Created in COMSOL Multiphysics 5.5

# Multi-Turn Coil Above an Asymmetric Conductor Plate

## Introduction

This model solves the Testing Electromagnetic Analysis Methods (TEAM) problem 7, "Asymmetrical Conductor with a Hole" — a benchmark problem concerning the calculation of eddy currents and magnetic fields produced when an aluminum conductor is placed asymmetrically above a multi-turn coil carrying a sinusoidally varying current. The simulation results at specified positions in space are compared with measured data from the literature and agreement is shown.

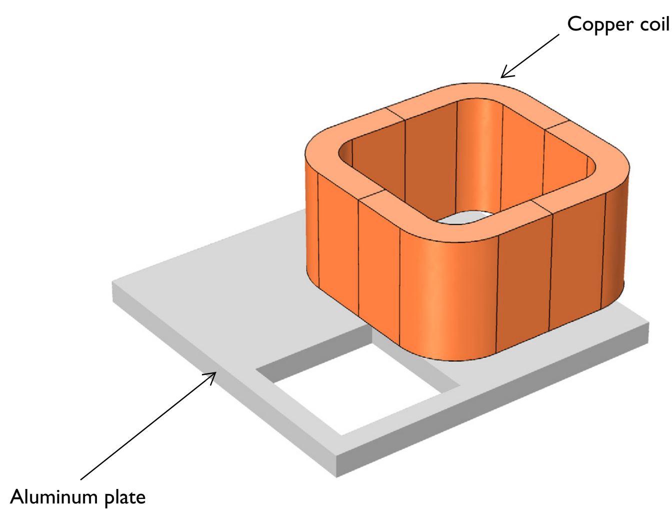



*Figure 1: A multi-turn coil placed asymmetrically over an aluminum plate with a hole.*

## Model Definition

Because the geometry has no symmetries, the problem must be solved for the entire geometry. As shown in Figure 1, the geometry consists of a coil placed asymmetrically above a thick aluminum conductor with an eccentric square hole. The coil has 2742 turns and carries a sinusoidally varying current of 1 A/turn. The problem is to compute the magnetic field and the eddy currents induced in the conductor for coil currents of frequencies 50 Hz and 200 Hz, and to compare the simulation results along specified locations in space with experimental data given in Ref. 1.

## Results and Discussion

Figure 2 visualizes the induced current at 50 Hz using a combined surface and arrow plot. The black arrows show the current density in the conductor while the red arrows indicate the coil current direction is shown. Figure 3 shows the corresponding results at 200 Hz.

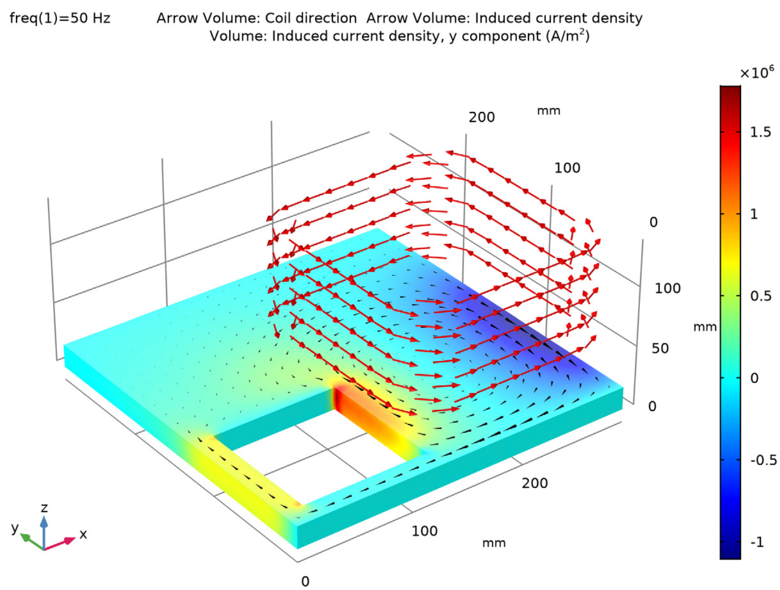



*Figure 2: A 3D surface plot of the y-component of the induced current density, $J_y$ ($A/m^2$) in the conductor combined with the arrow volume plots of the coil current direction and the induced current density in the conductor. This simulation results are at 50 Hz.*

