Iron Sphere in a Magnetic Field — 20 kHz

Introduction

This tutorial is part of a series on modeling an iron sphere in a background magnetic field within the Introduction to Electromagnetics tutorial group. This tutorial focuses the case of an magnetically permeable iron sphere in a spatially uniform magnetic field where the magnetic field sinusoidally varies in time at a frequency of 20 kHz. At this frequency, the skin depth of the iron used in the model is ~ 17 μm, which means the signal penetrates part way into the iron sphere.

Model Definition

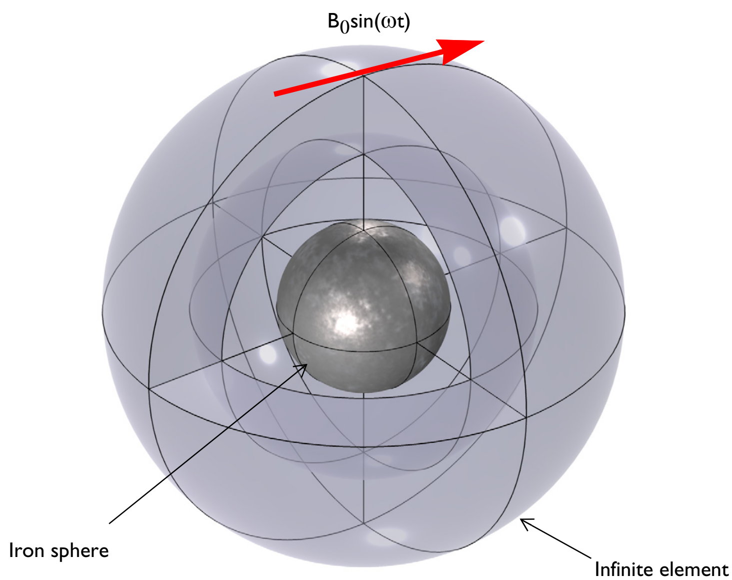


Figure 1: A magnetically permeable iron sphere in a spatially uniform background magnetic field that sinusoidally varies in time with angular frequency, ω. The sphere at the center is surrounded by air and enclosed in a region of Infinite Elements.

Each model in this tutorial series uses the same basic structure illustrated in Figure 1. It consists of a 0.25 mm diameter iron sphere, with a relative permeability of, $\mu_r = 4000$, placed in a spatially uniform background magnetic field of strength $B_0 = 1$ mT. In this case, that magnetic field oscillates at a frequency of 20 kHz.

The intermediary nature of the skin depth being a significant part of the sphere radius means there is a significant amount of detail in the magnetic field and the induced currents near the surface of the sphere. This is modeled by creating a tailored mesh with elements that follow the symmetry of the model and are sufficiently smaller than the scales of interest. The mesh shown in Figure 2 was used to resolve this fine detail near the surface of the sphere.

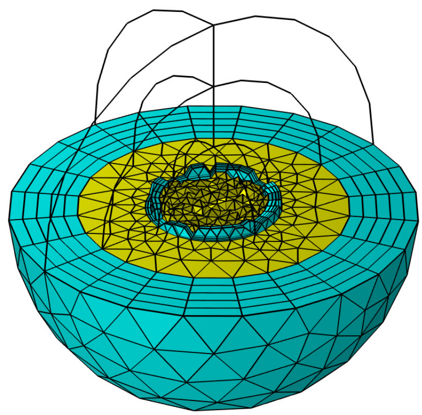


Figure 2: Mesh plot showing the regions of tetrahedral mesh, yellow, that make up the majority of the volume of the model and the boundary layer mesh regions, blue, that resolve the detail near the surface.

Results and Discussion

The magnetic flux density and the induced currents are shown in Figure 3. The magnetic field and current density are strongest near the surface of the sphere.

