Created in COMSOL Multiphysics 6.0

Topology Optimization of a Magnetic Circuit

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Introduction

This model presents an example of topology optimization of the magnetic circuit of a loudspeaker driver. Topology optimization is used to find the design of a nonlinear iron pole piece and top plate that maximize the performance, defined by a given objective, while constraining the amount of iron, obtaining a light design. The model sets up two different objectives for the optimization solved separately. The first maximized the magnetic field strength in the air gap, while the second generates a flat $\mathrm{BL}(x)$ curve. The final geometry features a loudspeaker that uses a smaller volume of iron and has much better characteristics than the traditional design.

The geometry and simulation parameters are similar to those used in the tutorial Loudspeaker Driver — Frequency-Domain Analysis. More insight in the vibroacoustics analysis of that geometry can be found in the documentation relative to the model.

This model illustrates:

- How different objectives result in designs with different topologies:
  - one objective maximizes the magnetic field strength in the magnetic gap
  - another objective ensures a flat $\mathrm{BL}(x)$ curve for larger displacements of the voice coil
- How the optimization result can be verified with a body-fitted mesh
- The use of a user-defined permeability to apply a nonlinear iron magnetic material to a topology optimization

Model Definition

The magnetic circuit of a loudspeaker is used to concentrate the magnetic flux generated by a permanent magnet into an air gap in which a coil is placed, with the coil windings perpendicular to magnetic flux lines. The coil is mechanically connected to the membrane of the loudspeaker. When a current is run through the coil, electromagnetic forces act on it inducing movement. The movement of the coil is transferred to the membrane, which interacts with the air producing sound waves.

In a loudspeaker, the pole piece and top plate that constitute the magnetic circuit must be designed to maximize the flux concentrated at the coil, and to provide a uniform field across the coil. In order to estimate the performance of a loudspeaker magnetic circuit, it is useful to introduce the BL factor, defined as the product of magnetic flux in the air gap B and coil length L. The larger this parameter, the higher the performance of the magnetic circuit.

If the magnetic circuit is axisymmetric and the coils are winded in the azimuthal direction inside the air gap, as in the present model, the BL factor is defined as

$$\mathrm{BL}(x) = \frac{2\pi N_0}{A}\int rB_r(x)dA$$

where B_r is the r-component of the magnetic flux density, N_0 is the number of turns of the coil, A the cross-section area of the coil, and x is the location of voice coil. Here the BL factor will depend on the location of the voice coil, as the r-component of the magnetic flux density is not uniform for all positions of the speaker.

When loudspeakers are excited at high frequencies, the displacement of the membrane is always relatively small. This means that at high frequencies, the BL factor along the path of the coil is almost constant and the most relevant characteristic of the magnetic circuit is the BL factor at the resting position, that is, $\mathrm{BL}(x = 0)$. At low frequencies, this displacement becomes significant and the variation of the BL factor becomes more relevant. This variation of the BL factor along the path of the coil is an undesired effect as it introduces distortion in the speaker. This effect is further explained in Figure 1.

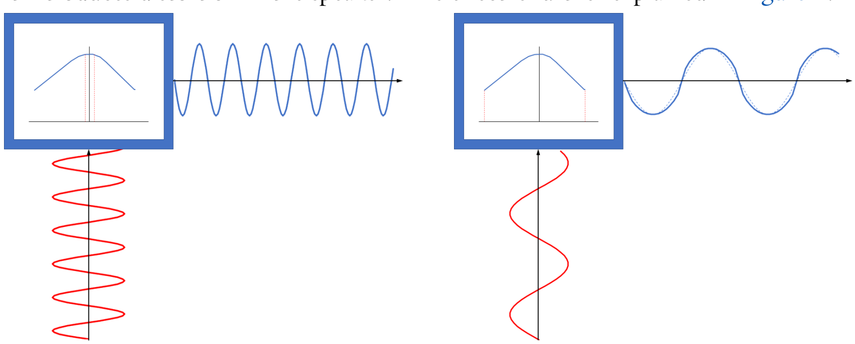

Figure 1: Lorentz force over the voice coil (blue curves along the horizontal axis) when a high frequency (left) and low frequency (right) current travels through the voice coil (red curves along the vertical axis). At high frequency the displacement of the voice coil is small, meaning that the BL factor remains almost constant through the movement, producing negligible distortion. At low frequencies, the large displacement of the coil means that the BL factor will vary along the path, producing distortion in the displacement and the sound.

For these reasons, the model includes two different optimization studies with different objectives. The first optimization study maximizes the BL factor at the resting position $x = 0$, making this design ideal for tweeters and loudspeakers designed for performance at high frequencies. The second optimization study minimizes the distance between the $\mathrm{BL}(x)$ curve and a constant value, making the magnetic circuit closer to an ideal linear speaker. This type of design is more relevant for woofers and loudspeakers intended for low frequency applications.

