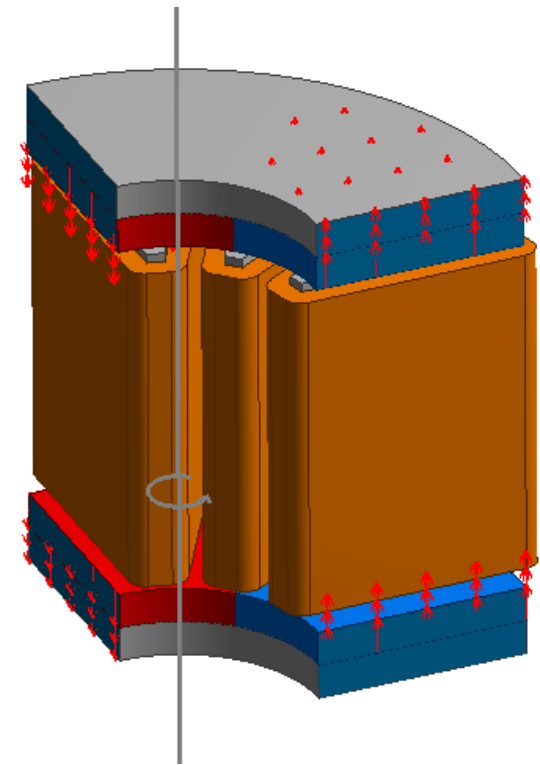
Center:

**Division Size of Slide Mesh in the Axis Direction**

Automatically set the general mesh size

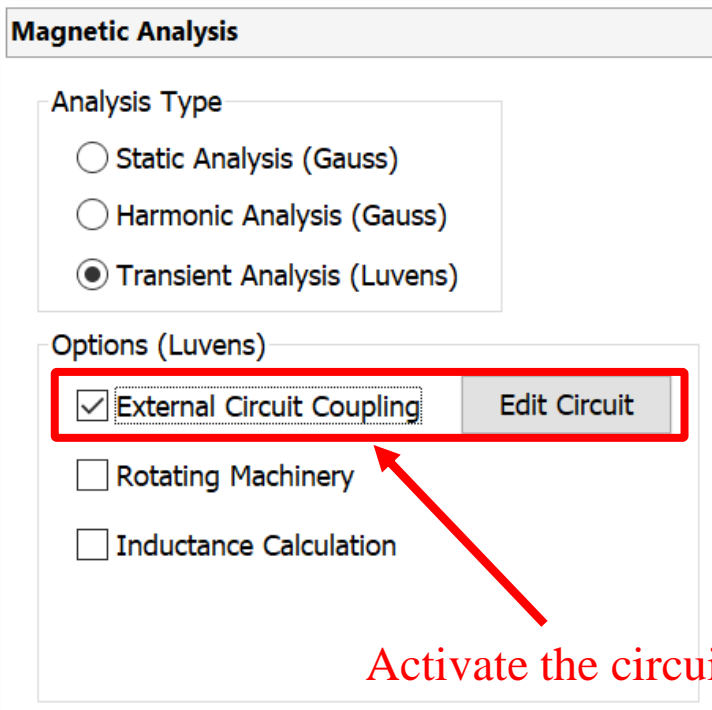
Divide at uniform interval with specified mesh size:  [mm]

Table for specifying mesh size

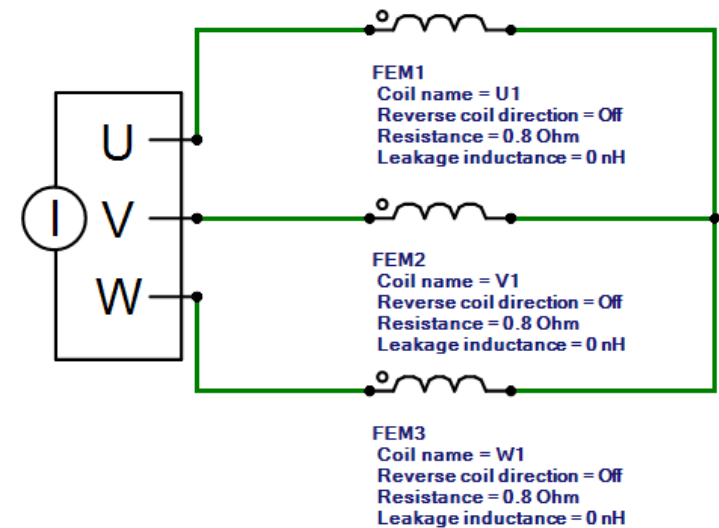


# Analysis Conditions: External Circuit

Setting of coupling with an external circuit for transient analysis.



IUVW1  
Waveform type = AC [cos wave]  
Current [Amplitude] = 5 A  
Frequency = 60 Hz  
U Phase = 85.6 deg  
Phase sequence = U-W-V  
Source connection type = Y



# Analysis Conditions: External Magnetic Field

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.

**External Magnetic Field**

Input Type

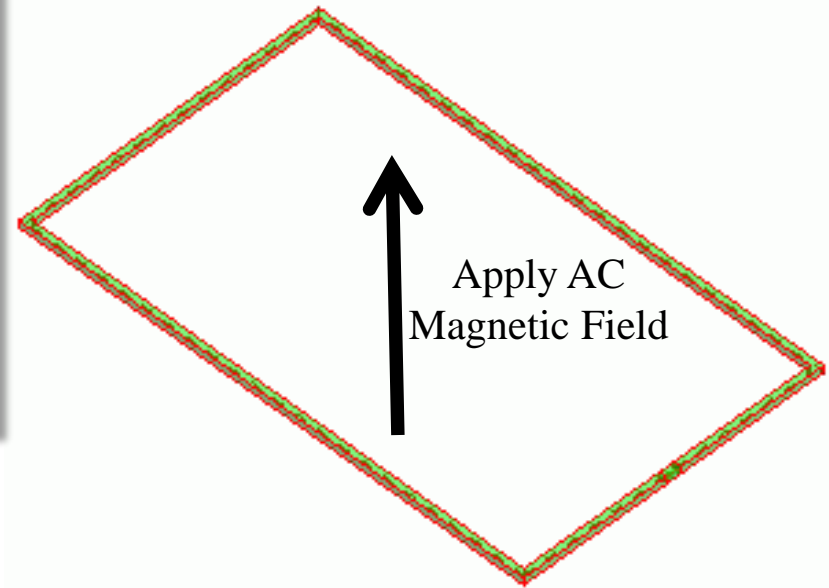
Magnetic flux density [T]

Magnetic field [A/m]

Strength of the external magnetic field

X	<input type="text" value="0.0"/>	X10 <input type="text" value="0"/>	[T]
Y	<input type="text" value="0.0"/>		
Z	<input type="text" value="1"/>		

Note: If the external magnetic field is set, the outer boundary condition is changed to the external magnetic field.



Electromotive Force of Coil

# Material Property

3 types of material properties are available.

Electric Conductivity  
Permeability  
Iron Loss

**Electric Conductivity**

Conductivity Type

Insulator

Conductor

Semiconductor

Multilayer Electrode

Perfect Conductor

Electric Conductivity

X10  [S/m]

**Permeability**

Material Type

Soft Magnetic Material

Permanent Magnet

Magnetization Characteristic Type  Anisotropy

Linear (Constant)

B-H Curve

Relative permeability

X10

tanD

X10

Use the tensor permeability [Hertz]

Use the minor-loop permeability to analyze superimposed DC characteristic

**Iron Loss**

Iron Loss Calculation Type

Joule Loss Only (calculation from current distribution)

Iron loss table

Iron loss empirical formula

Add Table

Frequency  X10  [Hz]

Edit/Check Table

Frequency  [Hz]

# Material Property Setting for Magnetic Materials

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

[Soft Magnetic Material]

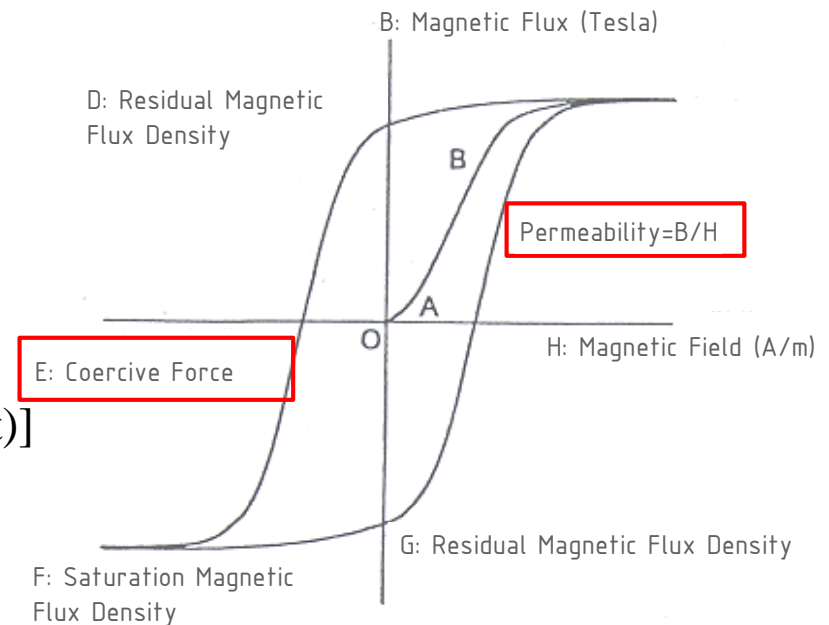
Having low coercive force and large permeability.

- 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.



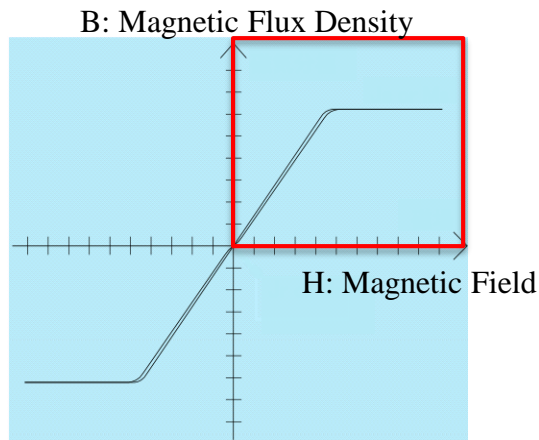
B-H Curve (Magnetic Hysteresis Curve)

# Material Property Setting: Soft Magnetic Material

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

The screenshot shows the 'Permeability' tab in the software. Red boxes and numbers indicate the steps for setting up a soft magnetic material:

- (1) Select **Soft Magnetic Material** under Material Type.
- (1) Select **Linear (Constant)** under Magnetization Characteristic Type.
- (2) Enter **3000** in the Relative Permeability field.
- (2) Enter B-H curve data in the B-H Curve Table.

No.	Magnetic	Magnetic
1	0	0
2	58	0.42
3	90	0.8
4	180	1.19
5	380	1.27
6	1100	1.48
7	2000	1.53
8	3000	1.608
9	11000	1.81
10	20000	1.91

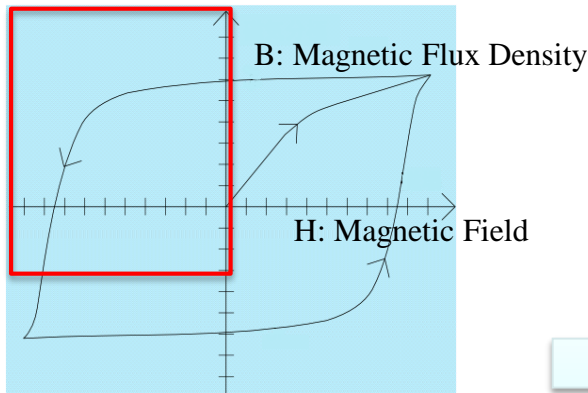


# Material Property Setting: Permanent Magnet

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



**Permeability**

Material Type

Soft Magnetic Material  
 **Permanent**  
 Magnetizing Material  
 Soft Magnetic Material (with minor loop)  
 Use Magnetization Result

Magnetization Characteristic Type

**(1)**  **Linear (Constant)**  
**(2)**  B-H Curve ...  
 M-H Curve ...

B-H Curve Table

**(1)** Magnetization Strength (Residual I)  [T]

\*The magnetization direction to in the [Direction] tab of [Body A]

Relative Permeability

**(2)** B-H Curve Table

No.	Magnetiz.	Magnetiz.
1	-0.923	1.16
2	-4.5	1.2
3	0	1.25
4	4.5	1.3
5		
6		
7		
8		
9		
10		

Exp         Smooth Interpolation  
 Unit    [A/m]    [T]

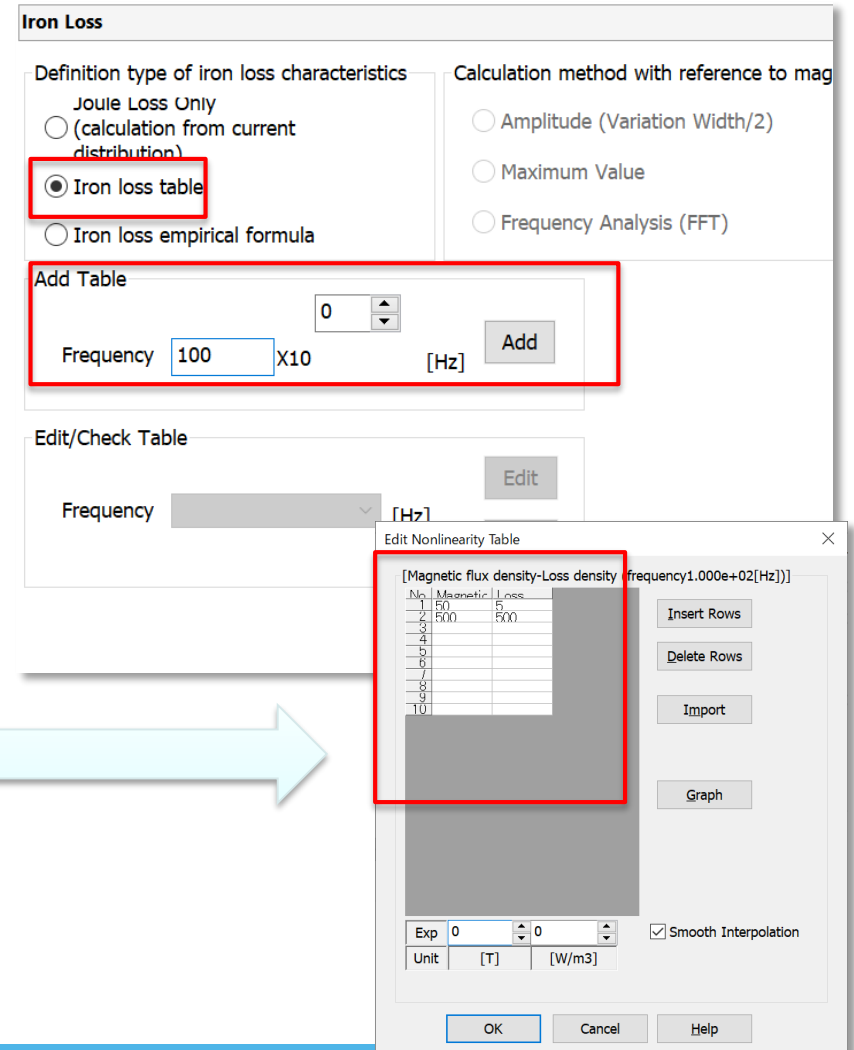
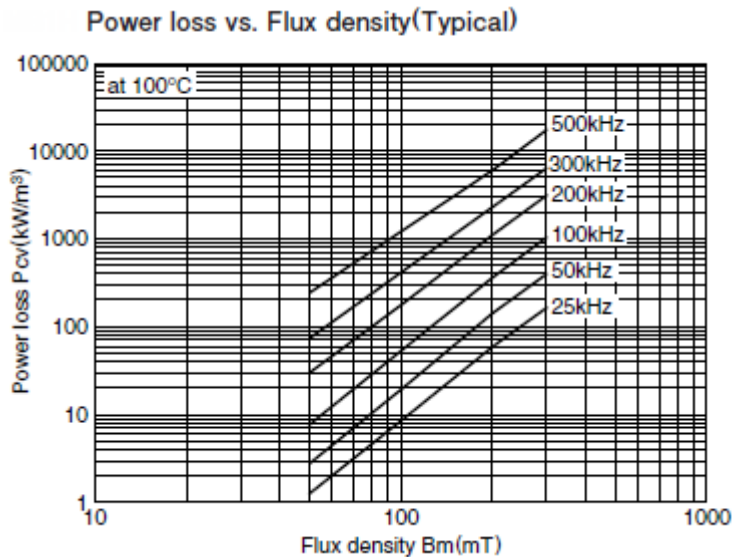
# Material Property Setting: Iron Loss

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.



