Model created in COMSOL Multiphysics 6.4

Nonlinear Ferromagnetic Diaphragm

Introduction

A magnetic diaphragm is a flexible, thin structure that interacts with magnetic fields to perform mechanical or sensing functions. When subjected to an external magnetic field, the diaphragm deforms due to magnetomechanical interactions, converting magnetic energy into mechanical displacement or, conversely, mechanical deformation into changes in the magnetic field distribution. In this model, you will study the magnetomechanics of a magnetic diaphragm using the Magnetomechanics, Shell multiphysics interface. This interface combines the Shell and Magnetic Fields physics with moving mesh functionality, allowing simulation of the coupled mechanical deformation and magnetic field interactions for thin, flexible structures.

Model Definition

As shown in Figure 1, the model consists of two coupled parts: an electromagnet that generates a magnetic field when driven by a prescribed current input, and a thin elastic magnetic diaphragm driven by the magnetic field. The geometry is defined in an axisymmetric configuration, capturing the circular symmetry of the system. The model is geometrically similar to the one used in Ref. 1.

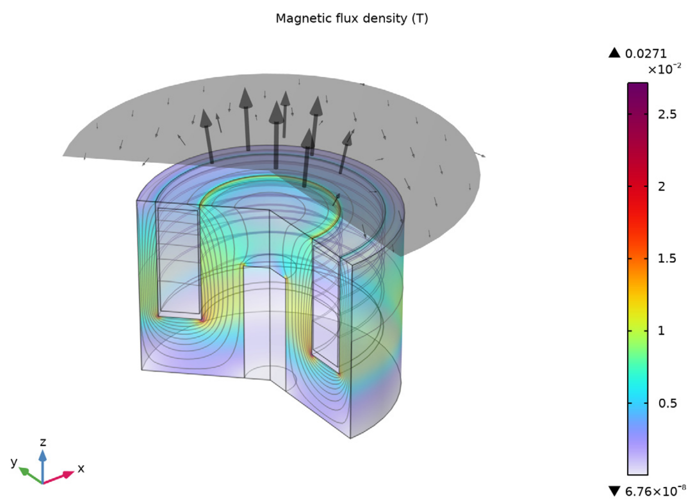


Figure 1: Model geometry definition. The axisymmetric model consists of an electromagnet and a magnetic diaphragm.

A radial pretension is also applied to the diaphragm, which will strongly affect its mechanical response to the magnetic loading. This setup allows for investigation of the magnetomechanical coupling between the electromagnetic field and the diaphragm. Such coupled models are relevant for the design of magnetically actuated thin structures, sensors, and vibration control devices.

The constitutive relation for the diaphragm material is nonlinear with the magnetization model given by Ref. 1:

$$B = \mu_0(H + M_0(\tanh(kH))) .$$

Note that, in general, you can use other type of B-H relation. For details, see the *AC/DC Module User's Guide*.

Results and Discussion

Figure 2 shows the displacement magnitude as a function of the input current for several pretension levels.

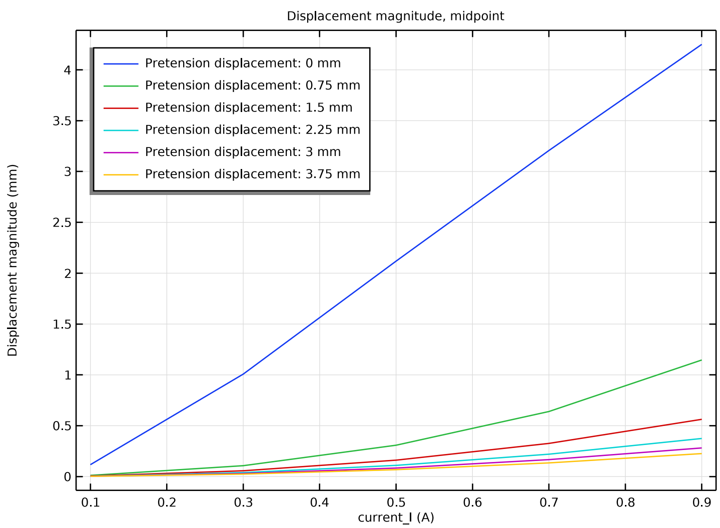


Figure 2: The displacement of the center of the diaphragm as a function of the current.

The blue curve on the top, which represents the case without pretension, shows an almost linear relationship between displacement and current and exhibits the largest displacement. As the pretension increases, the displacement decreases accordingly. This result demonstrates that the diaphragm becomes stiffer and more resistant to deformation when subjected to radial stretching, which is consistent with physical intuition.

Figure 3 shows the magnetic flux density on the diaphragm.