In the present model, the electromagnetic problem is solved using the Magnetic Fields interface. The models uses a soft iron material from the material library available in COMSOL. This material uses a B-H curve, in order to take into account magnetic saturation. In the model, it is explicitly shown that using a given magnetic B-H curve is equivalent to using a relative permeability:

$$\mu_{r,BH}(|\mathbf{B}|) = \frac{H(|\mathbf{B}|)}{\mu_0|\mathbf{B}|} \tag{1}$$

Using the relative permeability instead of the B-H curve is useful for the purpose of applying topology optimization. The permeability of the design space is defined in terms of the penalized material volume factor, θ_p, with the formula:

$$\mu_r(\theta_\mathrm{p}, |\mathbf{B}|) = 1 + \theta_\mathrm{p}\left(\frac{H(|\mathbf{B}|)}{\mu_0|\mathbf{B}|} - 1\right) \tag{2}$$

$$\theta_\mathrm{p} = \theta_\mathrm{min} + (1 - \theta_\mathrm{min})\theta^{p_\mathrm{simp}} \tag{3}$$

Where θ_min is the minimum penalized volume fraction and p_simp is the SIMP exponent. The relative permeability takes the value of the permeability of air for $\theta_\mathrm{p} = 0$ and the permeability of the iron for $\theta_\mathrm{p} = 1$. The θ field depends on the control variable field θ_c via a Helmholtz filter. This introduces a minimum length scale for the θ field, see the *Topology Optimization of an MBB Beam* tutorial in the Optimization Module Application Library for more details. In this model the minimum length scale is taken as the element size. Topology optimization is performed by searching for the values of θ_c in the interval $[0, 1]$ for each element in the yoke, while constraining the volume averaged value of θ. The latter is directly proportional to the volume of iron in the design, since the θ field indicates the regions consisting of iron.

In the model there is a single domain where the iron could be placed, and in both optimization setups this leads to two isolated areas of iron. These results are similar to the traditional design of a pole piece and a top plate. For this domain, the constraint is set to a volume of about 94 cm^3, which is below the volume of the original geometry, of about 110 cm^3. By computing the optimal shape as a function of the constraint, it is possible to derive the Pareto front giving the relationship between the value of the objective and the volume of iron in the loudspeaker.

The third study in the model takes the results from the second topology optimization and created a solid geometry from the contour. Iron properties are added to the areas (domain) with density above 0.5 and air properties on the rest. This step validates the approach used in Equation 2.

Results and Discussion

The norm of the magnetic flux density and the output material volume factor for the two optimization studies is shown in Figure 2. The left column shows the results that maximize the BL factor at the resting position; and the right column shows the results that generate a flat $\mathrm{BL}(x)$ curve. The figure shows that both optimization setups lead to designs consisting in two separate parts; a central component connected to the bottom of the magnet, usually called the yoke or polepiece, and a separated part connected to the top of the magnet, usually called the top plate or front plate.

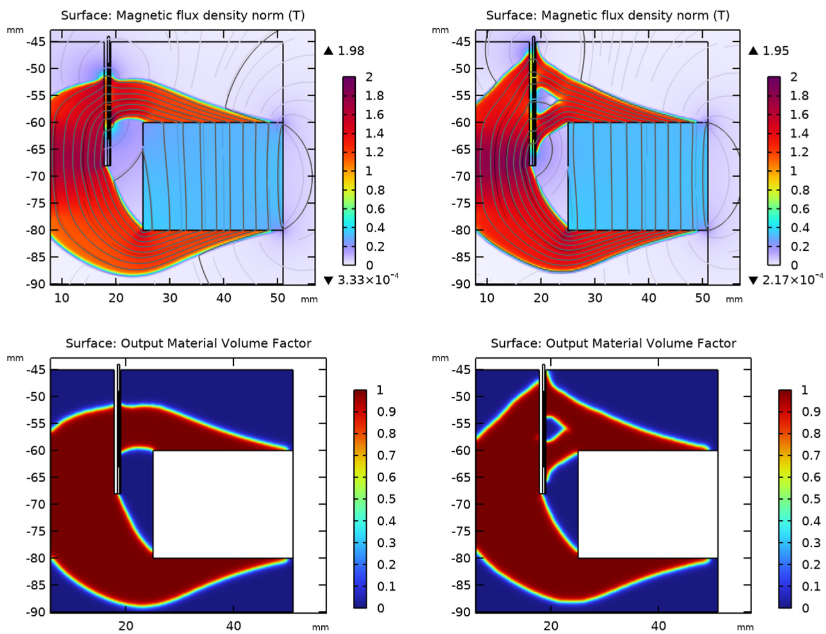

Figure 2: Magnetic flux density norm (top) and Output material volume factor (bottom) for the studies maximizing the BL factor at the resting position (left) and creating a flat BL curve (right)