**Iron Loss**

Definition type of iron loss characteristics

- Joule Loss Only (calculation from current distribution)
- Iron loss table
- Iron loss empirical formula

Calculation method with reference to mag

- Amplitude (Variation Width/2)
- Maximum Value
- Frequency Analysis (FFT)

Add Table

Frequency  X10 [Hz]

Edit/Check Table

Frequency  [Hz]

Edit Nonlinearity Table

No.	Magnetic Loss	Loss density
1	50	5
2	500	500
3		
4		
5		
6		
7		
8		
9		
10		

Exp    Smooth Interpolation

Unit [T] [W/m³]

# Material Property Setting: Iron Loss

## 2. Iron Loss Empirical Formula

Enter the coefficients of  
the iron loss empirical formula.

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

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

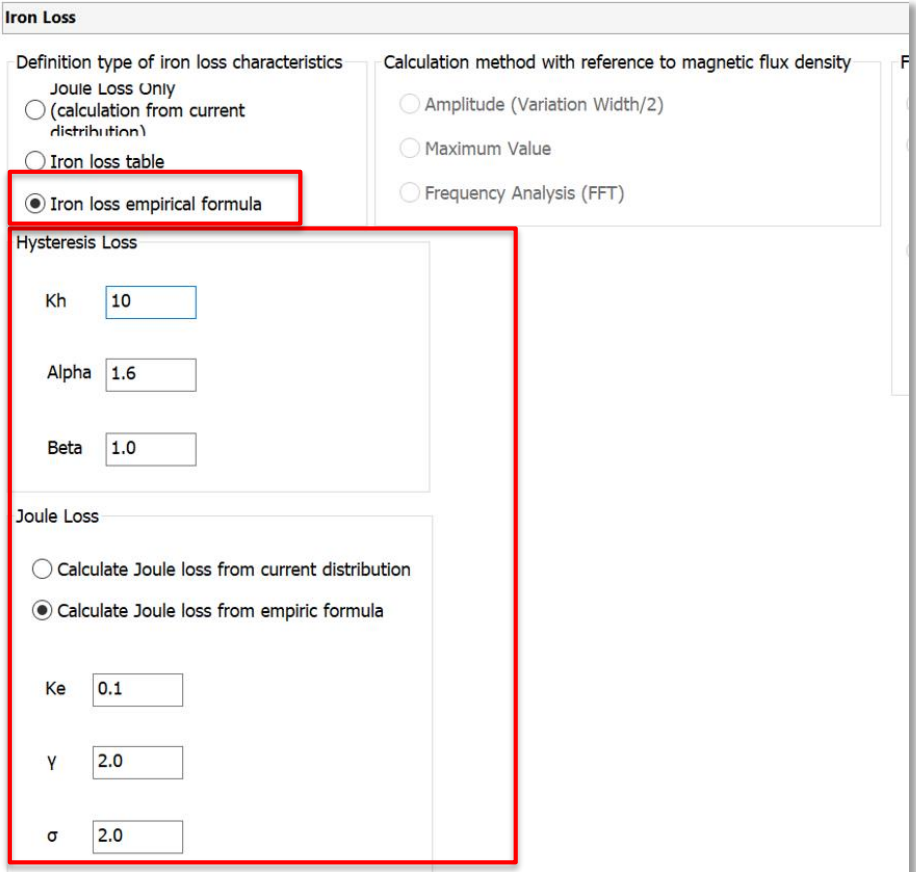
where:

$Wh$ : Hysteresis loss density [W/m<sup>3</sup>]

$We$ : Joule loss density [W/m<sup>3</sup>]

$B$ : Magnetic flux density [T]

$f$ : Frequency [Hz]

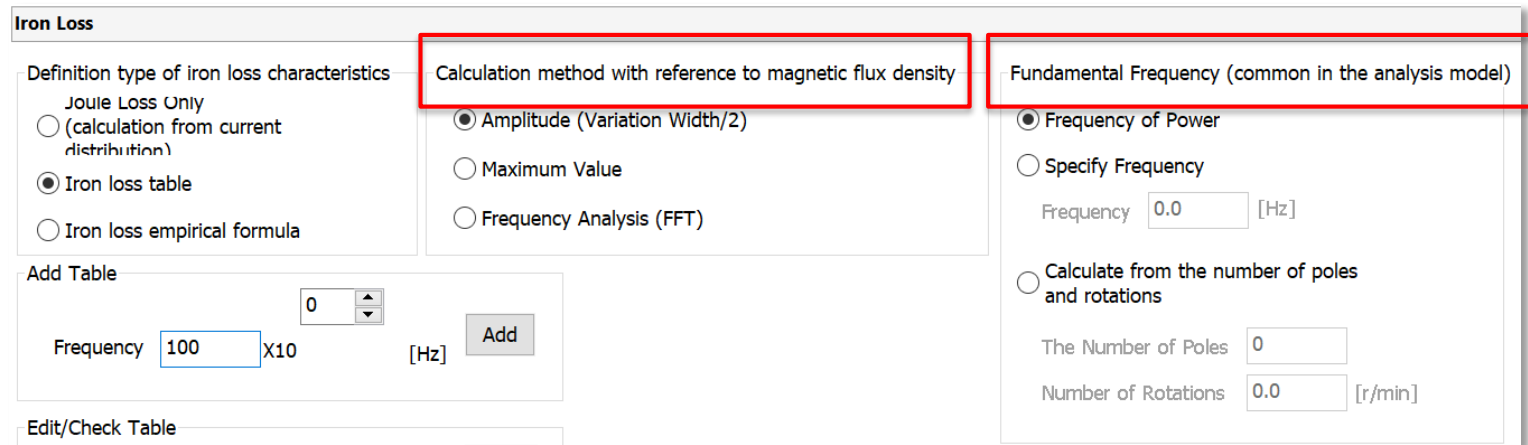


The screenshot shows the 'Iron Loss' configuration window. It is divided into two main sections: 'Definition type of iron loss characteristics' and 'Calculation method with reference to magnetic flux density'. In the first section, the 'Iron loss empirical formula' option is selected. The 'Hysteresis Loss' section contains three input fields: 'Kh' (10), 'Alpha' (1.6), and 'Beta' (1.0). The 'Joule Loss' section has two radio buttons, with 'Calculate Joule loss from empiric formula' selected. Below this, there are three input fields: 'Ke' (0.1), 'γ' (2.0), and 'σ' (2.0). A red box highlights the 'Iron loss empirical formula' option and the 'Hysteresis Loss' and 'Joule Loss' sections.

# Material Property Setting: Iron Loss

## 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.



**Iron Loss**

Definition type of iron loss characteristics

- Joule Loss Only (calculation from current distribution)
- Iron loss table
- Iron loss empirical formula

Calculation method with reference to magnetic flux density

- Amplitude (Variation Width/2)
- Maximum Value
- Frequency Analysis (FFT)

Fundamental Frequency (common in the analysis model)

- Frequency of Power
- Specify Frequency
- Calculate from the number of poles and rotations

Frequency: 0.0 [Hz]

The Number of Poles: 0

Number of Rotations: 0.0 [r/min]

Add Table

Frequency: 100 X10 [Hz] Add

Edit/Check Table

### [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].

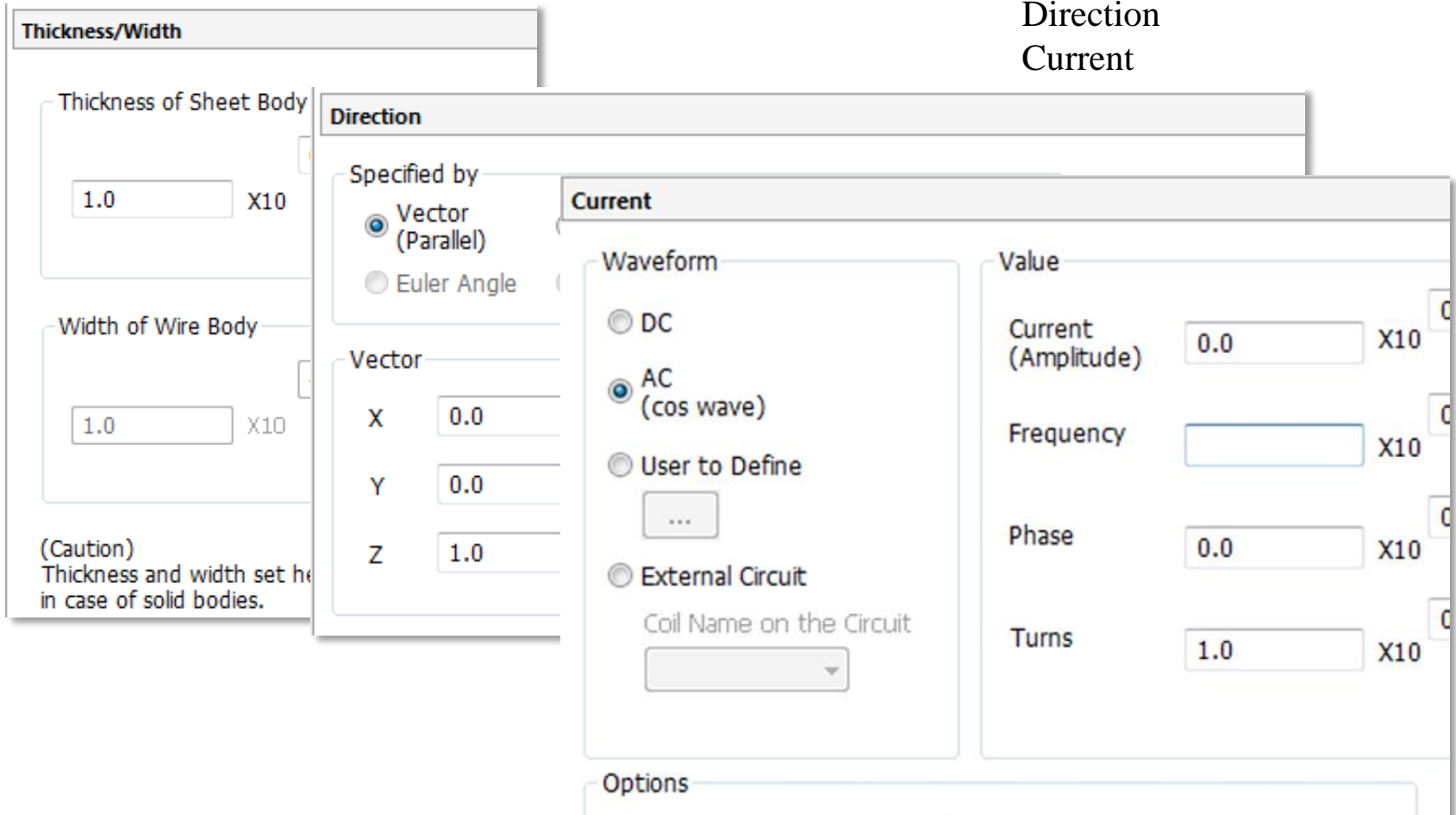
If the waveform is arbitrary, the frequency is determined by the time range of the table.

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

3 types of body attributes are available.

Thickness/Width  
Direction  
Current



The image shows three overlapping dialog boxes in a software interface:

- Thickness/Width Dialog:**
  - Thickness of Sheet Body:  X10
  - Width of Wire Body:  X10
  - (Caution) Thickness and width set here in case of solid bodies.
- Direction Dialog:**
  - Specified by:
    - Vector (Parallel)
    - Euler Angle
  - Vector:
    - X:
    - Y:
    - Z:
- Current Dialog:**
  - Waveform:
    - DC
    - AC (cos wave)
    - User to Define
    - External Circuit
  - Coil Name on the Circuit:
  - Value:
    - Current (Amplitude):  X10
    - Frequency:  X10
    - Phase:  X10
    - Turns:  X10

# Body Attribute: Direction

Magnetization direction is specified.

**Direction**

Specified by

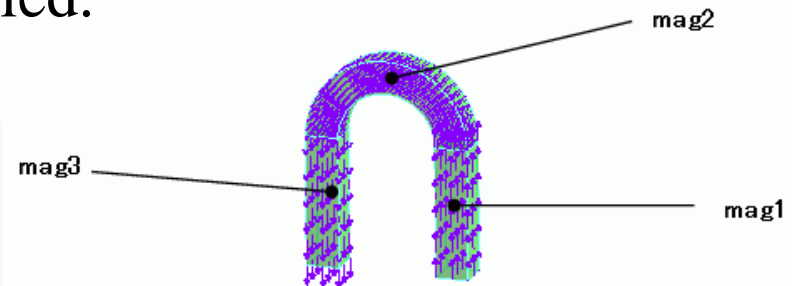
Vector (Parallel)    
  Centripetal Direction (Radial)    
  Polar Anisotropy  
 Euler Angle    
  Circumferential Direction    
  Halbach

Vector

X

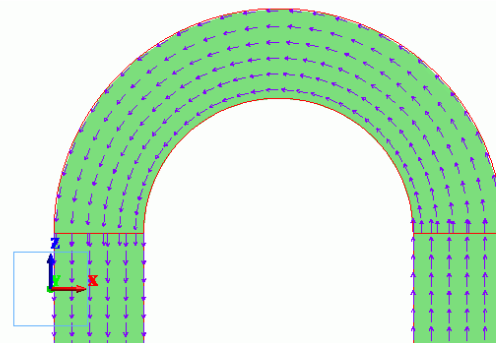
Y  X10

Z



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
mag3	Direction	Direction Type	Vector
		Vector	X=0, Y=0, Z=-1

The resulting magnetizing directions are as follows.