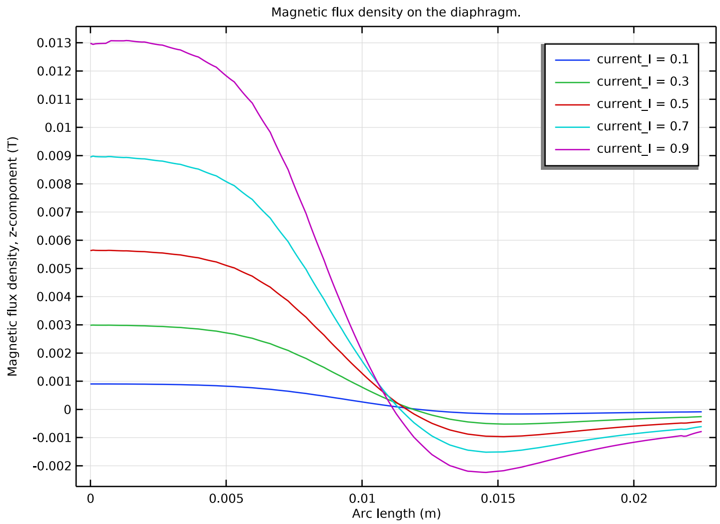


Figure 3: The z component of the magnetic flux density distribution on the diaphragm.

One can see that the magnetic flux density responds to the current input accordingly.

Initially, the applied current input is relatively weak, resulting in only small deformations of the magnetic diaphragm. This allows you to study the fundamental coupling between the electromagnetic and structural domains without introducing large nonlinear effects. To further explore the system behavior, you can increase the current input or modify the magnetic B–H curve. This provides valuable insight into how material properties and excitation levels influence both the stiffness and sensitivity of the diaphragm.

You can perform an additional study with the current increased to 4 A. Figure 4 shows the resulting geometry of the thin diaphragm. In this case, the diaphragm undergoes a large deformation and is strongly attracted to the magnet.

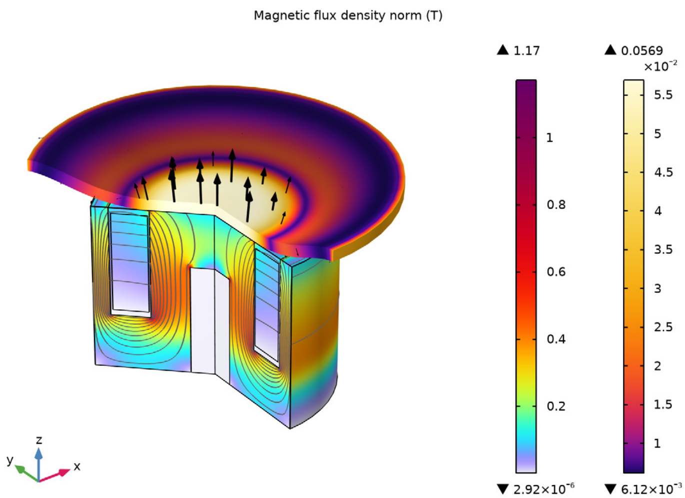


Figure 4: Magnetic flux density norm and field lines for a 4 A current. At this high current, the diaphragm is fully attracted to the magnet.

Reference

1. V.R. Jayaneththi, K.C. Aw, and A.J. McDaid, “Coupled magneto-mechanical modeling of non-linear ferromagnetic diaphragm systems,” *Int. J. Mech. Sci.*, vol. 155, pp. 360–369, 2019.

Application Library path: `Structural_Mechanics_Module/Magnetomechanics/magnetic_diaphragm`

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 **2D Axisymmetric**.
2 In the **Select Physics** tree, select **AC/DC > Electromagnetics and Mechanics > Magnetomechanics > Magnetomechanics, Shell**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies > Stationary**.
6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 In the table, enter the following settings:

Name	Expression	Value	Description
EM1_r_outer	30[mm]/2	0.015 m	
EM1_r_core	3[mm]	0.003 m	
diaphragm_r	45[mm]/2	0.0225 m	
diaphragm_thickness	1.5[mm]	0.0015 m	
gray_area_width	EM1_r_outer/3	0.005 m	
EM1_hollow_height	EM1_height-gap_distance*1.5	0.015 m	
gap_distance	5[mm]	0.005 m	
EM1_height	EM1_r_outer*1.5	0.0225 m	
current_I	1[A]	1 A	
N_turn	100	100	
pretension_disp	0[m]	0 m	
k	3*10^(-5) [m/A]	3E-5 m/A	
M_inf	1000000 [A/m]	1E6 A/m	
H	0 [A/m]	0 A/m	

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

5 In the table, enter the following settings:

Name	Expression	Value	Description
EM1_r_outer	30[mm]/2	0.015 m	Outer radius of the electromagnet
EM1_r_core	3[mm]	0.003 m	Inner radius of the electromagnet
diaphragm_r	45[mm]/2	0.0225 m	Radius of the diaphragm
diaphragm_thickness	1.5[mm]	0.0015 m	Thickness of the diaphragm
gray_area_width	EM1_r_outer/3	0.005 m	Width of the coil
EM1_hollow_height	EM1_height-gap_distance*1.5	0.015 m	Height of the hollow region of the electromagnet
gap_distance	5[mm]	0.005 m	Gap size
EM1_height	EM1_r_outer*1.5	0.0225 m	Height of the electromagnet
current_I	1[A]	1 A	Current
N_turn	100	100	Number of turns of the Coil
pretension_disp	0[m]	0 m	Prescribed displacement
k	3*10^(-5) [m/A]	3E-5 m/A	Rate of magnetization
M_inf	1000000 [A/m]	1E6 A/m	Saturation magnetization
H	0 [A/m]	0 A/m	Magnetic field

GEOMETRY 1

Rectangle 1 (r1)

1. In the **Geometry** toolbar, click **Rectangle**.
2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type EM1_r_outer.
4. In the **Height** text field, type EM1_height.

whole space

1. Right-click **Rectangle 1 (r1)** and choose **Duplicate**.
2. In the **Settings** window for **Rectangle**, type whole space in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `EM1_r_outer*2`.