The topology optimization study produces a density map that varies between the [0,1] interval. Ideally with all of the elements in the design space should go to the minimum or the maximum density in the range. The **Filter** dataset transforms this density map into a geometry by removing elements (or parts of elements) with a density below a certain threshold. By choosing an intermediate density value of 0.5, it is possible to obtain a geometry that can be used to validate the B-H relation used in the topology optimization step. Figure 3 shows the geometry resulting from applying the **Filter** dataset to the two optimization studies.

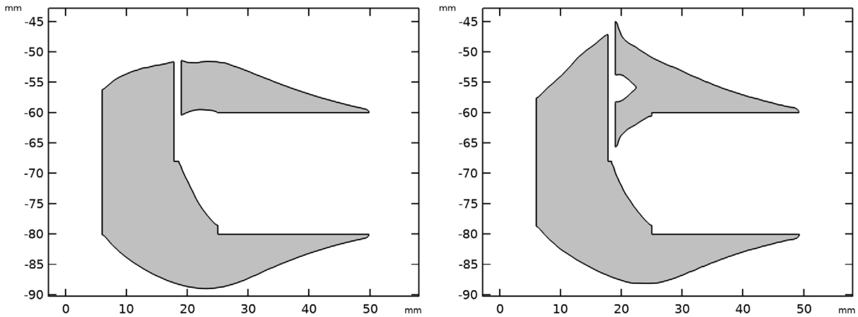

Figure 3: Filtered results for the studies maximizing the BL factor at the resting position (left) and creating a flat BL curve (right)

The filtered results of the second optimization setup is used in a validation step, where iron properties are applied to the areas/domains with density above the threshold and air properties are applied to the rest of the design space. Figure 4 shows that the differences between the optimization model and the validation model are minimal.

As a summary, Figure 4 shows the $\mathrm{BL}(x)$ curve of the different models. The horizontal axis represents the voice coil offset x (the axial displacement of the voice coil) and the vertical axis represents the BL factor. The figure also includes the BL curve from a traditional design, taken from the Loudspeaker Driver — Frequency-Domain Analysis model.

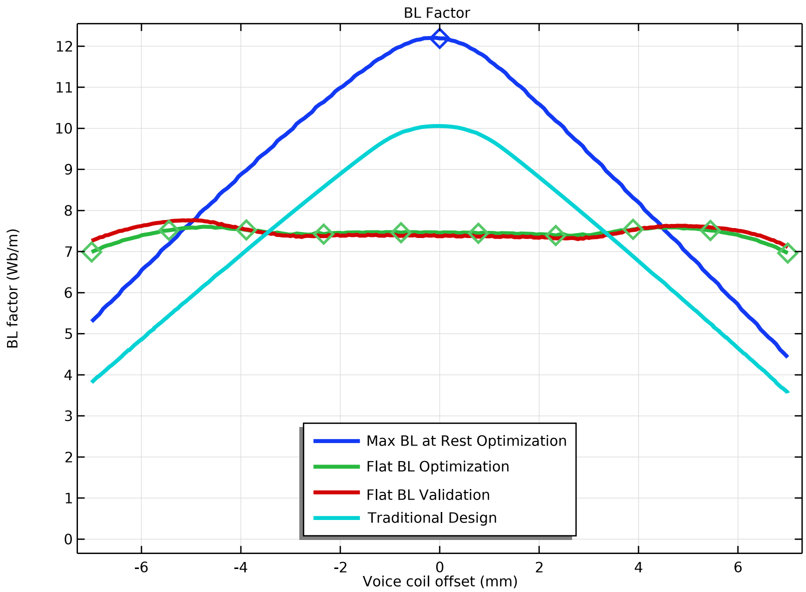

Figure 4: BL Curve comparison. The plot includes the BL curve of the Optimization maximizing the BL factor at the resting position (blue), the optimization creating a flat BL curve (green), the validation model using the results from the second optimization (red), and the results of a traditional design with similar dimensions and a larger iron volume (light blue).