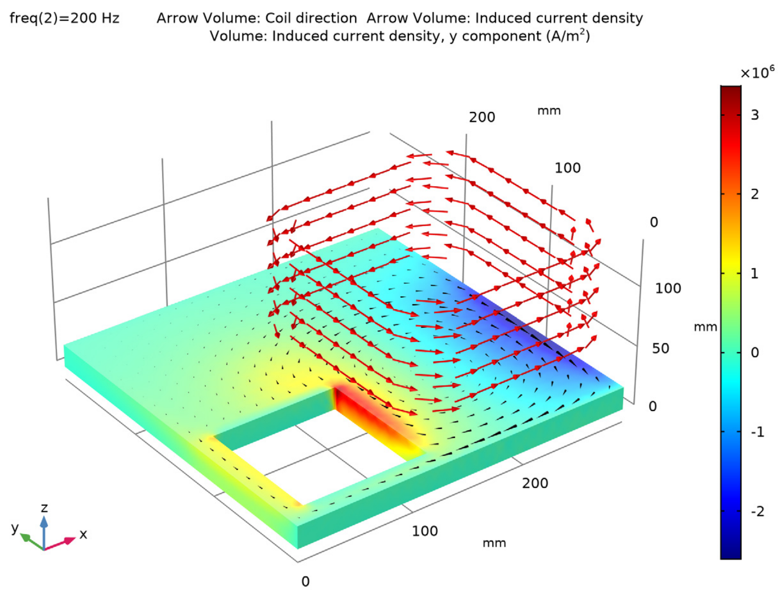



*Figure 3: A 3D surface plot of the y-component of the induced current density in the conductor combined with the arrow volume plots of the coil current direction and the induced current density in the conductor. This simulation results are at 200 Hz.*

Figure 4 and Figure 5 show comparisons between the simulation and the measured data. In Figure 4, the $z$-component values of the magnetic flux density, $B_z$ (SI unit: mT), at 50 Hz and 200 Hz are compared with measured data from Ref. 1. These results are compared for $0 \leq x \leq 288$ mm at $y$ = 72 mm and $z$ = 34 mm. In Figure 5, similarly, the $y$-component values of the induced current density, $J_y$ (SI unit: $A/m^2$) at 50 Hz and 200 Hz are compared with the corresponding measured data. These results are compared for $0 \leq x \leq 288$ mm at $y$ = 72 mm and $z$ = 19 mm. As is evident from the plots, there is close agreement between the simulation results and the measured data.

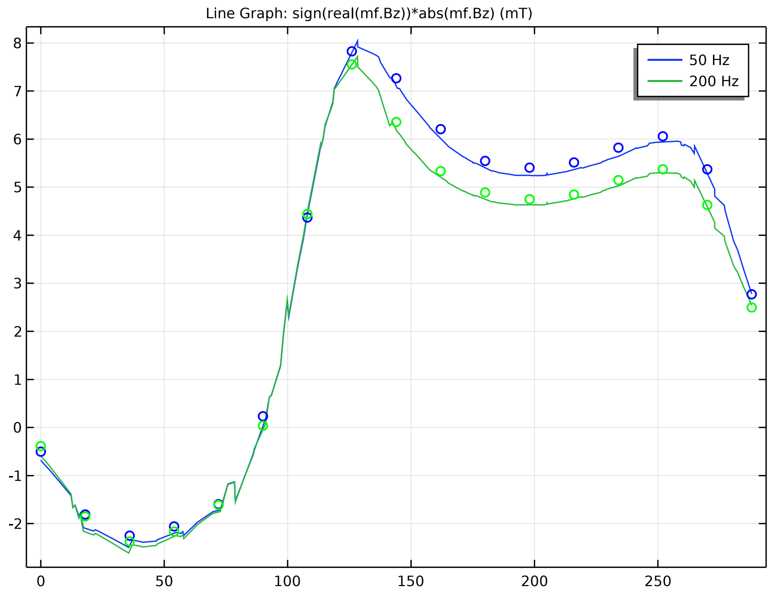



*Figure 4: z-components of the flux densities, $B_z$ (mT) for $0 \leq x \leq 288$ mm at $y = 72$ mm, $z = 34$ mm for 50 Hz and 200 Hz. The solid lines are simulations results while the circles are the corresponding measured data from* Ref. 1.