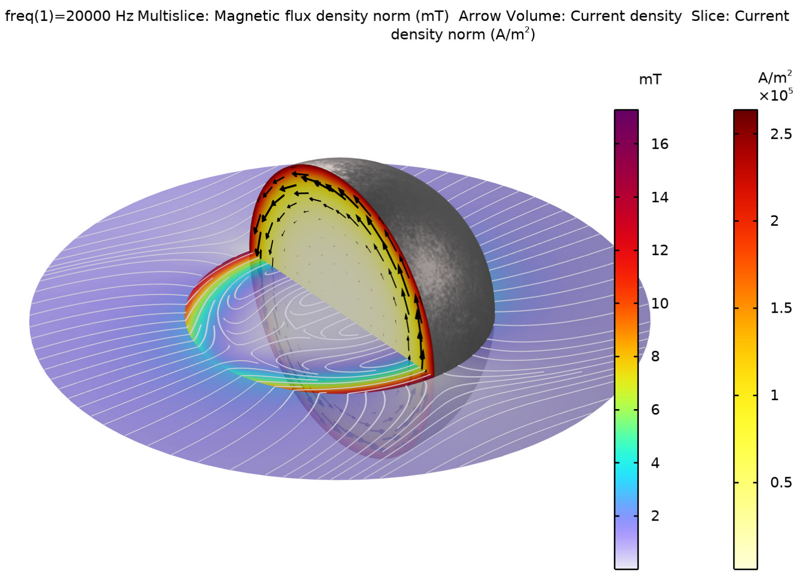


Figure 3: Cross-section of the iron sphere showing the induced current in the sphere and the magnetic flux.

Application Library path: `ACDC_Module/Introductory_Electromagnetics/iron_sphere_bfield_03_20khz`

Modeling Instructions

This tutorial will demonstrate the physics of an iron sphere in a spatially uniform magnetic field sinusoidally varying at 20 kHz. The instructions on the following pages will help you to build, configure, solve, and analyze the model. If anything seems out of order, please retrace your steps. The finalized model — available in the model's Application Libraries folder — can help you out. You can compare it directly to your current model by means of the **Compare** option in the **Developer** toolbar.

ROOT

The geometry, materials, and selections have been prepared in the *Introduction* tutorial (chapter 1). They have been saved in the file `iron_sphere_bfield_00_introduction.mph`. You can start by opening this file and saving it under a new name.

Hint: if you are new to COMSOL Multiphysics, it is worthwhile to check out the Introduction tutorial first.

1 From the **File** menu, choose **Open**.
2 Browse to the model's Application Libraries folder and double-click the file `iron_sphere_bfield_00_introduction.mph`.
3 From the **File** menu, choose **Save As**.
4 Browse to a suitable folder and type the filename `iron_sphere_bfield_03_20khz.mph`.

MAGNETIC FIELDS (MF)

Free Space 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Magnetic Fields (mf)** node, then click **Free Space 1**.
2 In the **Settings** window for **Free Space**, locate the **Domain Selection** section.
3 In the list, select **9 (overridden)**.

To begin, enter the parameters specific for this model. This model uses a stabilization conductivity of 50 S/m.

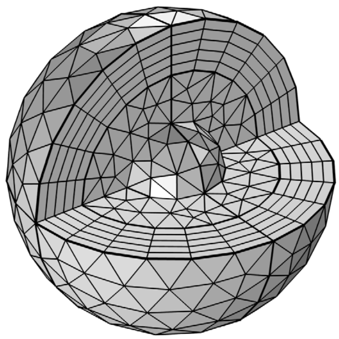
4 Locate the **Stabilization** section. Find the **Typical frequency** subsection. From the f_{typ} list, choose **User defined**.
5 From the σ_{stab} list, choose **User defined**. In the associated text field, type `50`.

MESH 1

To begin, we can demonstrate the results produced with the default mesh.

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

2 Click the **Zoom to Selection** button in the **Graphics** toolbar.



Note: In the introduction modeling steps, the nearest upper quarter sphere was hidden to improve visibility in the result plots. This allows the visibility of the mesh layers of the Infinite Element Domain and the Analysis Domain.

STUDY 1

Step 1: Frequency Domain

1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Frequency Domain**.

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

3 In the **Frequencies** text field, type `20[kHz]`.

4 In the **Home** toolbar, click **Compute**.

RESULTS

Selection

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Study 1/Solution 1 (sol1)** and choose **Selection**.