Notes About the COMSOL Implementation

USING THE DEST() OPERATOR TO DERIVE THE BL CURVE

As the coil has the same permeability as the surrounding air, the magnetic field will be equivalent for every position of the voice coil. This means that it is possible to obtain the BL curve by just averaging/integrating the B field over the different positions of the voice coil using a single stationary case. This is implemented in the model by defining an integration operation over all possible locations of the voice coil. Then, the variable `coil_location_z` defined as `(z>(dest(z)-h_coil/2))*(z<(dest(z)+h_coil/2))` discerns whether the point should contribute to the integral or not. This logical variable will take the value of 1 when z is within the height of the coil around a given position. Note that the axial position is given by the z-coordinate in the model, while it is typically named x, hence the common name BL(x).

USING PROBE POINTS TO COMPUTE THE OPTIMIZATION OBJECTIVES

The objectives of the optimizations are defined using probe points. In the first optimization, a single point at the resting position of the coil is used to obtain the BL factor and maximize it during the optimization. In the second optimization, a series of points along the path of the BL curve, given by the parameter `n_points`, are used to compute the squared difference between the BL(x) factor at the points (x-locations) and the objective constant BL value, given by the parameter `BL_0`. The optimization minimizes this squared difference, thus making the BL(x) curve as flat as possible.

Application Library path: `Acoustics_Module/Optimization/magnetic_circuit_topology_optimization`

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>Electromagnetic Fields>Magnetic Fields (mf)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Stationary**.

6 Click **Done**.

GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

4 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

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

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

GLOBAL DEFINITIONS

Geometry Parameters

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, type `Geometry Parameters` in the **Label** text field.

Model Parameters

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `Model Parameters` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

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

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 Global Materials** in the window toolbar.

5 In the tree, select **AC/DC>Soft Iron (With Losses)**.

6 Click **Add to Global Materials** in the window toolbar.

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

GLOBAL DEFINITIONS

Generic Ferrite

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

2 In the **Settings** window for **Material**, type `Generic Ferrite` in the **Label** text field.

3 Click to expand the **Material Properties** section. In the **Material properties** tree, select **Basic Properties>Electrical Conductivity**.

4 Click **Add to Material**.

5 In the **Material properties** tree, select **Basic Properties>Relative Permittivity**.

6 Click **Add to Material**.

7 In the **Material properties** tree, select **Electromagnetic Models>Remanent Flux Density>Recoil permeability (murec)**.

8 Click **Add to Material**.

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

Property	**Variable**	**Value**	**Unit**	**Property group**
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic
Recoil permeability	murec_iso ; murecii = murec_iso, murecij = 0	1	1	Remanent flux density
Remanent flux density norm	normBr	B0	T	Remanent flux density

Equivalent mur of mat2, Soft Iron (With Losses)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Analytic**.

2 In the **Settings** window for **Analytic**, type `Equivalent mur of mat2, Soft Iron (With Losses)` in the **Label** text field.

3 In the **Function name** text field, type `mur1`.

4 Locate the **Definition** section. In the **Expression** text field, type `sqrt(Bx^2+By^2+eps[T^2])/mat2.BHCurve.BH_inv(sqrt(Bx^2+By^2+eps[T^2]))/mu0_const`.

5 In the **Arguments** text field, type `Bx, By`.

6 Locate the **Units** section. In the **Function** text field, type `1`.

7 In the table, enter the following settings:

Argument	**Unit**
Bx	T
By	T

8 Locate the **Plot Parameters** section. In the table, enter the following settings:

Argument	Lower limit	Upper limit	Unit
Bx	0	2	T
By	0	2	T

9 Click **Plot**.

DEFINITIONS

Area to Obtain the BL Factor

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `Area to Obtain the BL Factor` in the **Label** text field.

3 In the **Operator name** text field, type `int_BL`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Voice Coil Possible Locations**.

5 Locate the **Advanced** section. In the **Integration order** text field, type `30`.

6 Clear the **Compute integral in revolved geometry** check box.

Global Variables

1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Global Variables` in the **Label** text field.

3 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
BL_integrand	-mf.Br*N0*2*pi*r/(w_coil*h_coil)	$kg/(m\cdot s^2\cdot A)$	Integrand to obtain the BL factor
coil_location_z	(z>(dest(z)-h_coil/2))*(z<(dest(z)+h_coil/2))		Logical condition to discern the position of the coil

Point Variables

1 Right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Point Variables` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Point**.

4 From the **Selection** list, choose **All points**.

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

Name	Expression	Unit	Description
BL_point	int_BL(BL_integrand* coil_location_z)	Wb/m	BL Factor at Point

Point Probe - Objective 1

1 In the **Definitions** toolbar, click **Probes** and choose **Point Probe**.

2 In the **Settings** window for **Point Probe**, type `Point Probe - Objective 1` in the **Label** text field.

3 In the **Variable name** text field, type `obj_1`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Voice Coil Center at Resting Position**.