Horseshoe Magnet

# Body Attribute: Current

Value and direction of current are specified.

**Current**

**Waveform**

DC

AC (cos wave)

User to Define

...

External Circuit Coupling

Coil Name on the Circuit

none

**Value**

Current (Amplitude)  X10  [A]

Frequency  X10  [Hz]

Phase  [deg]

Turns  [Turn]

**Direction**

Loop Coil/Magnetic Field Direction

Specify Inflow Face

Specify Inflow/Outflow faces

Specify Inflow/Outflow Faces (In the Air Box)  
\*Inflow/outflow faces are positioned in the air box

Specify Boundary Conditions

**Magnetic Field Vector**

X

Y

Z

**Options**

Distribute the current uniformly  
(Consider to opt for it when the number of turns is more than 1)

**Induced Current**

Yes

No

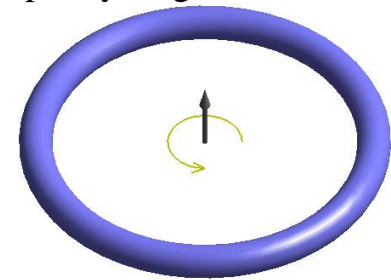
**Circuitry of Induced Current**

Open

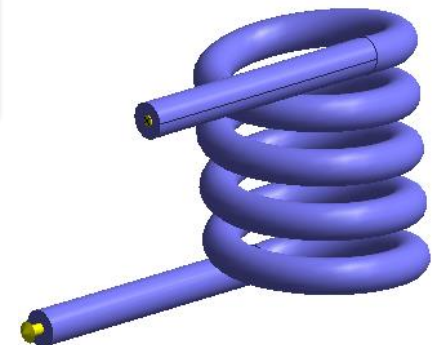
Short

<Direction Setting>

- Loop Coil  
Specify magnetic field vector.

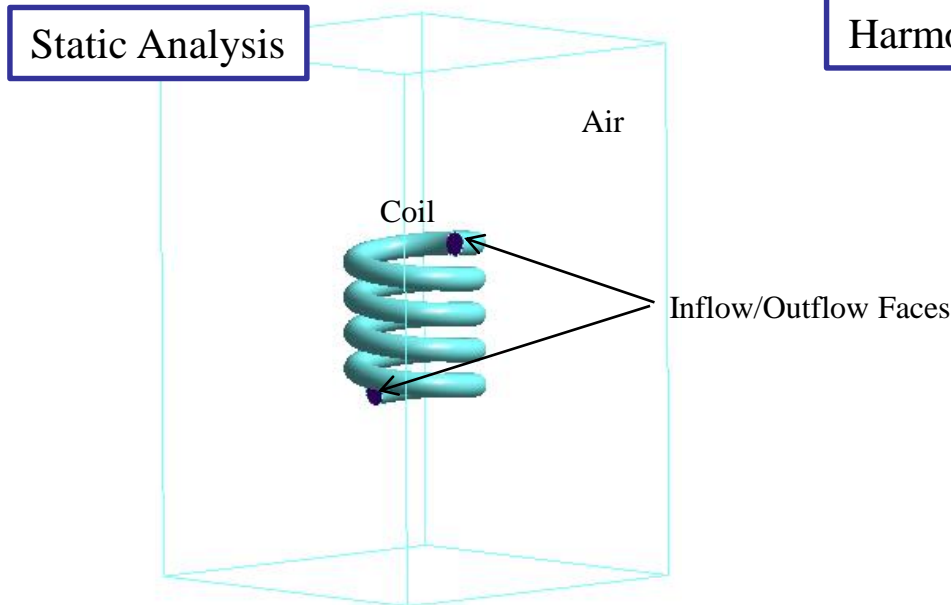


- Others  
Specify inflow/outflow faces.

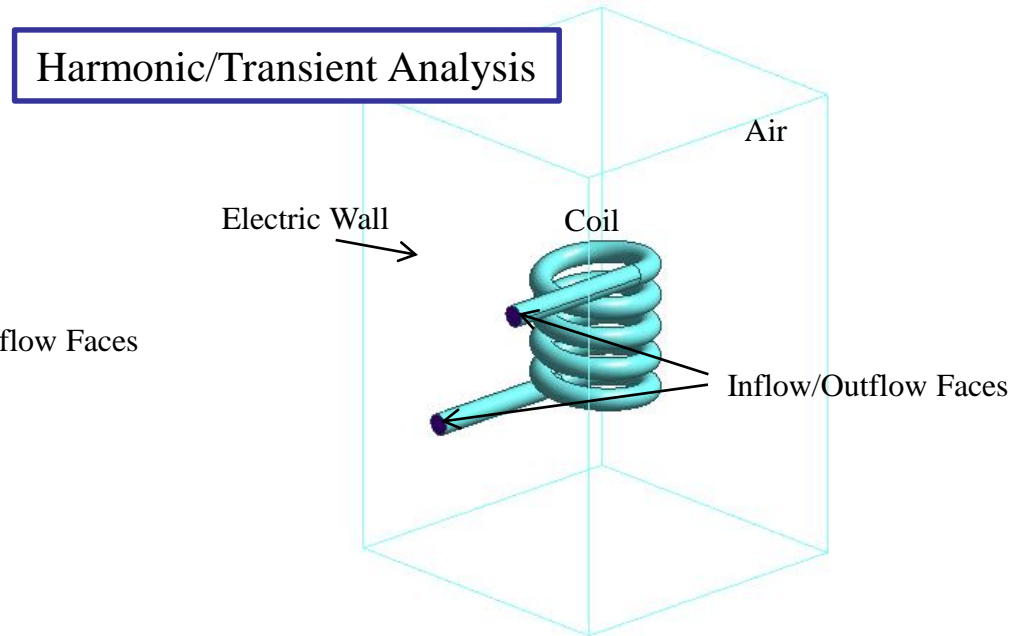


# Body Attribute: Current

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



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



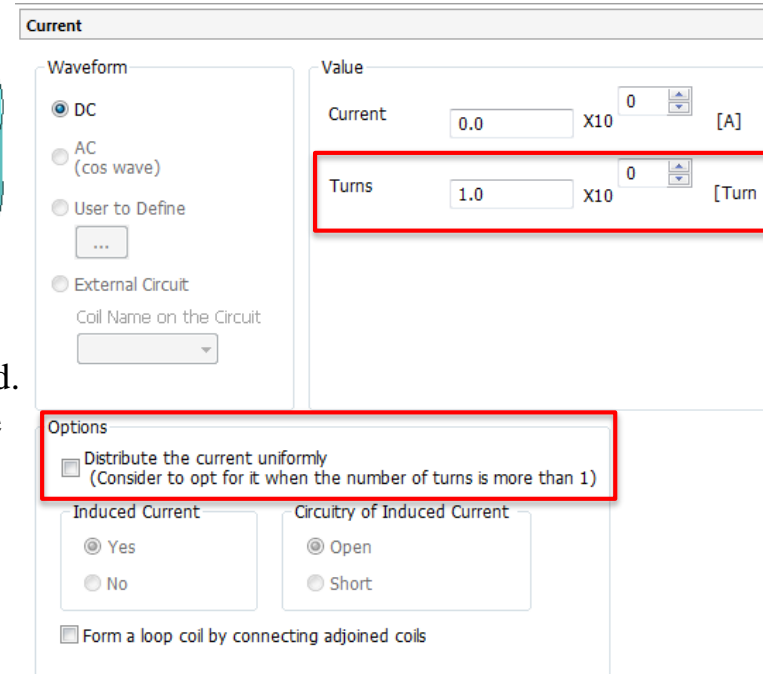
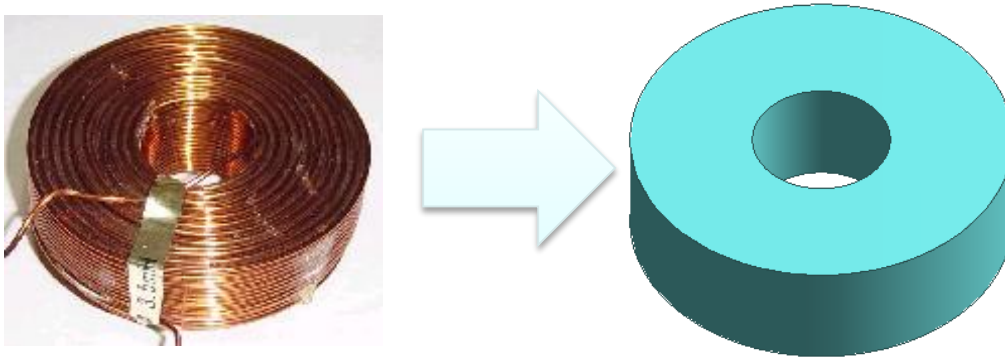
The inflow/outflow faces must be extended to the outside of the air body. The outer boundary condition must be electric wall. (Inflow/outflow faces are electrically connected)

\*This is not the case for the loop coil.

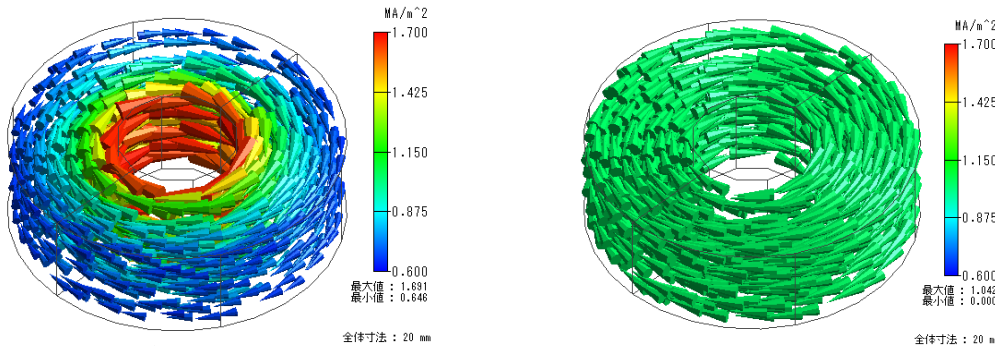


# Coil of Many Turns

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

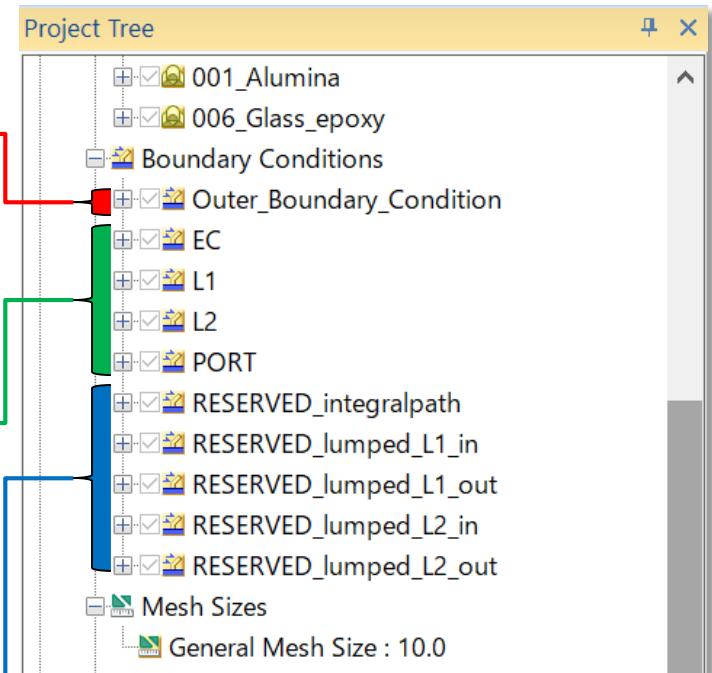
It is set to the outer perimeter of the model.  
Its type is selectable.

### 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 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**

Boundary Condition Type

Electric wall     Surface impedance     Multilayer Electrode

Open boundary     Port     Electric Resistance

Magnetic wall     Integral path

Plating wall     Lumped constant

**Symmetry/Continuity**

Symmetry

Reflective

Periodic

Continuity

Discontinuous

## 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(\*)

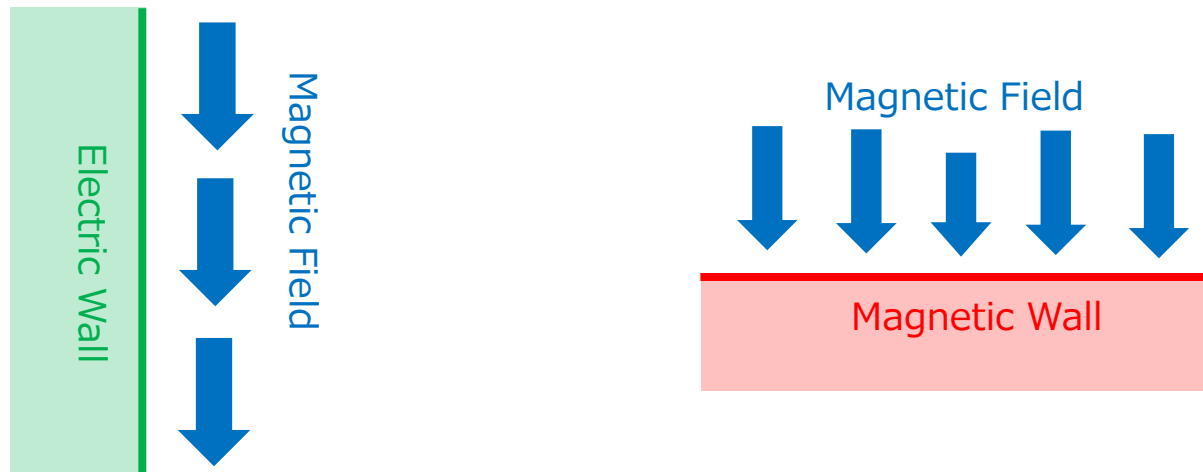
Input and output of electromagnetic waves

(\*)Port is rarely used.

Conditions except Port are explained on the following pages.