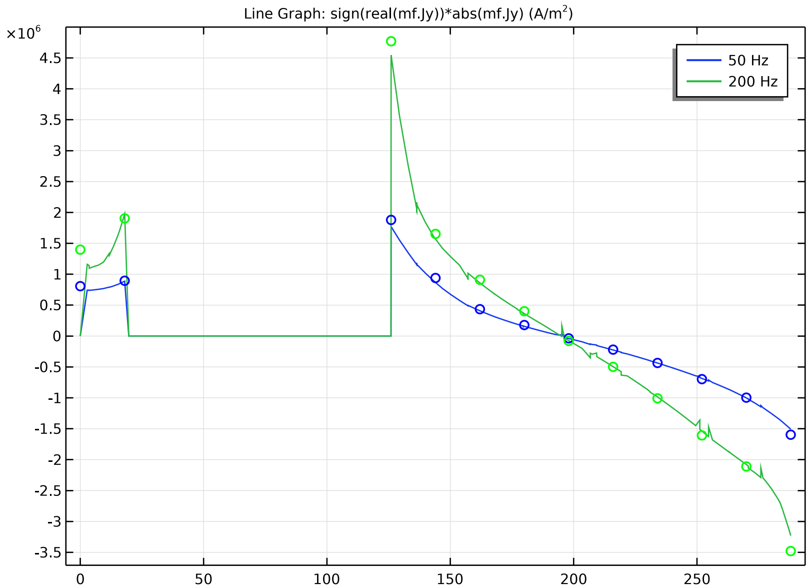



*Figure 5: y-components of the induced current densities, $J_y$ $(A/m^2)$ for $0 \leq x \leq 288$ mm at $y = 72$ mm, $z = 19$ mm for 50 Hz and 200 Hz. The solid lines are simulation results while the circles are the corresponding measured data from* Ref. 1.

## *Notes About the COMSOL Implementation*

The direction of the wires in the coil is computed using a Coil feature combined with a Coil Geometry Analysis study step. The eddy currents and the nonuniform magnetic field are computed using a Frequency Domain study step for the frequencies 50 Hz and 200 Hz.

## *Reference*

1. K. Fujiwara and T. Nakata, "Results for Benchmark Problem 7 (Asymmetrical Conductor with a Hole)," *Int. J. Comput. and Math. in Electr. and Electron. Eng.*, vol. 9, no. 3, pp. 137–154, 1990.

**Application Library path:** `ACDC_Module/Inductive_Devices_and_Coils/multiturn_coil_asymmetric_conductor`

## *Modeling Instructions*

From the **File** menu, choose **New**.

### NEW

In the **New** window, click **Model Wizard**.

### MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **AC/DC>Electromagnetic Fields>Magnetic Fields (mf)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Empty Study**.

6 Click **Done**.

### GEOMETRY 1

Insert the geometry sequence provided in a separate file.

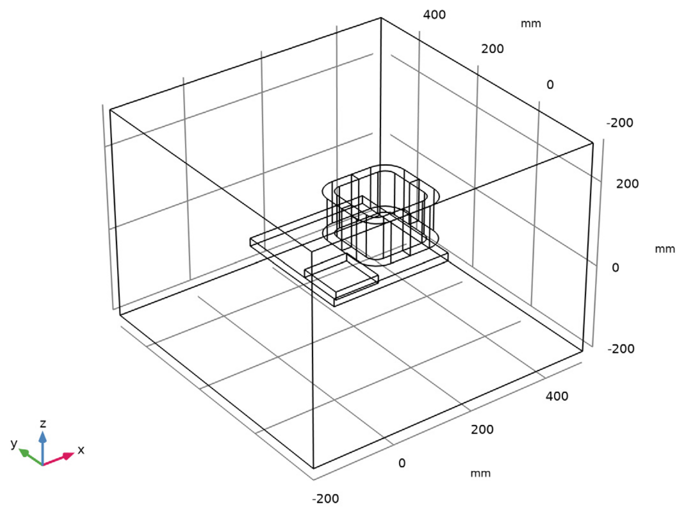
1 In the **Geometry** toolbar, click **Insert Sequence**.

2 Browse to the model's Application Libraries folder and double-click the file `multiturn_coil_asymmetric_conductor_geom_sequence.mph`.