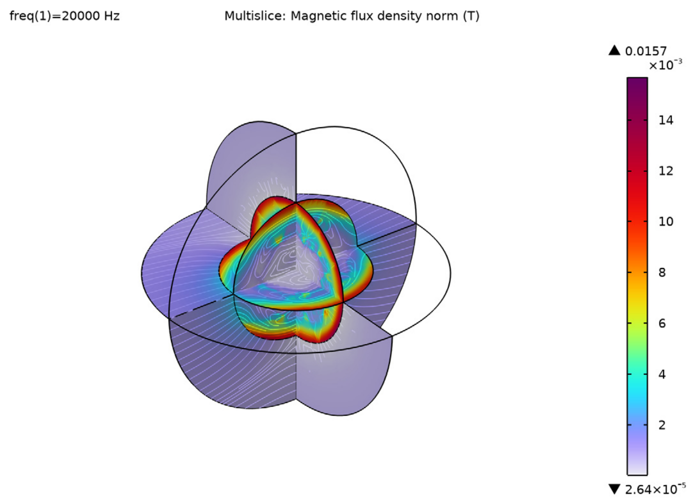
3 In the **Settings** window for **Selection**, locate the **Geometric Entity Selection** section.

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

5 From the **Selection** list, choose **Analysis domain**.

Magnetic Flux Density Norm (mf)

1. Click the **Zoom Extents** button in the **Graphics** toolbar.
2. In the **Model Builder** window, under **Results** click **Magnetic Flux Density Norm (mf)**.



The magnetic flux density within the sphere has not been solved well due to the large magnetic gradients not being resolved by large mesh elements. The next part will go through construction of a more appropriate mesh for the simulation parameters set in this tutorial. To assess the appropriate size of mesh elements for this study, we can refer to the skin depth of the iron sphere under this 20 kHz background magnetic field. This value is uniform across the domain and can be obtained by evaluating the maximum value in the volume.

Volume Maximum 1

1. In the **Results** toolbar, click **More Derived Values** and choose **Maximum> Volume Maximum**.
2. In the **Settings** window for **Volume Maximum**, locate the **Selection** section.
3. From the **Selection** list, choose **Iron Sphere**.
4. Click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields>Material properties>mf.deltaS - Skin depth - m**.

5 Click **Evaluate**.

The skin depth of the iron sphere in this case should be 0.0168 mm, so this is the scale of interest for this model. Ideally, the mesh element thickness near the surface of the iron sphere should be smaller than the scale of interest to adequately resolve the magnetic gradients. Also, due to the spherical symmetry of the model, we can use a boundary layer mesh with a thickness smaller than the scale of interest.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Size 1

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

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

3 From the **Selection** list, choose **Iron Sphere**.

4 Locate the **Element Size** section. From the **Predefined** list, choose **Extra fine**.

Boundary Layers 1

1 In the **Mesh** toolbar, click **Boundary Layers**.

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

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

4 From the **Selection** list, choose **Iron Sphere**.

Boundary Layer Properties

1 In the **Model Builder** window, click **Boundary Layer Properties**.

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

3 From the **Selection** list, choose **Iron Sphere Surface**.

4 Locate the **Layers** section. From the **Thickness specification** list, choose **First layer**.

5 In the **Thickness** text field, type `8[um]`.

6 In the **Number of layers** text field, type `4`.

7 Click **Build All**.

8 In the **Mesh** toolbar, click **Plot**.

RESULTS

Mesh 1

1 In the **Settings** window for **Mesh**, click to expand the **Title** section.

2 From the **Title type** list, choose **None**.

3 Locate the **Level** section. From the **Element type** list, choose **Prism**.

4 Locate the **Coloring and Style** section. From the **Element color** list, choose **Cyan**.

5 Click to expand the **Element Filter** section. Select the **Enable filter** check box.

6 In the **Expression** text field, type `z<0`.

7 Right-click **Results>Mesh Plot 2>Mesh 1** and choose **Duplicate**.

Mesh 2

1 In the **Model Builder** window, click **Mesh 2**.

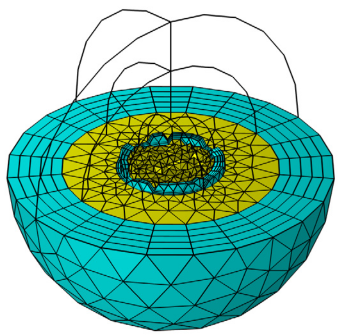
2 In the **Settings** window for **Mesh**, locate the **Level** section.