# Boundary Condition: Electric Wall and Magnetic Wall

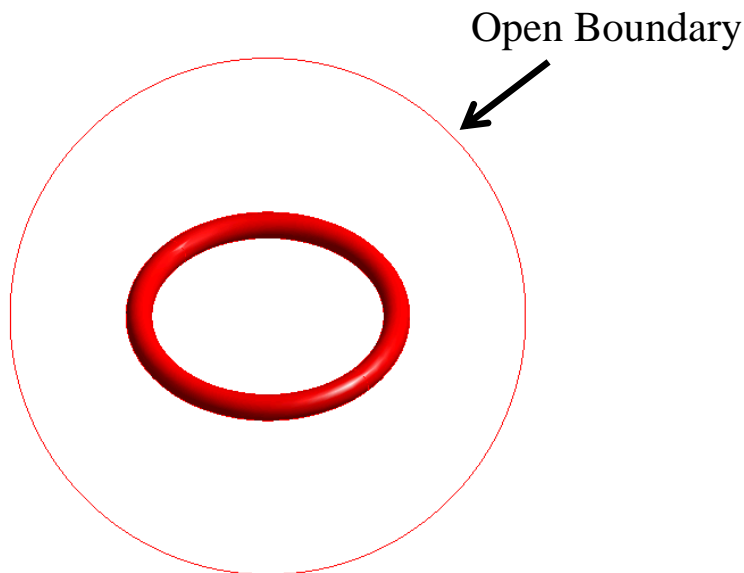
The magnetic field runs in parallel to the electric wall, and normal to the magnetic wall.  
The magnetic wall is used mainly when the external magnetic field is applied.  
The electric wall represents the analysis domain enclosed by conductor.  
The electric wall is set by default in the magnetic analysis.



# 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)

### Open Boundary

Type

Infinite Element

Absorbing Boundary

PML (Perfectly Matched Layers)

Coordinates of Origin

X

Y  x10  [m]

Z

Order of Absorbing Boundary

1st degree  2nd degree

Solver-specific Setting

No setting is necessary specifically for the solver you are currently using

PML Setting

PML  [Wavelength] Piezoelectric Analysis Setting

Caution

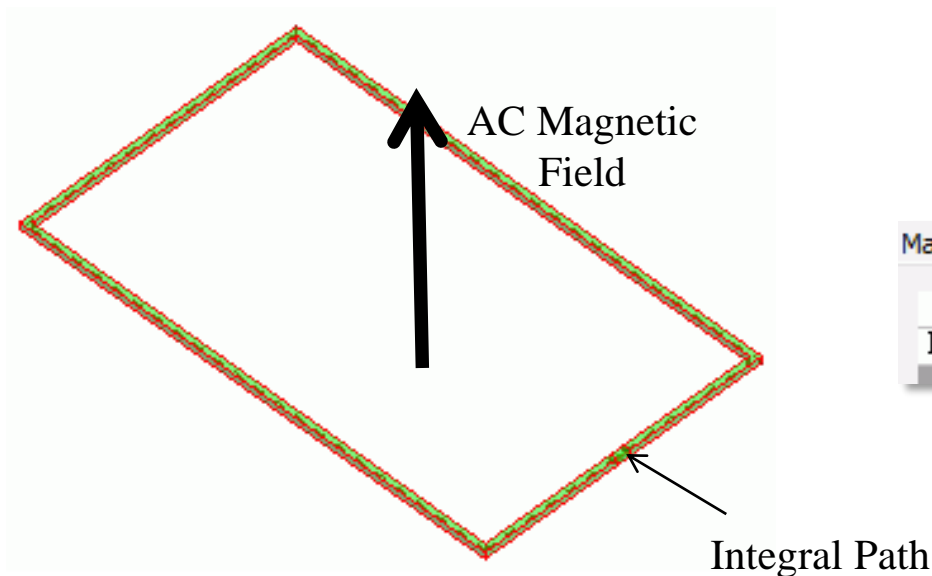
To use the open boundary defined on this tab, set the [open boundary] on the model. It's also possible to set it on the outer boundary unless it is PML.

<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.



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

Electromotive of Receiver Coil (NFC)

# Boundary Condition: Reflective

## Boundary condition setting on the face of symmetry

**Symmetry/Continuity**

**Symmetry**

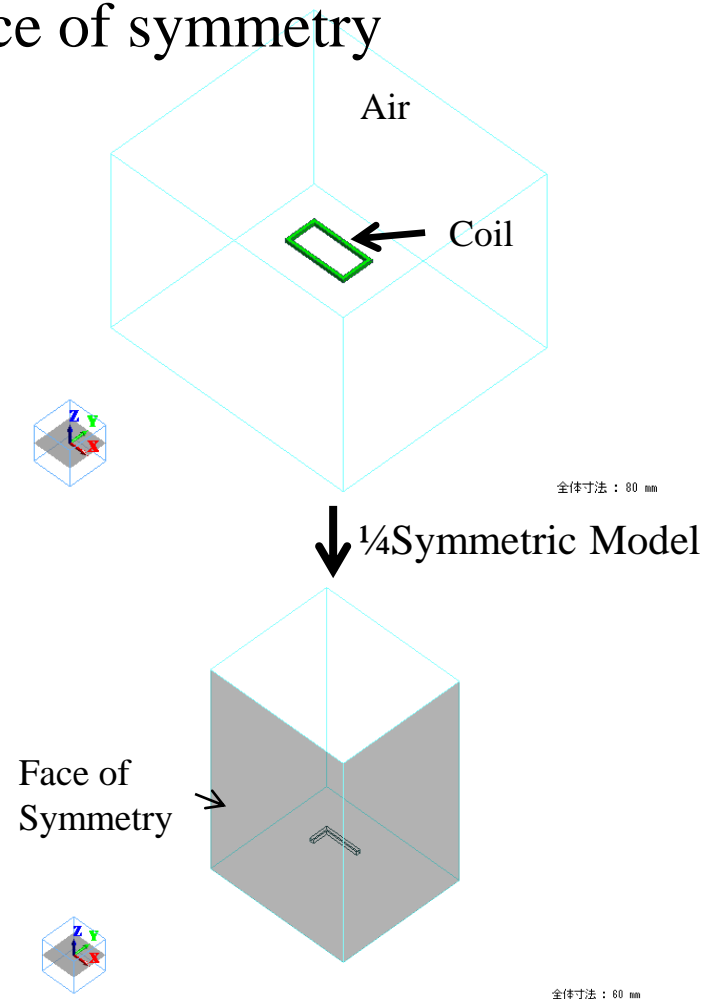
Reflective

Periodic

**Continuity**

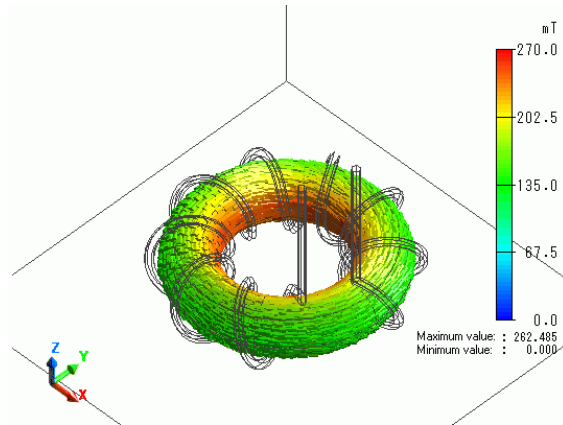
Discontinuous

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

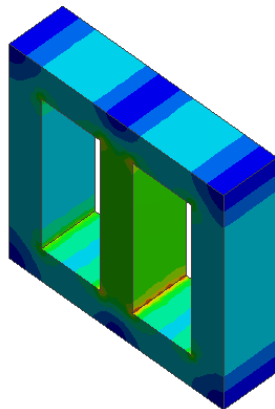


# Results: Field

Field shows the electromagnetic field visually.

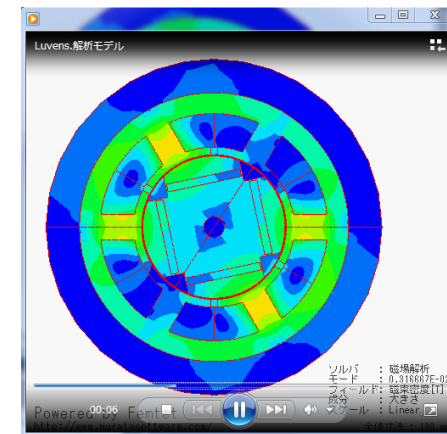


Vectors of Magnetic Flux Density



Contour Diagram of Loss 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

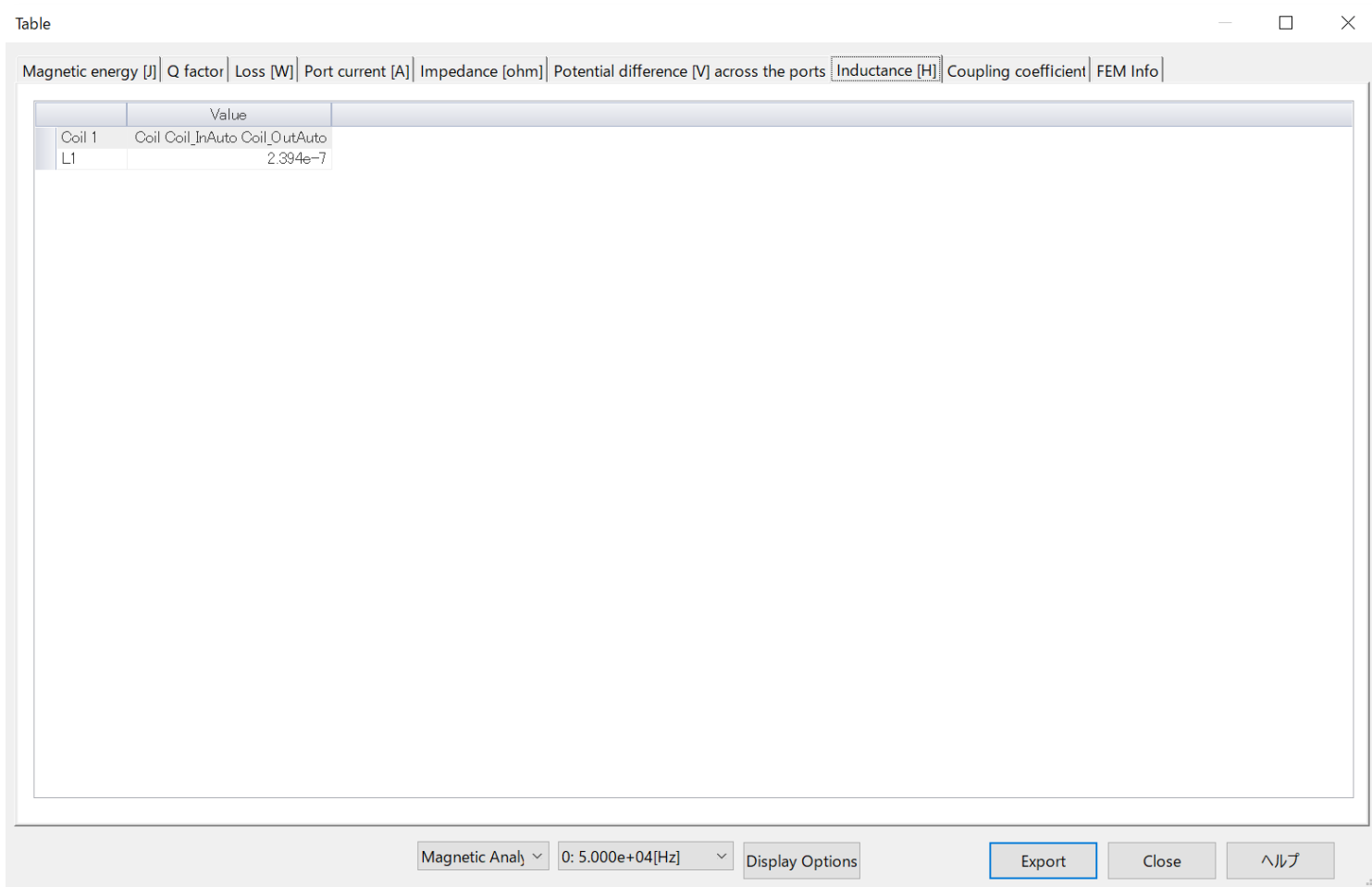


Animation



# Results: Table

Numerical results are displayed on the table.



Table

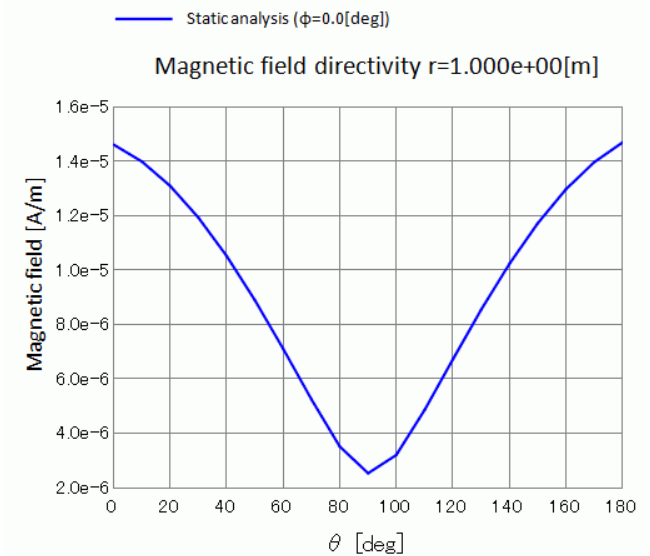
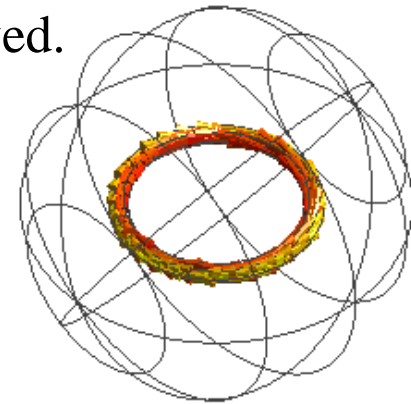
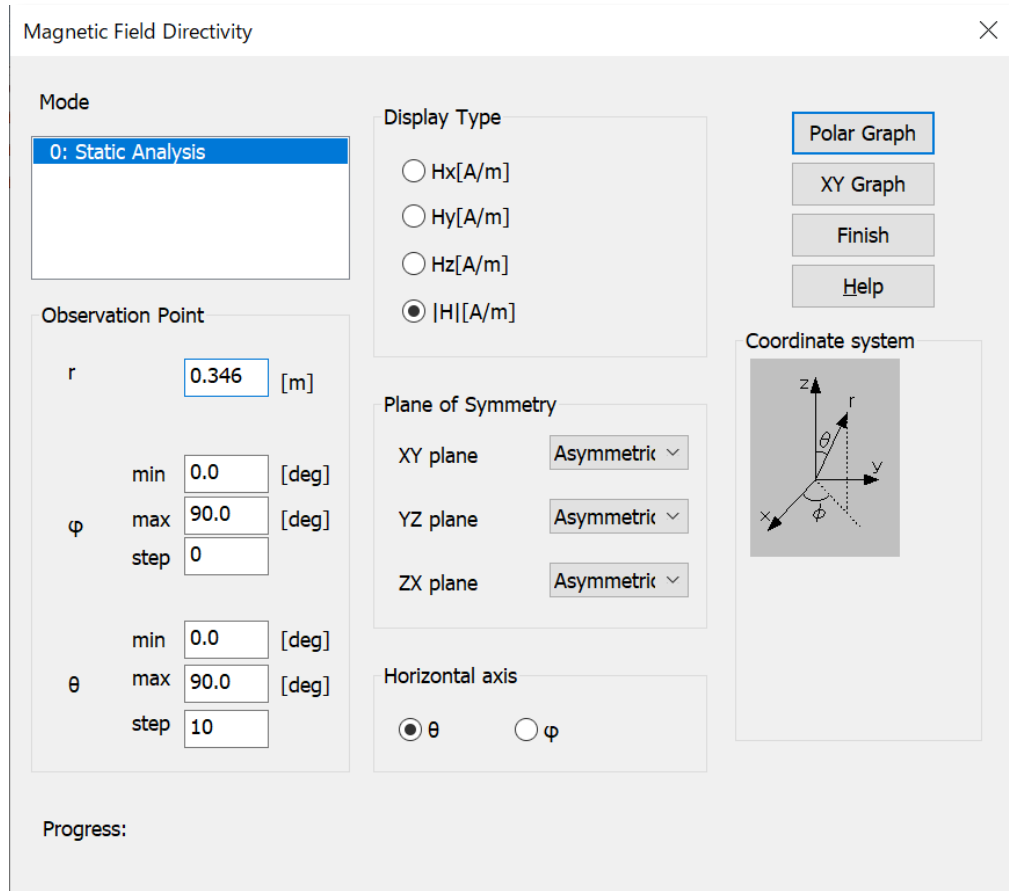
Magnetic energy [J] | Q factor | Loss [W] | Port current [A] | Impedance [ohm] | Potential difference [V] across the ports | Inductance [H] | Coupling coefficient | FEM Info