4 In the **Height** text field, type `EM1_height*1.5`.

hollow area

1 Right-click **whole space** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `hollow area` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `EM1_r_core`.

4 In the **Height** text field, type `EM1_hollow_height`.

Rectangle 4 (r4)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `gray_area_width`.

4 In the **Height** text field, type `EM1_hollow_height`.

5 Locate the **Position** section. In the **r** text field, type `EM1_height*0.35`.

6 In the **z** text field, type `EM1_height-EM1_hollow_height`.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 In the **z** text field, type `EM1_height+gap_distance`.

5 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

6 In the **r** text field, type `diaphragm_r`.

7 In the **z** text field, type `EM1_height+gap_distance`.

Rectangle 5 (r5)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `gray_area_width*0.9`.

4 In the **Height** text field, type `EM1_hollow_height*0.9`.

5 Locate the **Position** section. In the **r** text field, type `EM1_height*0.36`.

6 In the **z** text field, type `(EM1_height-EM1_hollow_height*0.95)`.

7 Click **Build All Objects**.

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

ADD MATERIAL

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

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

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

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

MATERIALS

Copper (mat1)

1 Select Domains 1–4 only.

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

3 Click **Clear Selection**.

4 Select Domain 5 only.

ADD MATERIAL

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

2 In the **Search** text field, type `Low Carbon Steel Soft Iron`.

3 Click **Search**.

4 In the tree, select **Nonlinear Magnetic** > **Low Carbon Steel** > **Low Carbon Steel Soft Iron**.

5 Click the **Add to Component** button in the window toolbar.

MATERIALS

Low Carbon Steel Soft Iron (mat2)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Materials** > **Low Carbon Steel Soft Iron (mat2)** node, then click **Low Carbon Steel Soft Iron (mat2)**.

2 Select Domain 2 only.

Magnetic polymer composites

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 **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 8 only.

5 In the **Label** text field, type `Magnetic polymer composites`.

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

Property	Variable	Value	Unit	Property group
Poisson's ratio	nu	0.499	1	Young's modulus and Poisson's ratio
Density	rho	1000	kg/m³	Basic

7 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Materials** > **Magnetic polymer composites (mat3)** node.

RESULTS

Global Evaluation Sweep 1

1. In the **Model Builder** window, expand the **Results** node.
2. Right-click **Results** > **Derived Values** and choose **More Derived Values** > **Global Evaluation Sweep**.
3. In the **Settings** window for **Global Evaluation Sweep**, locate the **Parameters** section.
4. In the table, enter the following settings:

Parameter name	Parameter value list
H	range(0,100,10^6)[A/m]

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

Expression	Unit	Description
mu0_const*(H+M_inf*tanh(k*H))	T	B

6. Click **Evaluate**.

MATERIALS

Magnetic polymer composites (mat3)

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** click **Magnetic polymer composites (mat3)**.
2. In the **Settings** window for **Material**, locate the **Material Contents** section.
3. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Young's modulus	E	34644	Pa	Young's modulus and Poisson's ratio

Moving Mesh

Deforming Domain 1

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

2 Select Domain 3 only.

Symmetry/Roller 1

1 In the **Model Builder** window, click **Symmetry/Roller 1**.

2 Select Boundaries 5, 7, and 8 only.

Magnetic Fields (MF)

Domain Coil 1

1 In the **Physics** toolbar, click **Domains** and choose **Domain Coil**.

2 Select Domain 5 only.

3 In the **Settings** window for **Domain Coil**, locate the **Material Type** section.

4 From the **Material type** list, choose **Solid**.

5 Locate the **Coil** section. From the **Conductor model** list, choose **Homogenized multiturn**.

6 In the I_{coil} text field, type `current_I`.

7 Locate the **Homogenized Conductor** section. In the N text field, type `N_turn`.

Ampère's Law in Solids 1

1 In the **Physics** toolbar, click **Domains** and choose **Ampère's Law in Solids**.

2 Select Domains 2 and 4 only.

Add Material

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

2 In the **Search** text field, type `epoxy resin`.

3 Click **Search**.

4 In the tree, select **Material Library** > **Epoxies, Adhesives, and Underfills** > **Filled epoxy resin (X238)** > **Filled epoxy resin (X238) [solid]**.