5 Locate the **Expression** section. In the **Expression** text field, type `BL_point`.

Point Probe - Objective 2

1 In the **Definitions** toolbar, click **Probes** and choose **Point Probe**.

2 In the **Settings** window for **Point Probe**, type `Point Probe - Objective 2` in the **Label** text field.

3 In the **Variable name** text field, type `obj_2`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Voice Coil Center Measuring Points**.

5 Locate the **Expression** section. In the **Expression** text field, type `(BL_point-BL_0)^2`.

6 In the **Definitions** toolbar, click **Optimization** and choose **Topology Optimization> Density Model**.

TOPOLOGY OPTIMIZATION

Density Model 1 (dtopo1)

1 In the **Settings** window for **Density Model**, locate the **Geometric Entity Selection** section.

2 From the **Selection** list, choose **Design Space**.

3 Locate the **Interpolation** section. From the p_{SIMP} list, choose **User defined**.

4 In the text field, type `10`.

5 From the θ_{min} list, choose **User defined**.

6 In the text field, type `0`.

7 Locate the **Control Variable Discretization** section. From the **Element order** list, choose **Constant**.

8 Locate the **Control Variable Initial Value** section. In the θ_0 text field, type `volfrac`.

MATERIALS

Air

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **More Materials>Material Link**.

2 In the **Settings** window for **Material Link**, type `Air` in the **Label** text field.

Topology Optimization

1 Right-click **Materials** and choose **More Materials>Material Link**.

2 In the **Settings** window for **Material Link**, type `Topology Optimization` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Design Space**.

4 Locate the **Link Settings** section. From the **Material** list, choose **Soft Iron (With Losses) (mat2)**.

Magnet

1 Right-click **Materials** and choose **More Materials>Material Link**.

2 In the **Settings** window for **Material Link**, type `Magnet` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Magnet**.

4 Locate the **Link Settings** section. From the **Material** list, choose **Generic Ferrite (mat3)**.

MAGNETIC FIELDS (MF)

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

2 In the **Settings** window for **Magnetic Fields**, click to expand the **Discretization** section.

3 From the **Magnetic vector potential** list, choose **Linear**.

Topology Optimization

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

2 In the **Settings** window for **Ampère's Law**, type `Topology Optimization` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Design Space**.

4 Locate the **Constitutive Relation B-H** section. From the μ_r list, choose **User defined**. From the μ_r list, choose **User defined**. In the associated text field, type `1+dtopo1.theta_p*(mur1(mf.Br,mf.Bz)-1)`.

Magnet

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

2 In the **Settings** window for **Ampère's Law**, type `Magnet` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Magnet**.

4 Locate the **Constitutive Relation B-H** section. From the **Magnetization model** list, choose **Remanent flux density**.

5 Specify the **e** vector as

0	r
0	phi
1	z

MESH 1

Mapped 1

1 In the **Mesh** toolbar, click **Mapped**.

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

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

4 From the **Selection** list, choose **Mapped Domains**.

Size 1

1 Right-click **Mapped 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Custom** button.

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

5 In the associated text field, type `mesh_size`.

Free Triangular 1

In the **Mesh** toolbar, click **Free Triangular**.

Size 1

1 Right-click **Free Triangular 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 **Design Space**.
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 `mesh_size`.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.
2 In the **Settings** window for **Size**, locate the **Element Size** section.
3 From the **Predefined** list, choose **Finer**.
4 Click **Build All**.

STUDY 1 - MAX BL AT REST OPTIMIZATION

1 In the **Model Builder** window, click **Study 1**.
2 In the **Settings** window for **Study**, type `Study 1 - Max BL at Rest Optimization` in the **Label** text field.

Topology Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Topology Optimization**.
2 In the **Settings** window for **Topology Optimization**, locate the **Optimization Solver** section.
3 In the **Maximum number of iterations** text field, type `20`.
4 Click **Add Expression** in the upper-right corner of the **Objective Function** section. From the menu, choose **Component 1 (comp1)>Definitions>comp1.obj_1 - Point Probe - Objective 1 - Wb/m**.
5 Locate the **Objective Function** section. From the **Type** list, choose **Maximization**.
6 From the **Objective scaling** list, choose **Initial solution based**.
7 Click **Add Expression** in the upper-right corner of the **Constraints** section. From the menu, choose **Component 1 (comp1)>Definitions>Density Model 1>Global>comp1.dtopo1.theta_avg - Average material volume factor**.
8 Locate the **Constraints** section. In the table, enter the following settings:

Expression	Lower bound	Upper bound
comp1.dtopo1.theta_avg		volfrac

9 Locate the **Output While Solving** section. From the **Probes** list, choose **None**.
10 In the **Study** toolbar, click **Get Initial Value**.