Coil 1	Value	
	Coil	Coil_InAuto Coil_OutAuto
L1		2.394e-7

Magnetic Anal ▾ 0: 5.000e+04[Hz] ▾ Display Options Export Close ヘルプ

# Results: Directivity

Magnetic directivity in the specified distance is displayed.



# Table of Contents

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## 1. Overview

## 2. Functions and Settings

## 3. Points to Note

- Calculation Accuracy and Speed
- Linear and Nonlinear Analysis
- Harmonic Analysis
- Loss and Magnetic Field-Thermal Coupled Analysis
- Floating Capacitance Calculation by Electric Field Analysis

Mesh

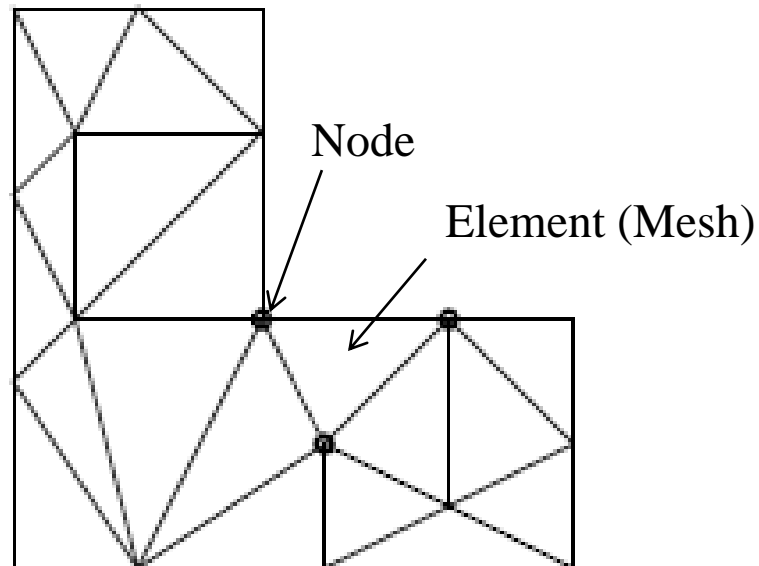
Air Size

Symmetric Model

# 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.

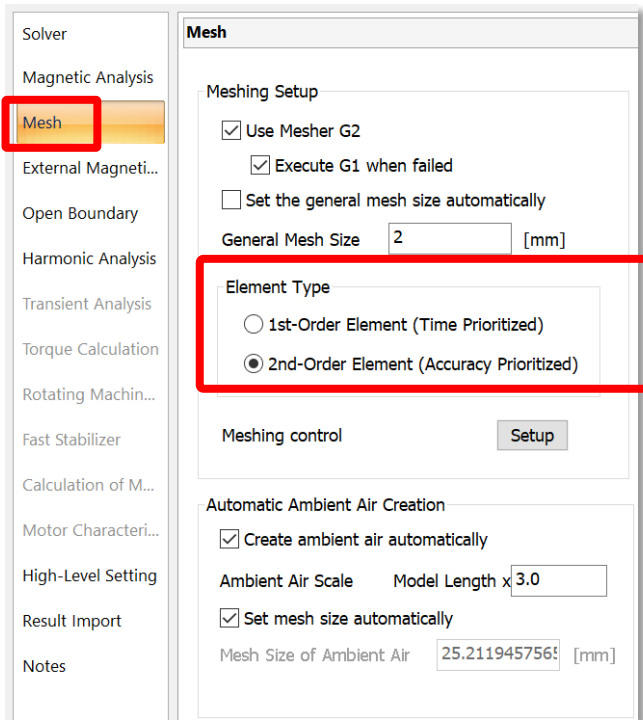
It subdivides an analysis domain into smaller parts called finite elements.

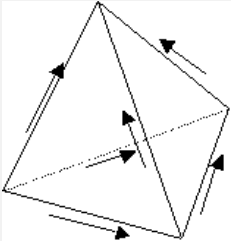
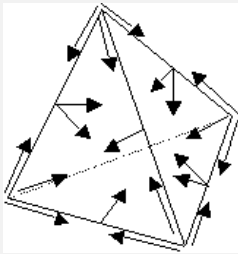


Subdivision of Analysis Domain

# Element Type

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

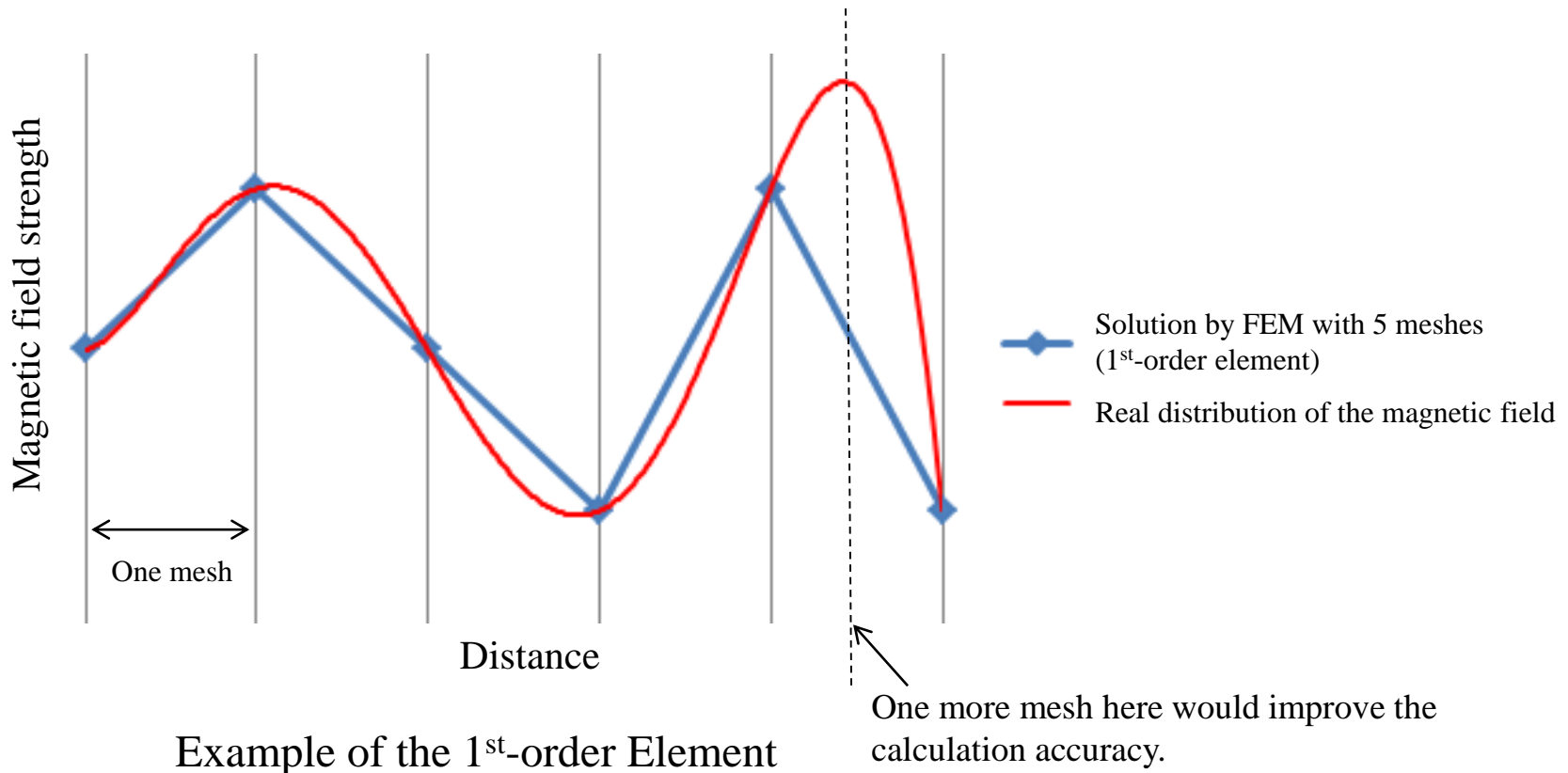


Element Type	Locations of Unknown Numbers	Calculation Time	Calculation Accuracy
1 <sup>st</sup> -order Element		Short	Low
2 <sup>nd</sup> -order Element		Long	High

↖ (Unknown Number)

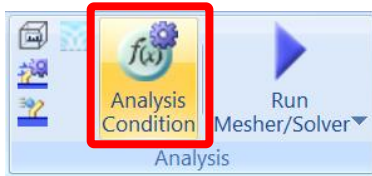
# Mesh Size

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.



# Mesh Size Setting

## General Mesh Size



### Meshing Setup

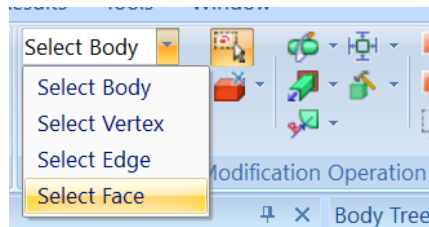
- Use Mesher G2
- Execute G1 when failed

Set the general mesh size automatically

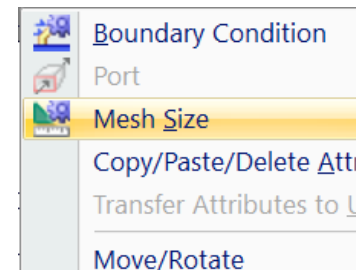
General Mesh Size  [mm]

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

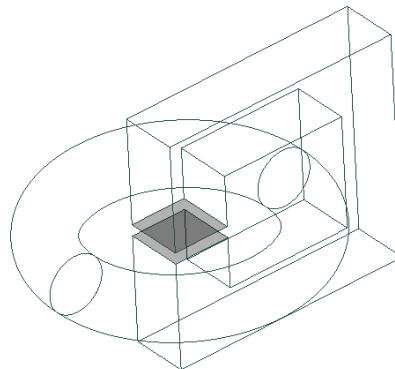
① Select mode



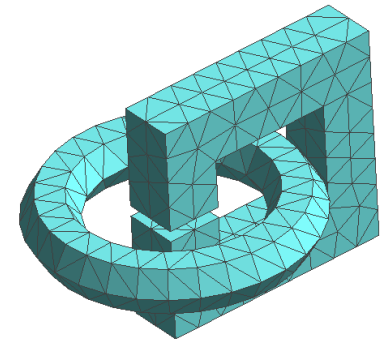
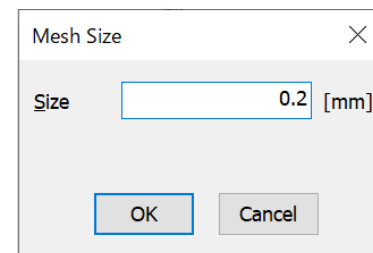
③ Right click



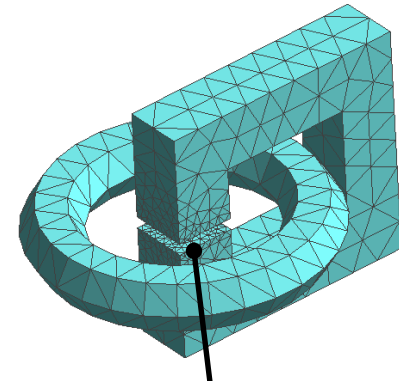
② Select target



④ Enter mesh size



Original Meshes



Finer Meshes on the Selected Area



# Air Size

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)

**Mesh**

Meshing Setup

- Use Mesher G2
  - Execute G1 when failed
- Set the general mesh size automatically

General Mesh Size  [mm]

Element Type

- 1st-Order Element (Time Prioritized)
- 2nd-Order Element (Accuracy Prioritized)

Meshing control

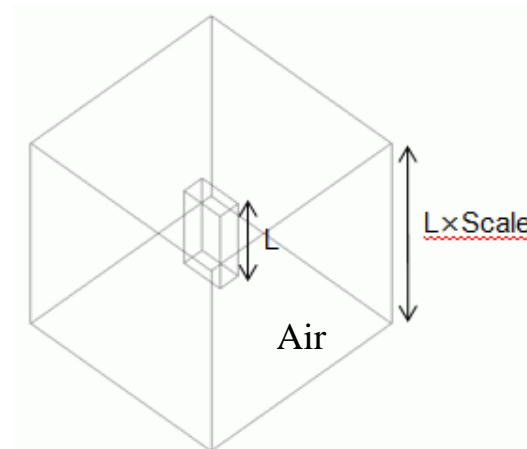
**Automatic Ambient Air Creation**

- Create ambient air automatically

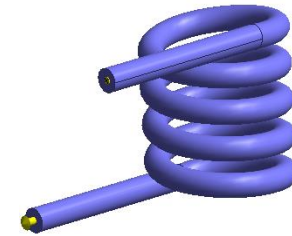
Ambient Air Scale Model Length x

- Set mesh size automatically

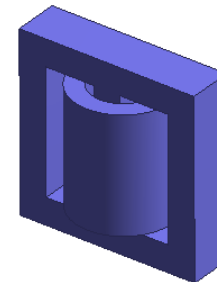
Mesh Size of Ambient Air  [mm]