5 Click the **Add to Component** button in the window toolbar.

6 In the **Materials** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Filled epoxy resin (X238) [solid] (mat4)

1 Select Domain 4 only.

2 In the **Model Builder** window, expand the **Filled epoxy resin (X238) [solid] (mat4)** node.

3 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Materials** > **Filled epoxy resin (X238) [solid] (mat4)** > **Basic (def)** node, then click **Filled epoxy resin (X238) [solid] (mat4)**.

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

5 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
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	1e-15	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	3.3	1	Basic

MAGNETIC FIELDS (MF)

Magnetic Shielding 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Magnetic Shielding**.

2 Select Boundary 8 only.

3 In the **Settings** window for **Magnetic Shielding**, locate the **Magnetic Shielding** section.

4 In the d_s text field, type `diaphragm_thickness`.

MATERIALS

Low Carbon Steel Soft Iron (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** click **Low Carbon Steel Soft Iron (mat2)**.

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

3 In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	3700	1	Basic

As a first step, we assume that the magnetic diaphragm exhibits linear magnetic properties.

MAGNETIC FIELDS (MF)

Magnetic Shielding 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Magnetic Fields (mf)** click **Magnetic Shielding 1**.
2. In the **Settings** window for **Magnetic Shielding**, locate the **Magnetic Shielding** section.
3. From the μ_r list, choose **User defined**. In the associated text field, type `100`.

SHELL (SHELL)

Thickness and Offset 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Shell (shell)** click **Thickness and Offset 1**.
2. In the **Settings** window for **Thickness and Offset**, locate the **Thickness and Offset** section.
3. In the d_0 text field, type `diaphragm_thickness`.

Prescribed Displacement/Rotation 1

1. In the **Physics** toolbar, click **Points** and choose **Prescribed Displacement/Rotation**.
2. Select Point 18 only.
3. In the **Settings** window for **Prescribed Displacement/Rotation**, locate the **Prescribed Displacement** section.
4. From the **Displacement in r direction** list, choose **Prescribed**.
5. In the u_{0r} text field, type `pretension_disp`.
6. From the **Displacement in z direction** list, choose **Prescribed**.
7. Locate the **Prescribed Rotation** section. From the **By** list, choose **Rotation**.
8. In the **Model Builder** window, click **Shell (shell)**.
9. In the **Settings** window for **Shell**, locate the **Boundary Selection** section.

10 In the list box, select **1 (not applicable)**.

11 Click **Clear Selection**.

12 Select Boundary 8 only.

Prescribed Displacement/Rotation 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Prescribed Displacement/Rotation**.

We assume that the diaphragm can undergo sufficiently large deformation to make contact with the magnet, though this is contingent on the magnitude of the applied current and the material properties.

2 Select Boundary 8 only.

3 In the **Settings** window for **Prescribed Displacement/Rotation**, locate the **Prescribed Displacement** section.

4 From the **Displacement in z direction** list, choose **Limited**.

5 In the $u_{0z,\min}$ text field, type `-gap_distance+diaphragm_thickness/2`.

MULTIPHYSICS

Magnetomechanics, Boundary 1 (mmfb1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Multiphysics** > **Magnetomechanics, Boundary 1 (mmfb1)** node, then click **Magnetomechanics, Boundary 1 (mmfb1)**.

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

3 Click **Clear Selection**.

4 Select Boundary 8 only.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Extra fine**.

4 Click **Build All**.

STUDY 1

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click + **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
pretension_disp (Prescribed displacement)	`range(0,0.5,2.6)*diaphragm_thickness`	m

Step 1: Stationary

1 In the **Model Builder** window, click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** checkbox.

4 Click + **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
current_I (Current)	`range(0.1,0.2,0.9)`	A

6 In the **Study** toolbar, click = **Compute**.

RESULTS

Magnetic Flux Density (mf)

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

2 From the **Parameter value (pretension_disp (m))** list, choose **0**.

3 From the **Parameter value (current_I (A))** list, choose **0.1**.

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

At this point, the user may pause to experiment with different values for the input current (current_I) and the magnetic properties of the material. Next, we will introduce a B–H curve for the magnetic shielding.

MATERIALS

Magnetic polymer composites (mat3)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** click **Magnetic polymer composites (mat3)**.

2 In the **Settings** window for **Material**, click to expand the **Material Properties** section.

3 In the **Material properties** tree, select **Electromagnetic Models** > **B-H Curve**.

4 Click Add to Material.

5 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** > **Magnetic polymer composites (mat3)** click **B-H curve (BHCurve)**.

6 In the **Settings** window for **B-H Curve**, locate the **Output Properties** section.

7 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Magnetic flux density norm	normB	`BH(normHin)`	T	1x1
Magnetic field norm	normH	`BH_inv(normBin)`	A/m	1x1
Magnetic coenergy density	Wpm	`BH_prim(normHin)`	J/m^3	1x1

Interpolation 1 (int1)

1 Right-click **Component 1 (comp1)** > **Materials** > **Magnetic polymer composites (mat3)** > **B-H curve (BHCurve)** and choose **Functions** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **Result table**.