3 In the **Geometry** toolbar, click **Build All**.

The model geometry is now complete. Choose wireframe rendering to get a better view of the interior parts.

**4** Click the **Wireframe Rendering** button in the **Graphics** toolbar.




*Conductor*

Define domain and boundary selections for the coil and the conductor.

**1** In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Difference 1 (dif1)**.

**2** In the **Settings** window for **Difference**, type `Conductor` in the **Label** text field.

**3** Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

*Coil*

**1** In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Extrude 1 (ext1)**.

**2** In the **Settings** window for **Extrude**, type `Coil` in the **Label** text field.

**3** Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

Hide the outer geometry boundaries to visualize the results only in the coil and the conductor domains.

**4** In the **Graphics** toolbar, click the **Click and Hide** button.

**5** In the **Graphics** toolbar, click the **Select Boundaries** button.

**6** Select the exterior boundaries of the block (boundaries 1–5 and 52).

**7** In the **Graphics** toolbar, click the **Click and Hide** button again to deactivate it.

### MAGNETIC FIELDS (MF)

Now set up the physics. **Ampère's Law** automatically applies on all the domains. Add the **Coil** feature to model the coil. This will automatically overwrite the **Ampère's Law** feature.

**1** In the **Model Builder** window, under **Component 1 (comp1)** right-click **Magnetic Fields (mf)** and choose **Group by Space Dimension**.

**2** Click the **Zoom Extents** button in the **Graphics** toolbar.

*Coil 1*

**1** In the **Model Builder** window, under **Component 1 (comp1)>Magnetic Fields (mf)** right-click **Domains** and choose **Coil**.

**2** In the **Settings** window for **Coil**, locate the **Domain Selection** section.

**3** From the **Selection** list, choose **Coil**.

**4** Locate the **Coil** section. From the **Conductor model** list, choose **Homogenized multi-turn**.

**5** From the **Coil type** list, choose **Numeric**.

**6** Locate the **Homogenized Multi-Turn Conductor** section. In the $N$ text field, type `2742`.

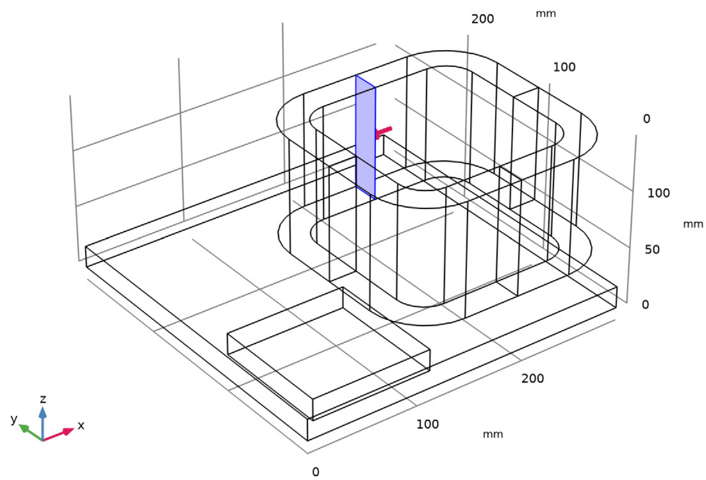
Apply the input on a cross-sectional coil boundary.

**7** In the **Model Builder** window, expand the **Coil 1** node.

*Input 1*

**1** In the **Model Builder** window, expand the **Component 1 (comp1)>Magnetic Fields (mf)>Domains>Coil 1>Geometry Analysis 1** node, then click **Input 1**.

**2** Select Boundary 37 only.




## MATERIALS

Add the material Air in all domains.

## ADD MATERIAL

**1** In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

**2** Go to the **Add Material** window.

**3** In the tree, select **Built-in>Air**.

**4** Click **Add to Component** in the window toolbar.

**5** In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

## MATERIALS

### *Air (mat1)*

The conductivity of air in the Material Library is 0 S/m. Change the conductivity to 1 S/m to improve the stability of the solution. The error caused by this small conductivity is negligible.

**1** In the **Settings** window for **Material**, locate the **Material Contents** section.

2 In the table, enter the following settings:

| Property | Variable | Value | Unit | Property group |
|---|---|---|---|---|
| Electrical conductivity | sigma_iso ; sigmaii = sigma_iso, sigmaij = 0 | `1[S/m]` | S/m | Basic |

Create a new material for the conductor, overriding the material properties of air.