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

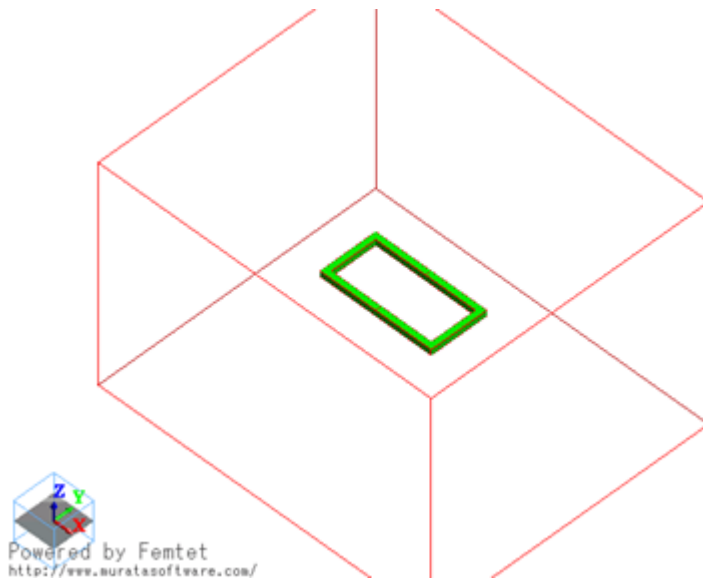


Closed Magnetic Circuit  
The scale of 1.2 is enough

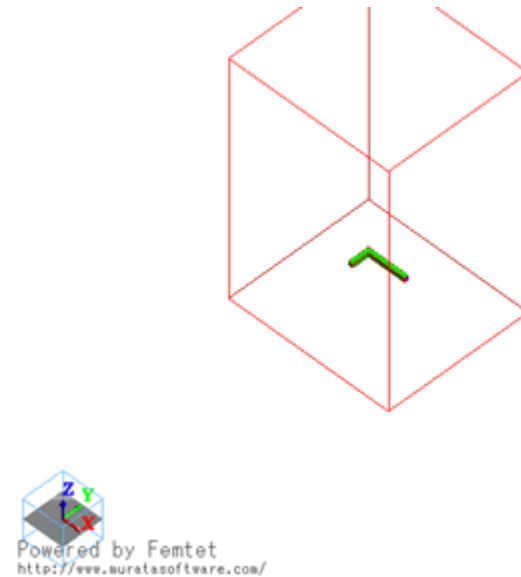
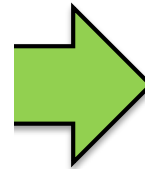


# Symmetric Model

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



Full Model

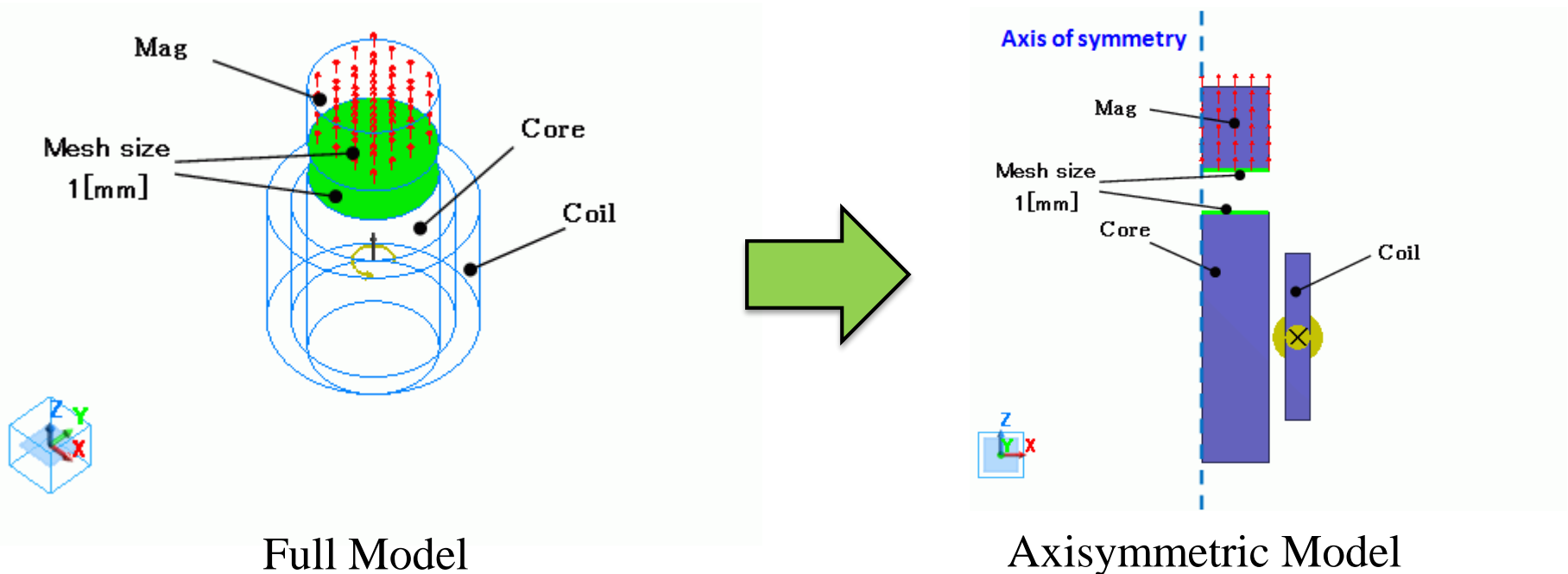


Symmetric Model

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

# 2D Axisymmetric Model

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

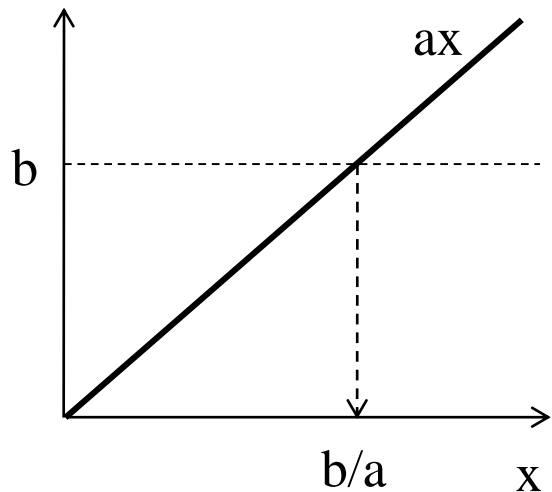


Linear and Nonlinear Analysis

Nonlinear Magnetic Analysis

## Linear Equation

$$ax = b \quad \text{a and b are constant}$$

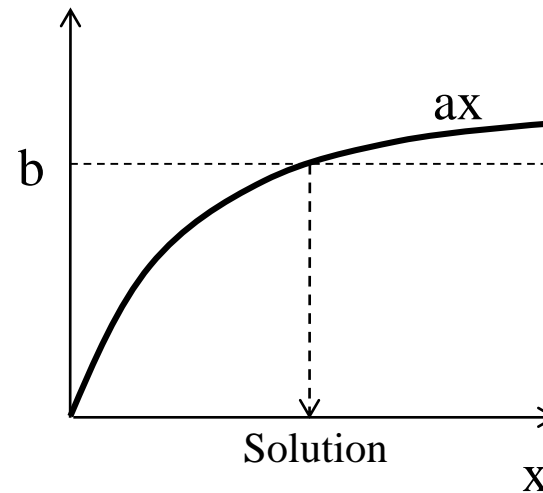


- Single calculation solves the equation.

Calculation Load → Small

## Nonlinear Equation

$$ax = b \quad \text{a and b are changed by x}$$



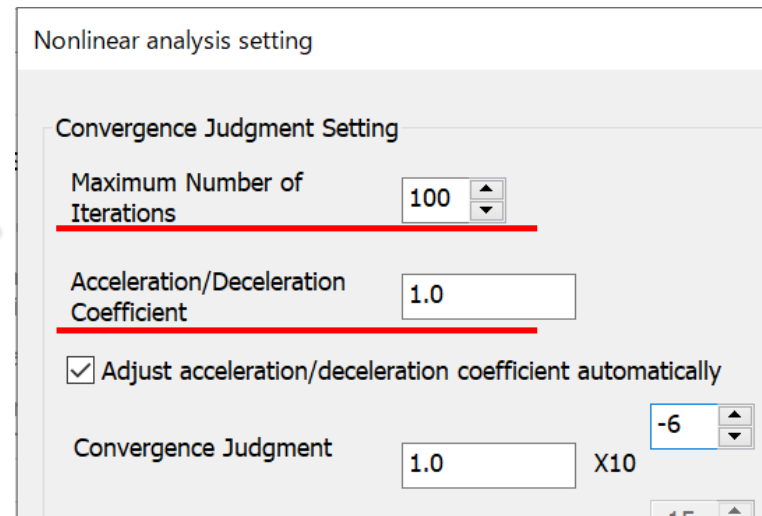
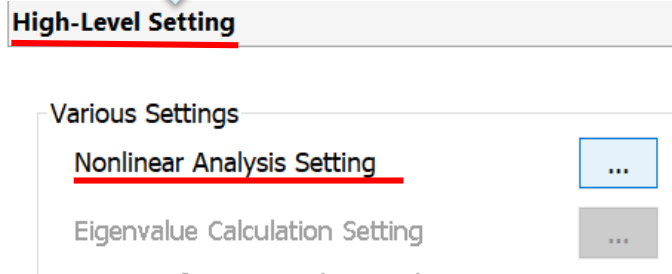
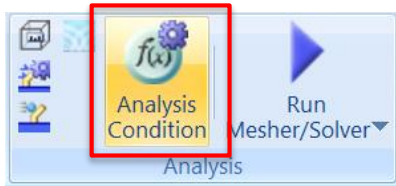
- Iterative calculations are required.
- Newton-Raphson method solves the equation.
- Solution may not be acquired in some cases.

Calculation Load → Large

# Nonlinear Magnetic Analysis

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.



Frequency Range for Calculation

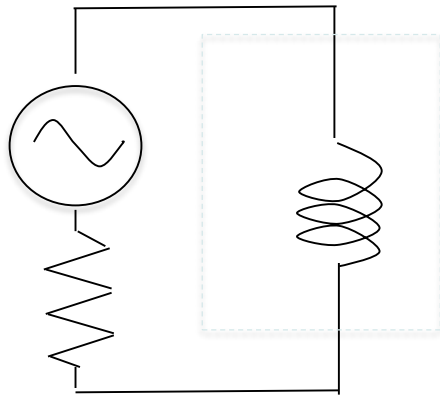
Inductance in the Harmonic Analysis

Skin Effect

Conductor in the Harmonic Analysis

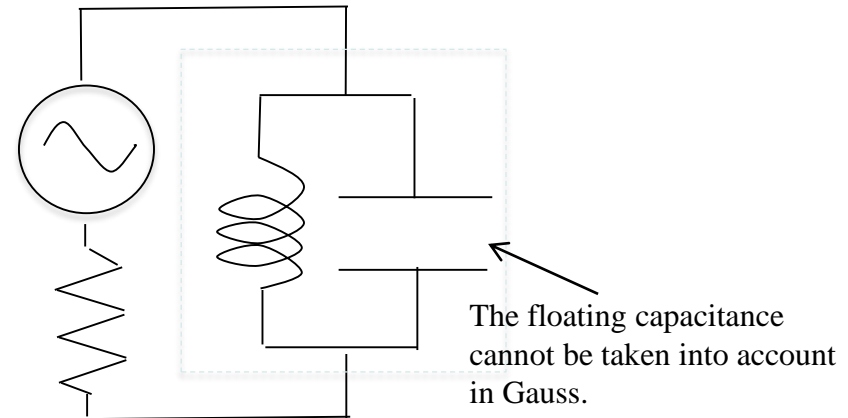
## Coil

Low Frequency



Can be solved by magnetic analysis (Gauss).

High Frequency



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

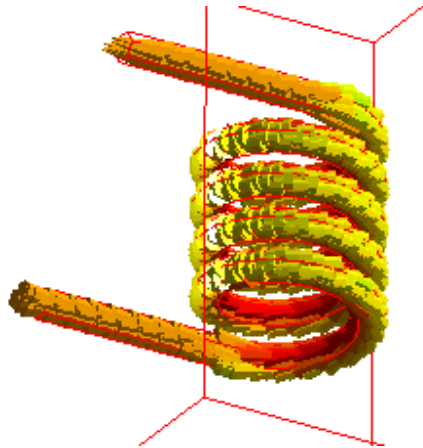
The minimum model size, which can be analyzed by the magnetic analysis (Gauss), is approx. 1/10 of a wavelength.



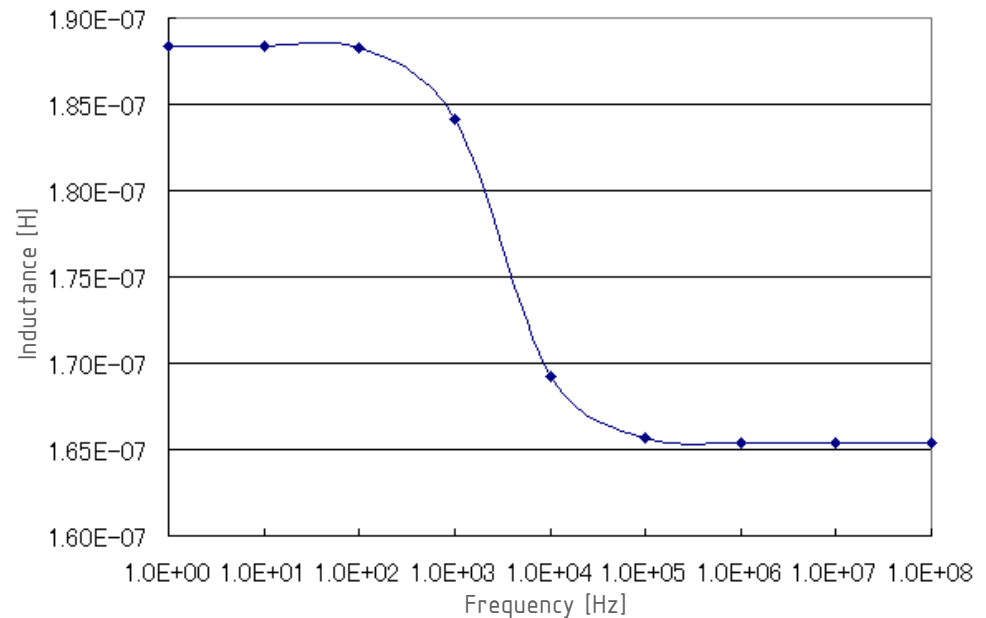
# Inductance and Frequency

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

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.