11 In the **Model Builder** window, click **Topology Optimization**.

12 In the **Settings** window for **Topology Optimization**, locate the **Output While Solving** section.

13 Select the **Plot** check box.

14 From the **Plot group** list, choose **Output material volume factor**.

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

RESULTS

Revolution 2D 1

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

2 Right-click **Results>Datasets>Revolution 2D 1** and choose **Delete**.

Filter - Max BL at Rest Optimization

1 In the **Model Builder** window, under **Results>Datasets** click **Filter**.

2 In the **Settings** window for **Filter**, type `Filter - Max BL at Rest Optimization` in the **Label** text field.

3 Locate the **Expression** section. In the **Expression** text field, type `if(isnan(dtopo1.theta_c),NaN,dtopo1.theta)`.

Threshold

1 In the **Model Builder** window, expand the **Results>Topology Optimization** node, then click **Threshold**.

2 In the **Threshold** toolbar, click **Plot**.

Magnetic Flux Density Norm (mf)

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

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

3 From the **View** list, choose **View 1**.

Surface 1

1 In the **Model Builder** window, expand the **Magnetic Flux Density Norm (mf)** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click to expand the **Range** section.

3 Select the **Manual color range** check box.

4 In the **Minimum** text field, type `0`.

5 In the **Maximum** text field, type `2`.

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

Magnetic Flux Density Norm (mf)

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

2 Drag and drop on **Topology Optimization**.

Max BL at Rest Optimization Results

1 In the **Model Builder** window, under **Results** click **Topology Optimization**.

2 In the **Settings** window for **Group**, type `Max BL at Rest Optimization Results` in the **Label** text field.

Output material volume factor

1 In the **Model Builder** window, click **Output material volume factor**.

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

3 From the **View** list, choose **View 1**.

Surface 1

1 In the **Model Builder** window, expand the **Output material volume factor** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `if(isnan(dtopo1.theta_c),NaN,dtopo1.theta)`.

4 Select the **Description** check box.

5 In the associated text field, type `Output Material Volume Factor`.

6 In the **Output material volume factor** toolbar, click **Plot**.

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 **Add Study** in the window toolbar.

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

STUDY 2 - FLAT BL OPTIMIZATION

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

2 In the **Settings** window for **Study**, type `Study 2 - Flat BL Optimization` in the **Label** text field.

Topology Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Topology Optimization**.

2 In the **Settings** window for **Topology Optimization**, locate the **Optimization Solver** section.

3 In the **Maximum number of iterations** text field, type 50.

4 Click **Add Expression** in the upper-right corner of the **Objective Function** section. From the menu, choose **Component 1 (comp1)>Definitions>comp1.obj_2 - Point Probe - Objective 2 - kg²·m²/(s⁴·A²)**.

5 Locate the **Objective Function** section. From the **Objective scaling** list, choose **Initial solution based**.

6 Click **Add Expression** in the upper-right corner of the **Constraints** section. From the menu, choose **Component 1 (comp1)>Definitions>Density Model 1>Global> comp1.dtopo1.theta_avg - Average material volume factor**.

7 Locate the **Constraints** section. In the table, enter the following settings:

Expression	Lower bound	Upper bound
comp1.dtopo1.theta_avg		volfrac

8 Locate the **Output While Solving** section. From the **Probes** list, choose **None**.

9 In the **Study** toolbar, click **Get Initial Value**.

10 In the **Model Builder** window, click **Topology Optimization**.

11 In the **Settings** window for **Topology Optimization**, locate the **Output While Solving** section.

12 Select the **Plot** check box.

13 From the **Plot group** list, choose **Output material volume factor 1**.

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

RESULTS

Revolution 2D 1

In the **Model Builder** window, under **Results>Datasets** right-click **Revolution 2D 1** and choose **Delete**.

Filter - Flat BL Optimization

1 In the **Model Builder** window, under **Results>Datasets** click **Filter**.

2 In the **Settings** window for **Filter**, type Filter - Flat BL Optimization in the **Label** text field.

3 Locate the **Expression** section. In the **Expression** text field, type `if(isnan(dtopo1.theta_c),NaN,dtopo1.theta)`.