*Aluminum*

1 In the **Model Builder** window, right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Conductor**.

4 Locate the **Material Contents** section. In the table, enter the following settings:

| Property | Variable | Value | Unit | Property group |
|---|---|---|---|---|
| Relative permeability | mur_iso ; murii = mur_iso, murij = 0 | `1` | 1 | Basic |
| Electrical conductivity | sigma_iso ; sigmaii = sigma_iso, sigmaij = 0 | `3.526e7` | S/m | Basic |
| Relative permittivity | epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0 | `1` | 1 | Basic |

5 Right-click **Material 2 (mat2)** and choose **Rename**.

6 In the **Rename Material** dialog box, type `Aluminum` in the **New label** text field.

7 Click **OK**.

### MESH 1

Use a finer mesh in the aluminum plate to better resolve the eddy currents and obtain a more accurate solution.

*Size 1*

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Conductor**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

7 In the associated text field, type 12.

*Size 2*

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Coil**.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

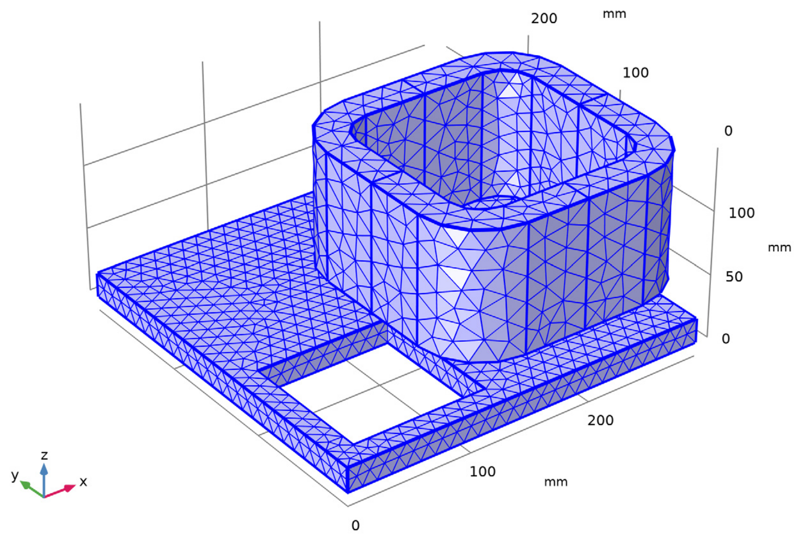
7 In the associated text field, type 20.

*Free Tetrahedral 1*

1 Right-click **Mesh 1** and choose **Free Tetrahedral**.

**2** In the **Settings** window for **Free Tetrahedral**, click **Build Selected**.

The mesh should look like that shown in the figure below.




## STUDY 1

Next, set up the study. Start by adding a **Coil Geometry Analysis** preprocessing study step before the Frequency Domain step.

### *Coil Geometry Analysis*

**1** In the **Study** toolbar, click **Study Steps** and choose **Other>Coil Geometry Analysis**.

This study step computes the direction of the wires in the coils.

Add the main Frequency Domain study step. Solve the problem in the frequency domain for 50 Hz and 200 Hz.

### *Frequency Domain*

**1** In the **Study** toolbar, click **Study Steps** and choose **Frequency Domain>Frequency Domain**.

**2** In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.

**3** In the **Frequencies** text field, type `50 200`.

**4** In the **Model Builder** window, click **Study 1**.

**5** In the **Settings** window for **Study**, locate the **Study Settings** section.

**6** Clear the **Generate default plots** check box.

**7** In the **Study** toolbar, click **Compute**.

### RESULTS

To reproduce the plot shown in Figure 2, create a 3D plot group and add an Arrow Volume plot of the coil current direction in the coil domain, computed by the Coil Geometry Analysis step. Add an Arrow Volume plot of the induced current on the conductor surface and a Volume plot of the $y$ component of the induced current density to the same plot group.

#### *Coil Direction and Induced Current Density, 50 Hz*

1. In the **Model Builder** window, expand the **Results** node.
2. Right-click **Results** and choose **3D Plot Group**.
3. In the **Settings** window for **3D Plot Group**, type `Coil Direction and Induced Current Density, 50 Hz` in the **Label** text field.
4. Locate the **Data** section. From the **Parameter value (freq (Hz))** list, choose **50**.