RESULTS

Global Evaluation Sweep 1

1 In the **Model Builder** window, expand the **Results** > **Tables** node, then click **Results** > **Derived Values** > **Global Evaluation Sweep 1**.

2 In the **Settings** window for **Global Evaluation Sweep**, click **Evaluate**.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 Click **Evaluate**.

5 Click next to **Evaluate**, then choose **Table 1 - Global Evaluation Sweep 1**.

Table 1

1 In the **Model Builder** window, under **Results** > **Tables** click **Table 1**.

2 In the **Settings** window for **Table**, click **Update**.

MATERIALS

Interpolation 1 (int1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** > **Magnetic polymer composites (mat3)** > **B-H curve (BHCurve)** click **Interpolation 1 (int1)**.

2 In the **Settings** window for **Interpolation**, click to expand the **Related Functions** section.

3 Select the **Define inverse function** checkbox.

4 Select the **Define primitive function** checkbox.

5 Select the **Define random function** checkbox.

6 In the **Inverse function name** text field, type `BH_inv`.

7 In the **Primitive function name** text field, type `BH_prim`.

8 Clear the **Define random function** checkbox.

9 Click **Plot**.

10 Locate the **Data Column Settings** section. In the table, click to select the cell at row number 1 and column number 2.

11 In the **Unit** text field, type `A/m`.

12 In the table, click to select the cell at row number 2 and column number 1.

13 In the **Unit** text field, type `T`.

14 Click **Plot**.

Magnetic polymer composites (mat3)

In the **Model Builder** window, expand the **Component 1 (comp1)** > **Materials** > **Magnetic polymer composites (mat3)** node.

Interpolation 1 (int1, BH_inv, BH_prim)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Materials** > **Magnetic polymer composites (mat3)** > **B-H curve (BHCurve)** node, then click **Interpolation 1 (int1, BH_inv, BH_prim)**.

2 In the table, click to select the cell at row number 2 and column number 1.

3 In the **Name** text field, type `BH`.

MAGNETIC FIELDS (MF)

Magnetic Shielding 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Magnetic Fields (mf)** click **Magnetic Shielding 1**.

2 In the **Settings** window for **Magnetic Shielding**, locate the **Magnetic Shielding** section.

3 From the μ_r list, choose **From material**.

4 From the **Magnetization model** list, choose **B-H curve**.

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

RESULTS

Displacement Magnitude

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

2 In the **Settings** window for **1D Plot Group**, type `Displacement Magnitude` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Displacement magnitude, midpoint`.

6 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

7 In the **Displacement Magnitude** toolbar, click **Plot**.

Point Graph 1

1 Right-click **Displacement Magnitude** and choose **Point Graph**.

2 Select Point 4 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `shell.disp`.

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

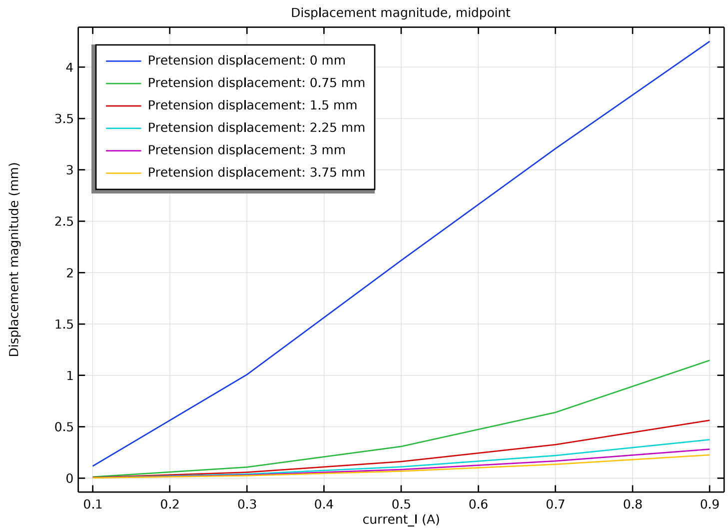
6 In the **Displacement Magnitude** toolbar, click **Plot**.