Filter - Initial Geometry

1 Right-click **Filter - Flat BL Optimization** and choose **Duplicate**.

2 In the **Settings** window for **Filter**, type `Filter - Initial Geometry` in the **Label** text field.

3 Locate the **Expression** section. In the **Expression** text field, type `1`.

Threshold 1

1 In the **Model Builder** window, expand the **Results>Topology Optimization** node, then click **Threshold 1**.

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

3 From the **View** list, choose **View 1**.

4 In the **Threshold 1** toolbar, click **Plot**.

Magnetic Flux Density Norm (mf) 1

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

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

3 From the **View** list, choose **View 1**.

Surface 1

1 In the **Model Builder** window, expand the **Magnetic Flux Density Norm (mf) 1** node, then click **Surface 1**.

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

3 Select the **Manual color range** check box.

4 In the **Minimum** text field, type `0`.

5 In the **Maximum** text field, type `2`.

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

Magnetic Flux Density Norm (mf) 1

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

2 Drag and drop on **Topology Optimization**.

Flat BL Optimization Results

1 In the **Model Builder** window, under **Results** click **Topology Optimization**.

2 In the **Settings** window for **Group**, type `Flat BL Optimization Results` in the **Label** text field.

Output material volume factor 1

1 In the **Model Builder** window, click **Output material volume factor 1**.

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

3 From the **View** list, choose **View 1**.

Surface 1

1 In the **Model Builder** window, expand the **Output material volume factor 1** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `if(isnan(dtopo1.theta_c),NaN,dtopo1.theta)`.

4 Select the **Description** check box.

5 In the associated text field, type `Output Material Volume Factor`.

6 In the **Output material volume factor 1** toolbar, click **Plot**.

Filter - Flat BL Optimization

In the **Model Builder** window, under **Results>Datasets** right-click **Filter - Flat BL Optimization** and choose **Create Mesh Part**.

MESH PART 1

Import 1

In the **Model Builder** window, under **Global Definitions>Mesh Parts>Mesh Part 1** right-click **Import 1** and choose **Build Selected**.

RESULTS

Filter - Initial Geometry

In the **Model Builder** window, under **Results>Datasets** right-click **Filter - Initial Geometry** and choose **Create Mesh Part**.

MESH PART 2

Import 1

In the **Model Builder** window, under **Global Definitions>Mesh Parts>Mesh Part 2** right-click **Import 1** and choose **Build Selected**.

ADD COMPONENT

In the **Model Builder** window, right-click the root node and choose **Add Component> 2D Axisymmetric**.

GEOMETRY 2

1 In the **Settings** window for **Geometry**, locate the **Units** section.

2 From the **Length unit** list, choose **mm**.

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.

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

3 From the **Source** list, choose **Mesh**.

4 From the **Mesh** list, choose **Mesh Part 1**.

5 Click **Build Selected**.

Import 2 (imp2)

1 In the **Home** toolbar, click **Import**.

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

3 From the **Source** list, choose **Mesh**.

4 From the **Mesh** list, choose **Mesh Part 2**.

5 Click **Build Selected**.

DEFINITIONS (COMP2)

Area to Obtain the BL Factor 2

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `Area to Obtain the BL Factor 2` in the **Label** text field.

3 In the **Operator name** text field, type `int_BL2`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Voice Coil Possible Locations (Import 2)**.

5 Locate the **Advanced** section. In the **Integration order** text field, type `30`.

6 Clear the **Compute integral in revolved geometry** check box.

Global Variables 2

1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Global Variables 2` in the **Label** text field.

3 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
`BL_integrand`	`-mf2.Br*NO*2*pi*r/(w_coil*h_coil)`		`Integrand to obtain the BL factor`
`coil_location_z`	`(z>(dest(z)-h_coil/2))*(z<(dest(z)+h_coil/2))`		`Logical condition to discern the position of the coil`

MATERIALS

Air

1. In the **Model Builder** window, under **Component 2 (comp2)** right-click **Materials** and choose **More Materials>Material Link**.
2. In the **Settings** window for **Material Link**, type `Air` in the **Label** text field.

Iron

1. Right-click **Materials** and choose **More Materials>Material Link**.
2. In the **Settings** window for **Material Link**, type `Iron` in the **Label** text field.
3. Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Design Space (Import 1)**.

Magnet

1. Right-click **Materials** and choose **More Materials>Material Link**.
2. In the **Settings** window for **Material Link**, type `Magnet` in the **Label** text field.
3. Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Magnet (Import 2)**.
4. Locate the **Link Settings** section. From the **Material** list, choose **Generic Ferrite (mat3)**.

Iron (matlnk5)

1. In the **Model Builder** window, click **Iron (matlnk5)**.
2. In the **Settings** window for **Material Link**, locate the **Link Settings** section.
3. From the **Material** list, choose **Soft Iron (With Losses) (mat2)**.

ADD PHYSICS

1. In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.
2. Go to the **Add Physics** window.
3. In the tree, select **AC/DC>Electromagnetic Fields>Magnetic Fields (mf)**.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check boxes for **Study 1 - Max BL at Rest Optimization** and **Study 2 - Flat BL Optimization**.