#### *Arrow Volume 1*

Right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Arrow Volume**.

#### *Selection 1*

1. Right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Selection**.
2. In the **Settings** window for **Selection**, locate the **Selection** section.
3. From the **Selection** list, choose **Coil**.

#### *Arrow Volume 1*

1. In the **Model Builder** window, click **Arrow Volume 1**.
2. In the **Settings** window for **Arrow Volume**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1>Magnetic Fields>Coil parameters>mf.coil1.eCoilx,...,mf.coil1.eCoilz - Coil direction**.
3. Locate the **Arrow Positioning** section. Find the **X grid points** subsection. In the **Points** text field, type `10`.
4. Find the **Y grid points** subsection. In the **Points** text field, type `10`.
5. Find the **Z grid points** subsection. In the **Points** text field, type `5`.
6. Locate the **Coloring and Style** section. Select the **Scale factor** check box.
7. In the associated text field, type `20`.

*Arrow Volume 2*

In the **Model Builder** window, right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Arrow Volume**.

*Selection 1*

1 Right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Conductor**.

*Arrow Volume 2*

1 In the **Model Builder** window, click **Arrow Volume 2**.

2 In the **Settings** window for **Arrow Volume**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1>Magnetic Fields> Currents and charge>mf.Jix,...,mf.Jiz - Induced current density**.

3 Locate the **Arrow Positioning** section. Find the **X grid points** subsection. In the **Points** text field, type 20.

4 Find the **Y grid points** subsection. In the **Points** text field, type 20.

5 Find the **Z grid points** subsection. From the **Entry method** list, choose **Coordinates**.

6 In the **Coordinates** text field, type 19.

7 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

8 From the **Arrow type** list, choose **Cone**.

*Volume 1*

In the **Model Builder** window, right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Volume**.

*Selection 1*

1 Right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Conductor**.

*Volume 1*

1 In the **Model Builder** window, click **Volume 1**.

2 In the **Settings** window for **Volume**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1>Magnetic Fields> Currents and charge>Induced current density - A/m²>mf.Jiy - Induced current density, y component**.

*Coil Direction and Induced Current Density, 50 Hz*

1 In the **Model Builder** window, click **Coil Direction and Induced Current Density, 50 Hz**.

2 In the **Settings** window for **3D Plot Group**, locate the **Plot Settings** section.

3 Clear the **Plot dataset edges** check box.

4 In the **Coil Direction and Induced Current Density, 50 Hz** toolbar, click **Plot**.

Duplicate the plot group just created and modify the copy to generate the plot shown in Figure 3. This figure is similar to the Figure 2 except the frequency is 200 Hz.

*Coil Direction and Induced Current Density, 200 Hz*

1 In the **Model Builder** window, right-click **Coil Direction and Induced Current Density, 50 Hz** and choose **Duplicate**.

2 In the **Settings** window for **3D Plot Group**, type `Coil Direction and Induced Current Density, 200 Hz` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (freq (Hz))** list, choose **200**.

4 In the **Coil Direction and Induced Current Density, 200 Hz** toolbar, click **Plot**.

To generate the plots shown in Figure 4 and Figure 5, begin by creating two cut-line datasets.

*Cut Line 3D 1*

1 In the **Results** toolbar, click **Cut Line 3D**.

2 In the **Settings** window for **Cut Line 3D**, locate the **Line Data** section.

3 In row **Point 1**, set **Y** to `72` and **z** to `34`.

4 In row **Point 2**, set **X** to `288`, **y** to `72`, and **z** to `34`.

*Cut Line 3D 2*

1 Right-click **Cut Line 3D 1** and choose **Duplicate**.

Specify a value of `z` slightly below the surface of the conductor.

2 In the **Settings** window for **Cut Line 3D**, locate the **Line Data** section.

3 In row **Point 1**, set **Z** to `18.99`.

4 In row **Point 2**, set **Z** to `18.99`.

*Tables*

Import the experimental data of $B_z$ and $J_y$ in two tables.

*Table 1*

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, locate the **Data** section.

3 Click **Import**.

4 Browse to the model's Application Libraries folder and double-click the file `multiturn_coil_asymmetric_conductor_table1.txt`.