7 Click to expand the **Legends** section. Select the **Show legends** checkbox.

8 From the **Legends** list, choose **Evaluated**.

9 In the **Legend** text field, type `Pretension displacement: eval(pretension_disp, mm) mm`.

10 In the **Displacement Magnitude** toolbar, click **Plot**.



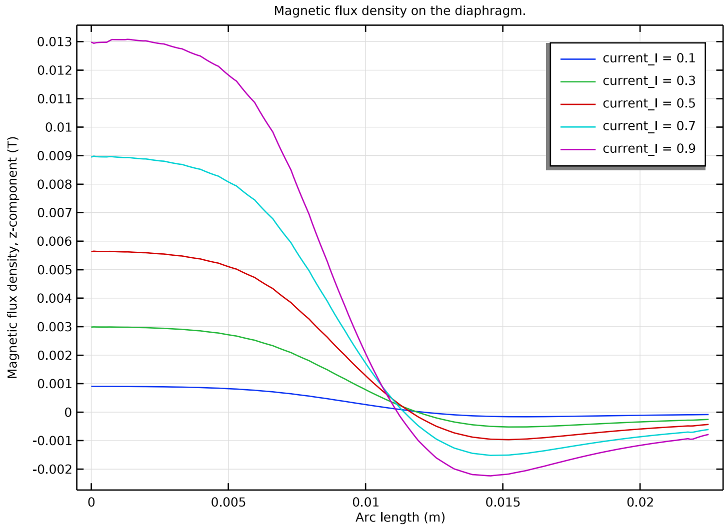
Magnetic Flux Density on the Diaphragm

1. In the **Results** toolbar, click **1D Plot Group**.
2. In the **Settings** window for **1D Plot Group**, type `Magnetic Flux Density on the Diaphragm` in the **Label** text field.
3. Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.
4. From the **Parameter selection (pretension_disp)** list, choose **First**.
5. Locate the **Title** section. From the **Title type** list, choose **Manual**.
6. In the **Title** text area, type `Magnetic flux density on the diaphragm.`.

Line Graph 1

1. Right-click **Magnetic Flux Density on the Diaphragm** and choose **Line Graph**.
2. Select Boundary 8 only.
3. In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
4. In the **Expression** text field, type `mf.Bz`.
5. In the **Magnetic Flux Density on the Diaphragm** toolbar, click **Plot**.
6. Click to expand the **Legends** section. From the **Legends** list, choose **Evaluated**.
7. Select the **Show legends** checkbox.

8 In the **Legend** text field, type `current_I = eval(current_I)`.



Revolution 2D 1

In the **Model Builder** window, expand the **Results > Datasets** node, then click **Revolution 2D 1**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

4 Select Domains 1, 2, 4, and 5 only.

Revolution 2D 2

Right-click **Revolution 2D 1** and choose **Duplicate**.

Selection

1 In the **Model Builder** window, expand the **Revolution 2D 2** node, then click **Selection**.

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

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

4 Select Boundary 8 only.

Revolution 2D 2

1 In the **Model Builder** window, click **Revolution 2D 2**.

2 In the **Settings** window for **Revolution 2D**, click to expand the **Revolution Layers** section.

3 Clear the **Add end caps if the revolution is not full** checkbox.

Arrow Surface 1

1 In the **Model Builder** window, expand the **Results** > **Magnetic Flux Density, Revolved Geometry (mf)** node.

2 Right-click **Magnetic Flux Density, Revolved Geometry (mf)** and choose **Arrow Surface**.

3 In the **Settings** window for **Arrow Surface**, locate the **Data** section.

4 From the **Dataset** list, choose **Revolution 2D 2**.

5 From the **Solution parameters** list, choose **From parent**.

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

7 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type `40`.

Surface 1

1 In the **Model Builder** window, right-click **Magnetic Flux Density, Revolved Geometry (mf)** and choose **Surface**.

2 Click the **Show Grid** button in the **Graphics** toolbar.

3 In the **Settings** window for **Surface**, locate the **Data** section.

4 From the **Dataset** list, choose **Revolution 2D 2**.

5 From the **Solution parameters** list, choose **From parent**.

6 In the **Magnetic Flux Density, Revolved Geometry (mf)** toolbar, click **Plot**.

7 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Volume 1**.

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

9 Click the **Transparency** button in the **Graphics** toolbar.

10 From the **Plot** list, choose **Contour 1**.

11 In the **Magnetic Flux Density, Revolved Geometry (mf)** toolbar, click **Plot**.

Magnetic Flux Density, Revolved Geometry (mf)

1 In the **Model Builder** window, click **Magnetic Flux Density, Revolved Geometry (mf)**.

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

3 From the **Parameter value (pretension_disp (m))** list, choose **7.5E-4**.

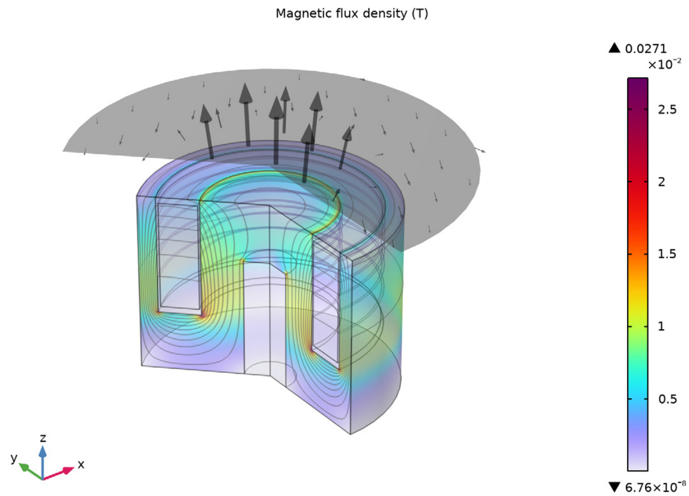
4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Magnetic flux density (T)`.