3 From the **Element type** list, choose **Tetrahedron**.

4 Locate the **Coloring and Style** section. From the **Element color** list, choose **Yellow**.

5 In the **Mesh Plot 2** toolbar, click **Plot**.

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



This new mesh has a much finer resolution normal to the surface of the iron sphere, where the steeper magnetic gradients are located. Now, rerun the study and compare the results.

STUDY 1

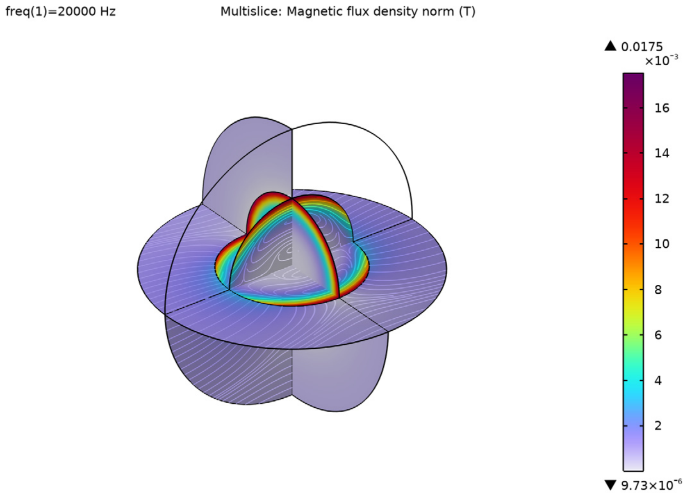
In the **Home** toolbar, click **Compute**.

RESULTS

Magnetic Flux Density Norm (mf)

1 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

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



The magnetic flux density plotted is now much smoother and has been resolved to a much higher precision. Next, plot the current density induced in the sphere.

Arrow Volume 1

1 Right-click **Magnetic Flux Density Norm (mf)** and choose **Arrow Volume**.

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 (comp1)> Magnetic Fields>Currents and charge>mf.Jx,mf.Jy,mf.Jz - Current density**.

3 Locate the **Arrow Positioning** section. Find the **x grid points** subsection. In the **Points** text field, type `1`.

4 Find the **y grid points** subsection. In the **Points** text field, type `30`.

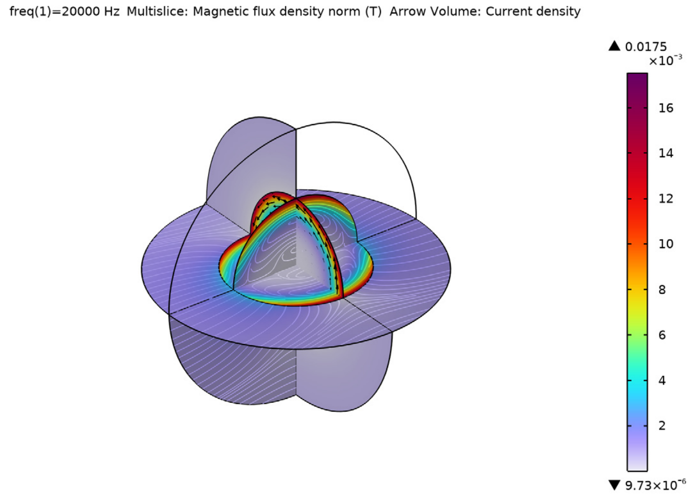
5 Find the **z grid points** subsection. In the **Points** text field, type `30`.

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

7 Select the **Scale factor** check box. In the associated text field, type `3e-7`.

8 In the **Magnetic Flux Density Norm (mf)** toolbar, click  **Plot**.

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



Here, it is shown that there is substantial more current induced near the surface of the iron sphere, as expected from the skin depth of iron at this frequency of background magnetic field. We can also evaluate the magnetic dissipation in the iron sphere from the work done on the sphere.

Volume Integration 1

1 In the **Results** toolbar, click 8.85 e-12 **More Derived Values** and choose **Integration> Volume Integration**.

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

3 From the **Selection** list, choose **Iron Sphere**.

4 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields>Heating and losses>mf.Qrh - Volumetric loss density, electric - W/m³**.

5 Click **Evaluate**.

In this model, the magnetic dissipation in the sphere is ~3.4 nW.