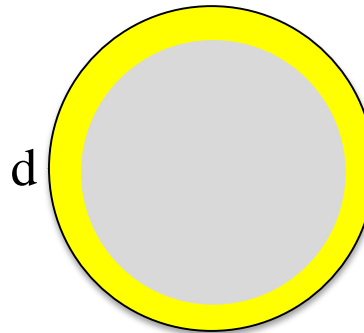
$$d = \sqrt{\frac{2}{\sigma\omega\mu}}$$

where:

$\sigma$  = Conductivity

$\omega$  = Angular frequency of current= $2\pi f$

$\mu$  = Permeability



Section of Conductor

Yellow area is where the magnetic field penetrates

Ref: Skin depth of copper

1Hz      65mm

1kHz     2.1mm

1MHz     65 $\mu$ m

1GHz     2.1 $\mu$ m

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

The skin effect is a phenomenon generated by the eddy current.

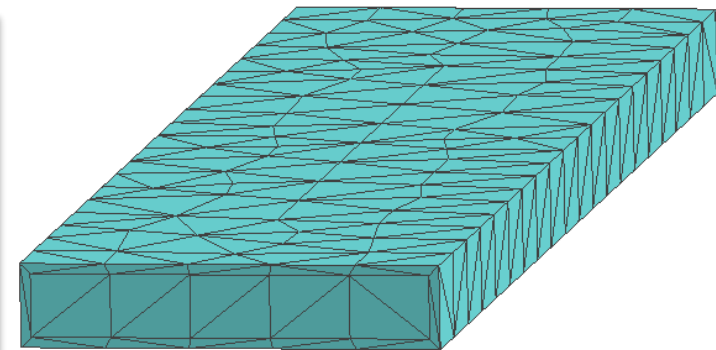
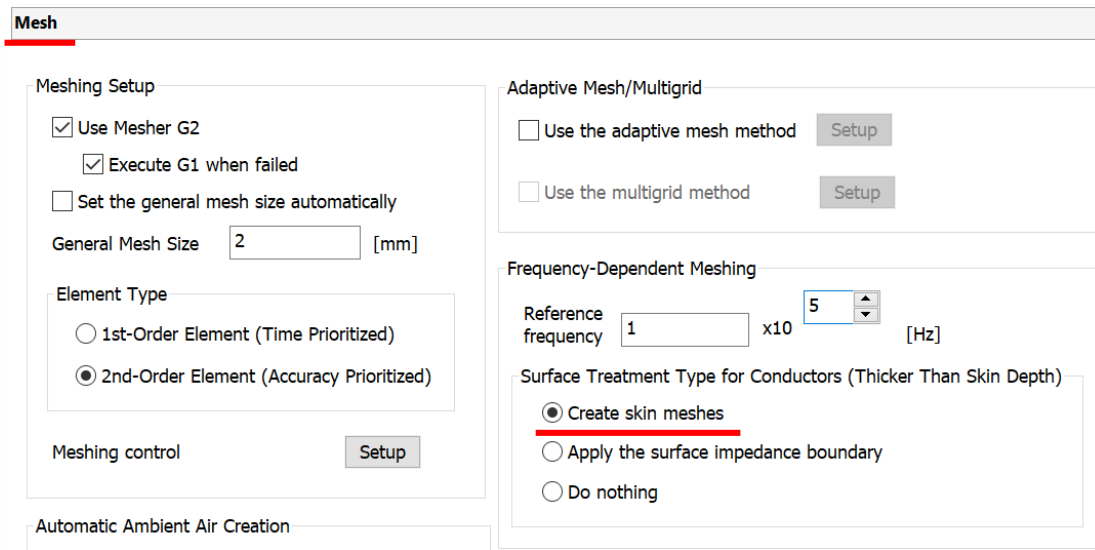
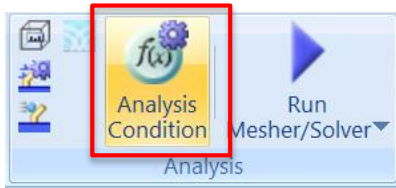
Because of the skin effect;

- 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

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	<u>Loss [W]</u>	Port current [A]	Impedance [ohm]	Po
		<u>Joule loss [W]</u>	<u>Iron loss [W]</u>	<u>Total loss [W]</u>	
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

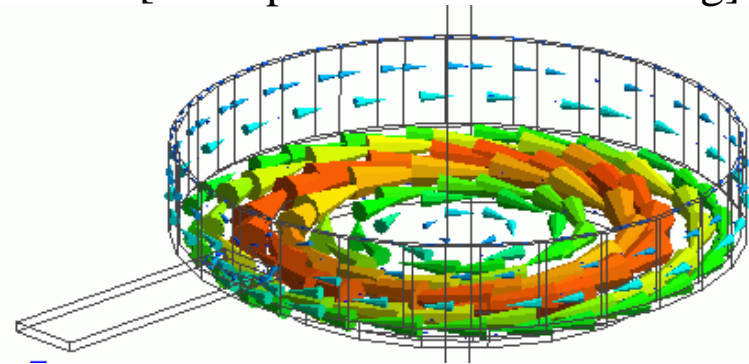
# Magnetic Field-Thermal Coupled Analysis

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.

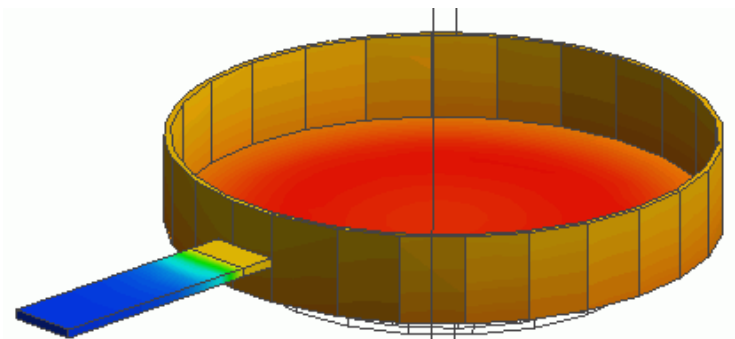
## Solver Selection

Solver	
<b>Mechanical Stress / Piezoelectric</b>	
<input type="checkbox"/>	Stress Analysis
<input type="checkbox"/>	Piezoelectric Analysis
<b>Acoustic / Fluid</b>	
<input type="checkbox"/>	Acoustic Analysis
<input type="checkbox"/>	Simple Fluid Analysis
<input type="checkbox"/>	Fluid Analysis
<b>Thermal</b>	
<input checked="" type="checkbox"/>	Thermal analysis
<input type="checkbox"/>	Electric-Thermal Coupled Analysis
<b>Electromagnetic Field</b>	
<input type="checkbox"/>	Electric Analysis
<input checked="" type="checkbox"/>	Magnetic Analysis
<input type="checkbox"/>	Electromagnetic Analysis

[Example: Inductance Heating]



Current Density Distribution



Temperature Distribution

# Magnetic Field-Thermal Coupled Analysis

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

**Thermal**

Boundary Condition Type

Temperature     Heat Flux     Thermal Resistance

Heat Transfer/Ambient Radiation     Body-to-Body Radiation     Measuring Terminal

Adiabatic (no setting)

0.0 [deg]

## Boundary Conditions:

Temperature

Heat Flux

Thermal Resistance

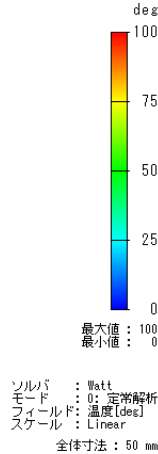
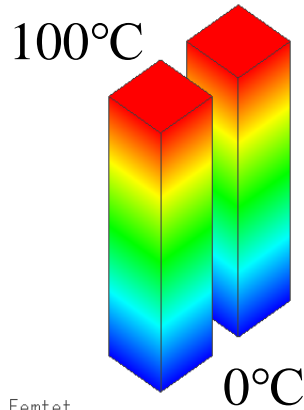
Thermal Conductivity

Ambient Radiation

Body-to-Body Radiation

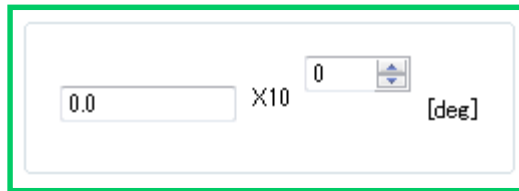
Adiabatic

# Boundary Condition of Thermal Analysis



## Specify the temperature

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



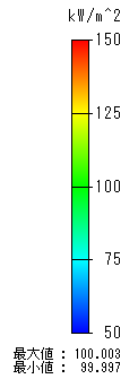
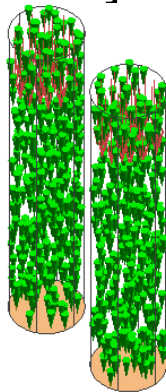
In the electric circuit,  
it would be:



Potential

Powered by Femtet  
<http://www.muratasoftware.com/>

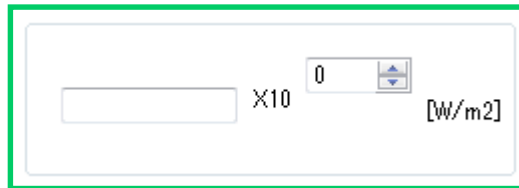
$1e5 [W/m^2]$



## 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.



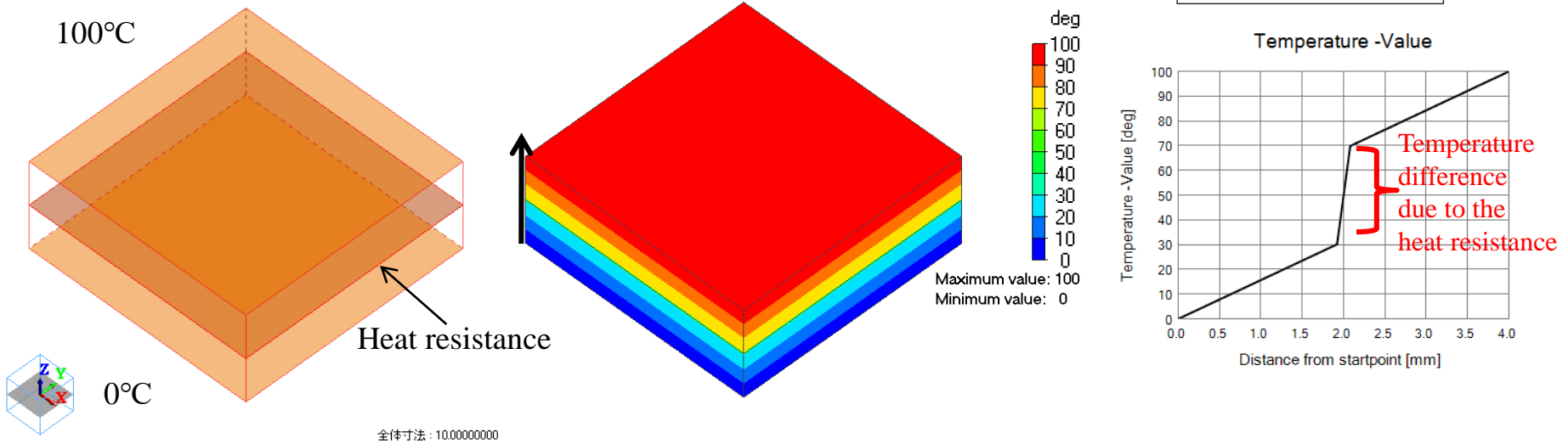
Current Density

Powered by Femtet  
<http://www.muratasoftware.com/>

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



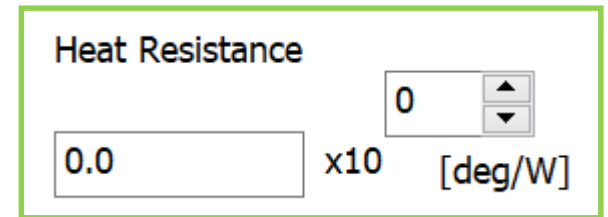
# Boundary Condition of Thermal Analysis



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

**Thermal**

Boundary Condition Type

Temperature
  Heat Flux
  Thermal Resistance
  Measuring Terminal

Heat Transfer/Ambient Radiation
 Body-to-Body Radiation

Adiabatic (no setting)

Room temperature (ambient temperature)

25.0 [deg]

Types of Heat Transfer / Ambient Radiation

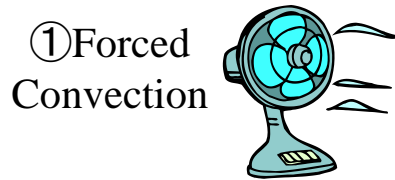
Heat transfer coefficient [W/m2/deg]

Forced convection

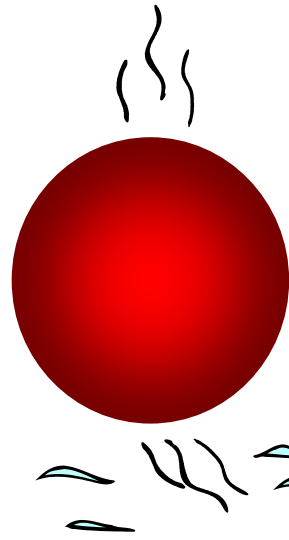
Natural convection (automatic calculation)

Ambient radiation

- ①
- ②
- ③



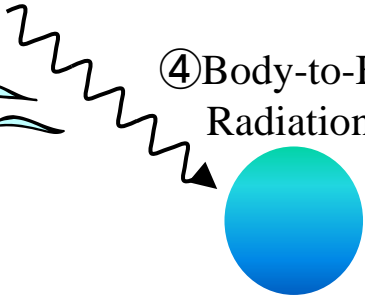
② Natural Convection



③ Ambient Radiation



④ Body-to-Body Radiation



**Thermal**

Boundary Condition Type

Temperature
  Heat Flux
  Thermal Resistance
  Measuring Terminal

Heat Transfer/Ambient Radiation
  Body-to-Body Radiation

Adiabatic (no setting)

④

# Boundary Condition of Thermal Analysis

**Thermal**

Boundary Condition Type

Temperature
  Heat Flux
  Thermal Resistance
  Time Dependency

Heat Transfer/Ambient Radiation
  Body-to-Body Radiation
  Measuring Terminal
  Use distribution data (Room temperature)
  Use distribution data (Heat transfer)
  Uniform Temperature

Adiabatic (no setting)

Room temperature (ambient temperature)

[deg]  **$\theta_a$**

Types of Heat Transfer / Ambient Radiation

Heat transfer coefficient  X10 [W/m2/deg]

Forced convection

Air flow speed  X10 [m/s]
 Characteristic length  X10 [m]

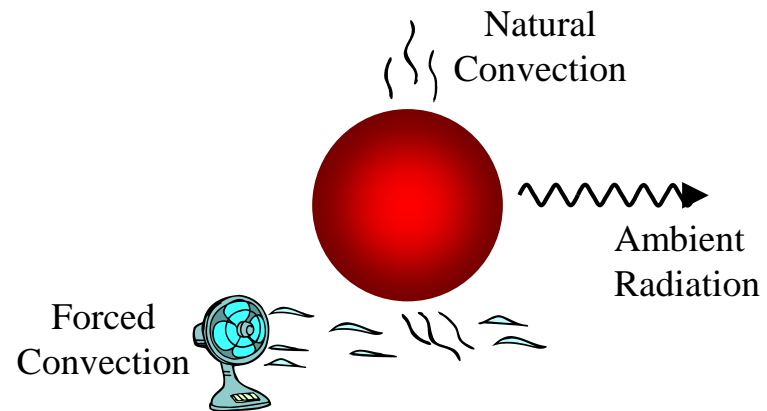
Natural convection (automatic calculation)
  Natural convection (direct entry)

Ambient radiation  X10 [W/m2/deg(5/4)]

Radiation rate  **rad**

## 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.



# Boundary Condition of Thermal Analysis

**Thermal**

Boundary Condition Type

Temperature   
  Heat Flux   
  Thermal Resistance  
 Heat Transfer/Ambient Radiation   
  Body-to-Body Radiation   
  Measuring Terminal  
 Adiabatic (no setting)

Temperature Dependency

No   
  Yes

Radiation Rate

0.999

Group number: 1

Reverse the radiation direction of the surface.