5 Locate the **Column Headers** section. In the table, enter the following settings:

| Column | Header |
|---|---|
| 1 | `x [mm]` |
| 2 | `Bz(x,72,34) at 50Hz` |
| 3 | `Bz(x,72,34) at 200Hz` |

*Table 2*

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, locate the **Data** section.

3 Click **Import**.

4 Browse to the model's Application Libraries folder and double-click the file `multiturn_coil_asymmetric_conductor_table2.txt`.

5 Locate the **Column Headers** section. In the table, enter the following settings:

| Column | Header |
|---|---|
| 1 | `x [mm]` |
| 2 | `Jy(x,72,19) at 50Hz` |
| 3 | `Jy(x,72,19) at 200Hz` |

Plot the $z$-component of the magnetic flux density, $B_z$, along the lines defined by the cut-line datasets just created.

*1D Plot Group 3*

In the **Results** toolbar, click **1D Plot Group**.

*Line Graph 1*

1 Right-click **1D Plot Group 3** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Cut Line 3D 1**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `sign(real(mf.Bz))*abs(mf.Bz)`.

5 From the **Unit** list, choose **mT**.

6 Click to expand the **Legends** section. Select the **Show legends** check box.

7 From the **Legends** list, choose **Manual**.

8 In the table, enter the following settings:

| Legends |
|---|
| 50 Hz |
| 200 Hz |

*Bz(x,72,34)*

Add a plot for the experimental value of $B_z$ at 50 Hz to the same plot group using a table graph.

1 In the **Model Builder** window, under **Results** click **1D Plot Group 3**.

2 In the **Settings** window for **1D Plot Group**, type `Bz(x,72,34)` in the **Label** text field.

*Table Graph 1*

1 Right-click **Bz(x,72,34)** and choose **Table Graph**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 From the **x-axis data** list, choose **x [mm]**.

4 From the **Plot columns** list, choose **Manual**.

5 In the **Columns** list, select **Bz(x,72,34) at 50Hz**.

6 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

7 From the **Color** list, choose **Blue**.

8 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

9 From the **Positioning** list, choose **In data points**.

Duplicate the table graph previously created and modify to plot the experimental value of $B_z$ at 200 Hz.

*Table Graph 2*

1 Right-click **Table Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 In the **Columns** list, select **Bz(x,72,34) at 200Hz**.

4 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

5 In the **Bz(x,72,34)** toolbar, click **Plot**.

Compare the resulting plot with that in Figure 4.

Plot the $y$-component of the current density on the surface of the conductor, $J_y$, along the line specified earlier. Use an approach similar to the one used to generate Figure 4.

*1D Plot Group 4*

In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

*Line Graph 1*

1 Right-click **1D Plot Group 4** and choose **Line Graph**.
2 In the **Settings** window for **Line Graph**, locate the **Data** section.
3 From the **Dataset** list, choose **Cut Line 3D 2**.
4 Locate the **y-Axis Data** section. In the **Expression** text field, type `sign(real(mf.Jy))*abs(mf.Jy)`.
5 Locate the **Legends** section. Select the **Show legends** check box.
6 From the **Legends** list, choose **Manual**.
7 In the table, enter the following settings:

| **Legends** |
| --- |
| 50 Hz |
| 200 Hz |

*Jy(x,72,19)*

1 In the **Model Builder** window, under **Results** click **1D Plot Group 4**.
2 In the **Settings** window for **1D Plot Group**, type `Jy(x,72,19)` in the **Label** text field.

*Table Graph 1*

1 Right-click **Jy(x,72,19)** and choose **Table Graph**.
2 In the **Settings** window for **Table Graph**, locate the **Data** section.
3 From the **Table** list, choose **Table 2**.
4 From the **x-axis data** list, choose **x [mm]**.
5 From the **Plot columns** list, choose **Manual**.
6 In the **Columns** list, select **Jy(x,72,19) at 50Hz**.
7 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.
8 From the **Color** list, choose **Blue**.
9 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.
10 From the **Positioning** list, choose **In data points**.

*Table Graph 2*

**1** Right-click **Table Graph 1** and choose **Duplicate**.

**2** In the **Settings** window for **Table Graph**, locate the **Data** section.

**3** In the **Columns** list, select **Jy(x,72,19) at 200Hz**.

**4** Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

**5** In the **Jy(x,72,19)** toolbar, click **Plot**. This plot reproduces Figure 5.