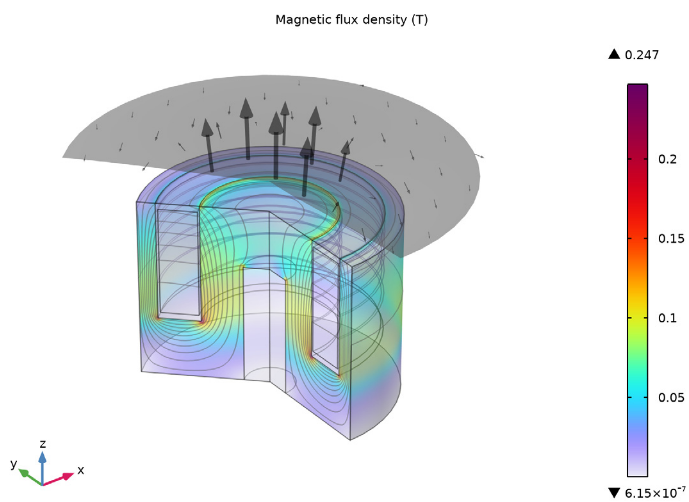
6 Clear the **Parameter indicator** text field.

7 In the **Magnetic Flux Density, Revolved Geometry (mf)** toolbar, click **Plot**.

8 Click **Plot First**.



9 Click **Plot Last**.



Next, we visually examine the mesh under different current inputs.

Moving Mesh

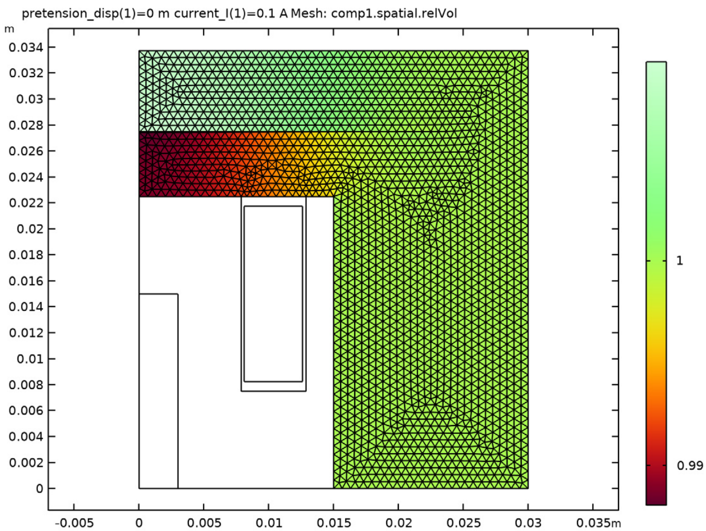
1 In the **Model Builder** window, click **Moving Mesh**.

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

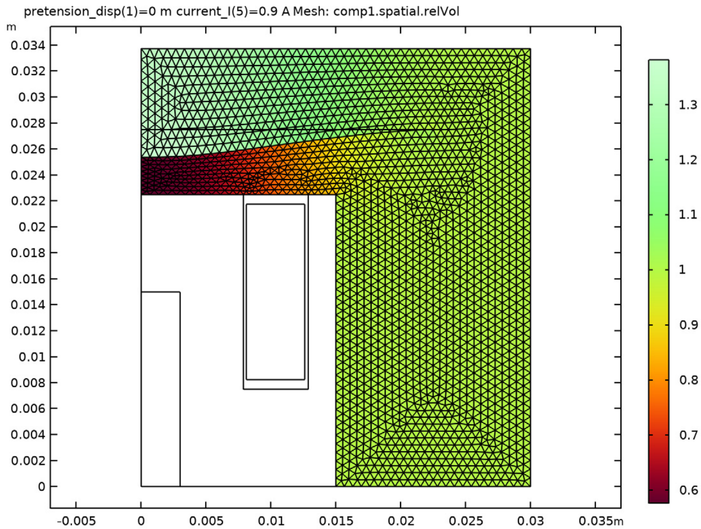
3 From the **Parameter value (pretension_disp (m))** list, choose **0**.

4 In the **Moving Mesh** toolbar, click **Plot**.

5 Click **Plot First**.



6 Click **Plot Last**.



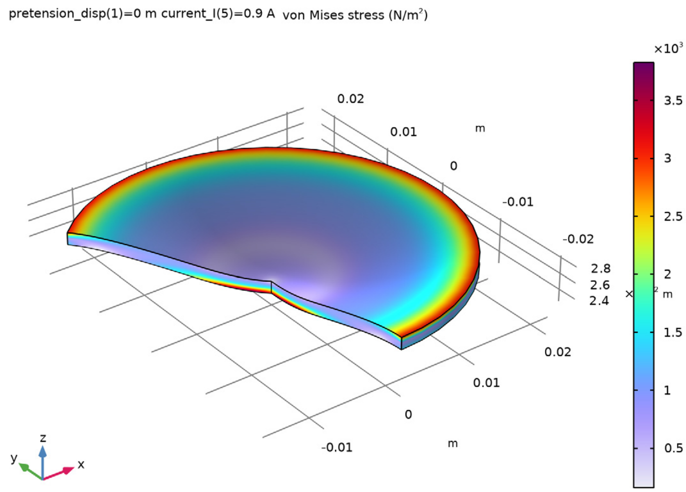
Stress, 3D (shell)

1 In the **Model Builder** window, click **Stress, 3D (shell)**.

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

3 From the **Parameter value (pretension_disp (m))** list, choose **0**.

4 In the **Stress, 3D (shell)** toolbar, click **Plot**.



Once comfortable with this basic model, more advanced effects—such as nonlinear magnetization and material anisotropy—can be incorporated to achieve a more accurate and comprehensive simulation. It is strongly recommended that the user experiment with different input currents and materials with varying mechanical properties to explore their effects on the diaphragm's behavior.