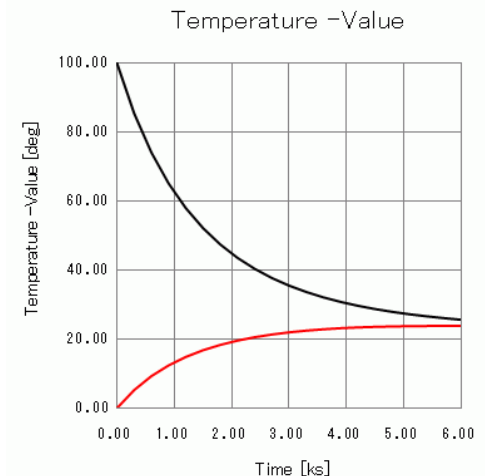
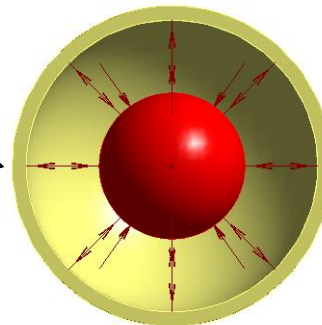
## Body-to-Body Radiation

Set the emissivity between the surfaces.

(Example 9)

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

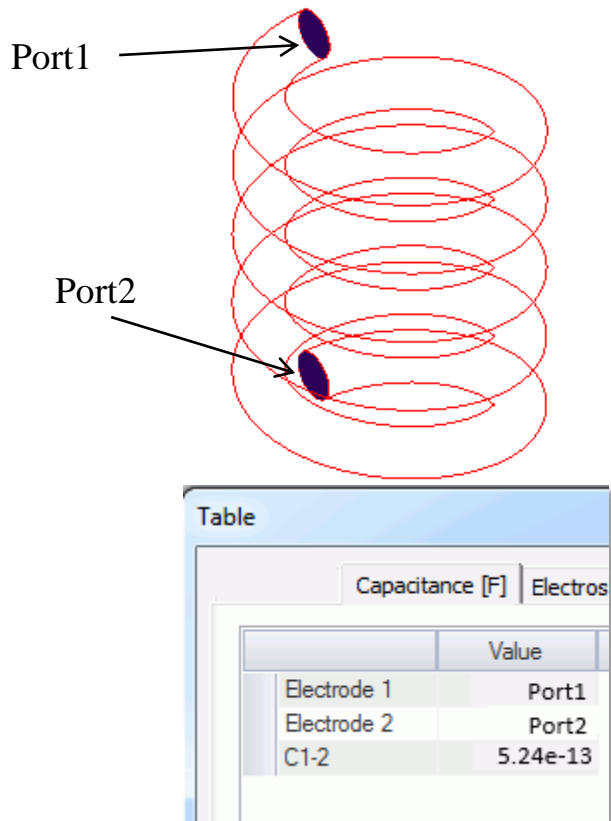
The boundary condition must be set seamlessly



- \*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.



## 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.

[Example 17] Inductor's Floating Capacitance

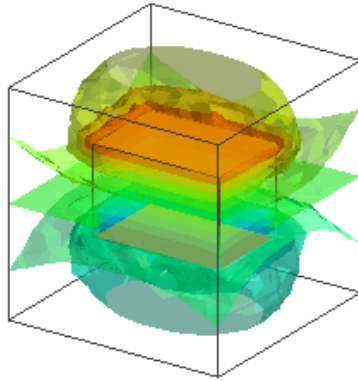
# Appendix

Examples

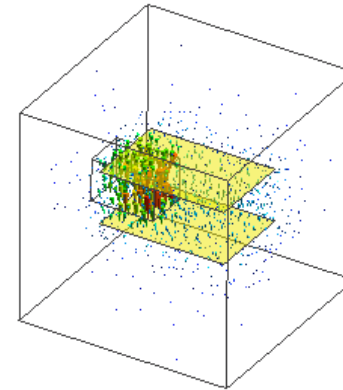
Analysis Condition

# Examples

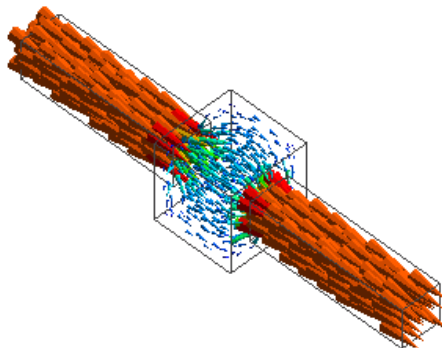
Capacitance of the Capacitor



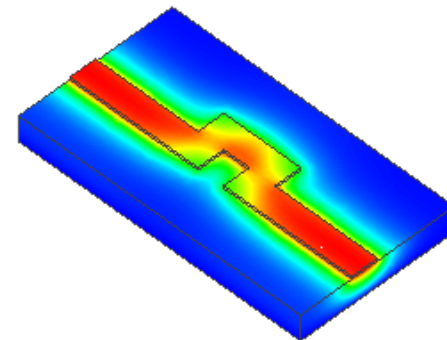
Electrostatic Force on the Dielectric Material



Resistance of the Conductor

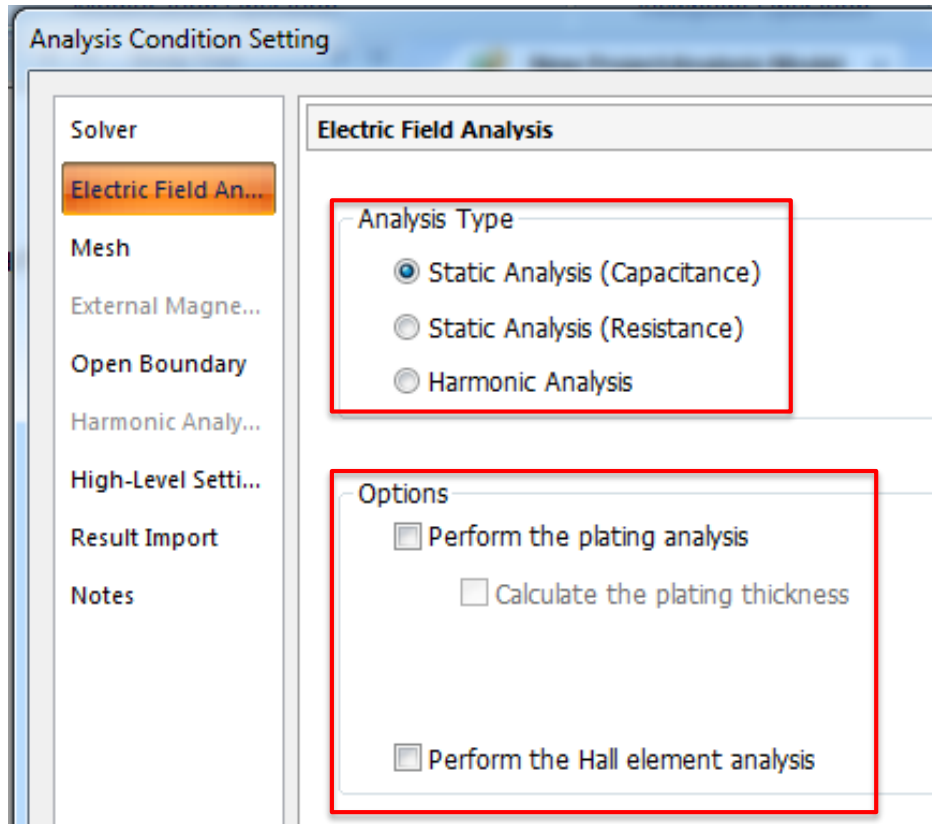


Heat of the Signal Line  
(Electric Field-Thermal Analysis)





# 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

$0 < \text{Frequency}$  (alternating current)

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

where  $\varepsilon$ : permittivity

$\varphi$ : potential

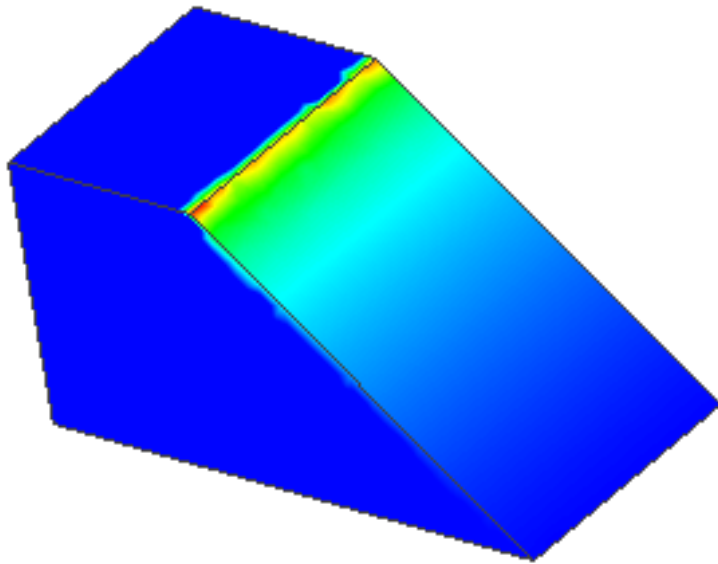
$\rho$ : charge density

$\sigma$ : conductivity

is solved.

# Plating Analysis

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



Plating Bath

Electric

Boundary Condition Type

Electric wall     Surface impedance     Multilayer Electrode

Open boundary     Port     Electric Resistance

Magnetic wall     Integral path

Plating wall     Lumped constant

Electrode Setting

Anode    Extracted Metal Setting

Overvoltage Type

Linear    ...

Nonlinear    ...

Tafel's Law    ...

Plating condition

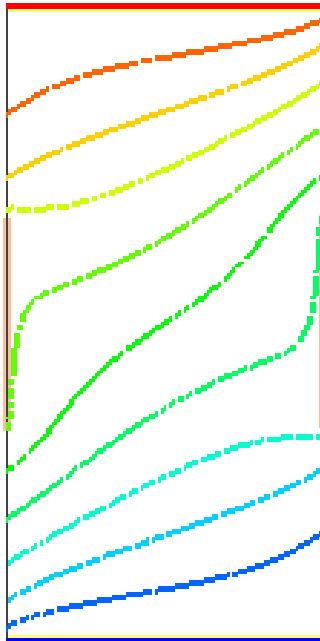
Current     x10<sup>0</sup> [A]

Voltage     x10<sup>0</sup> [V]

Analysis Condition Setting

# Hall Element Analysis

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



2D Hall Element

**Electric Conductivity**

Conductivity Type

- Insulator
- Conductor
- Semiconductor
- Multilayer Electrode
- Perfect Conductor

Anisotropy

- Isotropic
- Anisotropic

Temperature

- No
- Yes

...

Semiconductor

Hall Coefficient  X10  [m<sup>3</sup>/C]

Hall Mobility  X10  [m<sup>2</sup>/V/sec]

Material Property Setting

# Basic Equations in Harmonic Analysis

## Maxwell Equations

$$\nabla \times \mathbf{H} = \mathbf{J} + \delta \mathbf{D} / \delta t \quad (1)$$

$$\nabla \times \mathbf{E} = - \delta \mathbf{B} / \delta t \quad (2)$$

$$\nabla \cdot \mathbf{D} = \rho \quad (3)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (4)$$

where

**H:** Magnetic field strength [A/m]

**J:** Current density [A/m<sup>2</sup>]

**D:** Current flux density [C/m<sup>2</sup>]

**E:** Electric field strength [V/m]

**B:** Magnetic flux density [T]

**ρ:** Charge density [C/m<sup>3</sup>]

**J<sub>e</sub>:** Induced current density [A/m<sup>2</sup>]

J<sub>e</sub> is an unknown current generated by the Faraday's law.

In the equation (1),

set  $\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_e$ ,

$$\begin{aligned} \nabla \times \mathbf{H} &= (\mathbf{J}_0 + \mathbf{J}_e) + \delta \mathbf{D} / \delta t \\ &= (\mathbf{J}_0 + \sigma \mathbf{E}) + j\omega \epsilon \mathbf{E} \end{aligned}$$

by approximating  $j\omega \epsilon \mathbf{E} = 0$ ,

$$\nabla \times \mathbf{H} = \mathbf{J}_0 + \sigma \mathbf{E}$$

$$\mathbf{H} = (1/\mu)$$

$$\nabla \times (1/\mu) \mathbf{B} = \mathbf{J}_0 + \sigma \mathbf{E} \quad (5) \text{ is given.}$$

From the equation (4), the vector potential **A** is defined, which will give

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (6)$$

The scalar potential  $\phi$  is defined by replacing the equation (2) in (6).

$$\nabla \times \mathbf{E} = - \delta / \delta t (\nabla \times \mathbf{A})$$

$$\nabla \times (\mathbf{E} + \delta \mathbf{A} / \delta t) = 0$$

$$\mathbf{E} = - \nabla \phi - \delta \mathbf{A} / \delta t \quad (7)$$

By replacing the equations (6) and (7) in (5),

$$\nabla \times (1/\mu) \nabla \times \mathbf{A} = \mathbf{J}_0 - \sigma (\nabla \phi + \delta \mathbf{A} / \delta t) \text{ is given.}$$

## Calculation Method of Output Items

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### <Inductance>

Calculated by the interlinkage magnetic flux

$$L = \Phi / I$$

$\Phi$ : 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], the solver of the magnetic analysis, is named after Carl Friedrich Gauss.