ADD STUDY

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Stationary**.

4 Click the **Add Study** button in the window toolbar.

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

GLOBAL DEFINITIONS

Parameters 1

1 In the **Settings** window for **Parameters**, locate the **Parameters** section.

2 In the table, enter the following settings:

Name	Expression	Value	Description
current_I	4[A]	4 A	Current

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

RESULTS

Revolution 2D 3

In the **Model Builder** window, under **Results** > **Datasets** click **Revolution 2D 3**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

4 Select Domains 1, 2, 4, and 5 only.

Revolution 2D 4

In the **Model Builder** window, under **Results** > **Datasets** click **Revolution 2D 4**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

4 Select Boundary 8 only.

Arrow Surface 1

1 In the **Model Builder** window, expand the **Results** > **Magnetic Flux Density, Revolved Geometry (mf) 1** node.

2 Right-click **Results** > **Magnetic Flux Density, Revolved Geometry (mf)** > **Arrow Surface 1** and choose **Copy**.

Magnetic Flux Density, Revolved Geometry (mf) 1

1 In the **Model Builder** window, under **Results** click **Magnetic Flux Density, Revolved Geometry (mf) 1**.

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

3 From the **Title type** list, choose **Manual**.

4 In the **Magnetic Flux Density, Revolved Geometry (mf) 1** toolbar, click **Plot**.

Arrow Surface 1

Right-click **Magnetic Flux Density, Revolved Geometry (mf) 1** and choose **Paste Arrow Surface**.

Surface 1

In the **Model Builder** window, under **Results** > **Magnetic Flux Density, Revolved Geometry (mf)** right-click **Surface 1** and choose **Copy**.

Surface 1

In the **Model Builder** window, right-click **Magnetic Flux Density, Revolved Geometry (mf) 1** and choose **Paste Surface**.

Arrow Surface 1

1 In the **Settings** window for **Arrow Surface**, locate the **Coloring and Style** section.

2 Set the slider value to **0.8**.

Volume 1

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

2 In the **Settings** window for **Volume**, locate the **Coloring and Style** section.

3 Set the **Color calibration parameter** value to **-1.5**.

Arrow Surface 1

1 In the **Model Builder** window, click **Arrow Surface 1**.

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

3 From the **Dataset** list, choose **Revolution 2D 4**.

4 In the **Magnetic Flux Density, Revolved Geometry (mf) 1** toolbar, click **Plot**.

5 Locate the **Coloring and Style** section. In the **Scale factor** text field, type `0.08`.

6 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type `150`.

7 In the **Magnetic Flux Density, Revolved Geometry (mf) 1** toolbar, click **Plot**.

Surface 1

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

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

3 From the **Dataset** list, choose **Revolution 2D 4**.

4 Locate the **Inherit Style** section. From the **Plot** list, choose **Arrow Surface 1**.

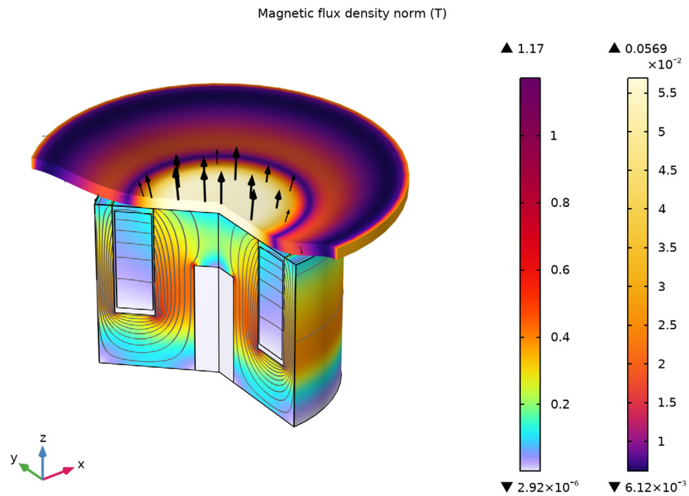
5 Locate the **Coloring and Style** section. From the **Color table** list, choose **HeatCamera**.

6 From the **Color table transformation** list, choose **Nonlinear**.

7 Set the **Color calibration parameter** value to **-1.5**.

8 In the **Magnetic Flux Density, Revolved Geometry (mf) 1** toolbar, click **Plot**.

9 Click the **Show Grid** button in the **Graphics** toolbar.



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