5 Click **Add to Component 2** in the window toolbar.

6 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

MAGNETIC FIELDS 2 (MF2)

Iron

1 Right-click **Component 2 (comp2)>Magnetic Fields 2 (mf2)** and choose **Ampère's Law**.

2 In the **Settings** window for **Ampère's Law**, type `Iron` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Design Space (Import 1)**.

4 Locate the **Constitutive Relation B-H** section. From the **Magnetization model** list, choose **B-H curve**.

Magnet

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

2 In the **Settings** window for **Ampère's Law**, type `Magnet` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Magnet (Import 2)**.

4 Locate the **Constitutive Relation B-H** section. From the **Magnetization model** list, choose **Remanent flux density**.

5 Specify the **e** vector as

0	r
0	phi
1	z

MESH 2

Mapped 1

1 In the **Mesh** toolbar, click **Mapped**.

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

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

4 From the **Selection** list, choose **Mapped Domains (Import 2)**.

Size 1

1 Right-click **Mapped 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Custom** button.

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

5 In the associated text field, type `mesh_size`.

Free Triangular 1

In the **Mesh** toolbar, click **Free Triangular**.

Size 1

1 Right-click **Free Triangular 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 **Design Space (Import 1)**.

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 `mesh_size`.

MESH 1

Size

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

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 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Magnetic Fields (mf)**.

5 Click **Add Study** in the window toolbar.

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

STUDY 3

Step 1: Stationary

1 In the **Settings** window for **Stationary**, click to expand the **Results While Solving** section.

2 From the **Probes** list, choose **None**.

3 In the **Model Builder** window, click **Study 3**.

4 In the **Settings** window for **Study**, type `Study 3 - Flat BL Validation` in the **Label** text field.

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

RESULTS

Magnetic Flux Density Norm (mf2)

1 In the **Model Builder** window, expand the **Results>Topology Optimization** node, then click **Results>Magnetic Flux Density Norm (mf2)**.

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

3 From the **View** list, choose **View 1**.

Surface 1

1 In the **Model Builder** window, expand the **Magnetic Flux Density Norm (mf2)** node, then click **Surface 1**.

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

3 Select the **Manual color range** check box.

4 In the **Minimum** text field, type `0`.

5 In the **Maximum** text field, type `2`.

6 In the **Magnetic Flux Density Norm (mf2)** toolbar, click **Plot**.

Magnetic Flux Density Norm (mf2)

1 In the **Model Builder** window, click **Magnetic Flux Density Norm (mf2)**.

2 Drag and drop on **Topology Optimization**.

Output material volume factor 2, Threshold 2

1 In the **Model Builder** window, under **Results>Topology Optimization**, Ctrl-click to select **Output material volume factor 2** and **Threshold 2**.

2 Right-click and choose **Delete**.

Flat BL Validation

1 In the **Model Builder** window, under **Results** click **Topology Optimization**.

2 In the **Settings** window for **Group**, type `Flat BL Validation` in the **Label** text field.

Filter, Revolution 2D 1, Study 3 - Flat BL Validation/Solution 3 (4) (sol3)

1 In the **Model Builder** window, under **Results>Datasets**, Ctrl-click to select **Study 3 - Flat BL Validation/Solution 3 (4) (sol3)**, **Revolution 2D 1**, and **Filter**.

2 Right-click and choose **Delete**.

Traditional Design BL Curve

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

2 In the **Settings** window for **Table**, type `Traditional Design BL Curve` in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

BL Factor

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

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

3 Locate the **Plot Settings** section. Select the **x-axis label** check box.

4 In the associated text field, type `Voice coil offset (mm)`.

5 Select the **y-axis label** check box.

6 In the associated text field, type `BL factor (Wb/m)`.

7 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

8 Locate the **Legend** section. From the **Position** list, choose **Lower middle**.

Line Graph 1

1 Right-click **BL Factor** and choose **Line Graph**.

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

3 From the **Selection** list, choose **Voice Coil Center Possible Locations**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `int_BL(BL_integrand*coil_location_z)`.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `(z-z_coil)`.

7 Select the **Description** check box.

8 In the associated text field, type `Coil Offset`.

9 Click to expand the **Coloring and Style** section. Set the **Width** value to **3**.

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

11 Find the **Include** subsection. Clear the **Solution** check box.

12 Find the **Prefix and suffix** subsection. In the **Prefix** text field, type `Max BL at Rest Optimization`.

13 In the **BL Factor** toolbar, click **Plot**.

Line Graph 2

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

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

3 From the **Dataset** list, choose **Study 2 - Flat BL Optimization/Solution 2 (sol2)**.

4 Locate the **Legends** section. Find the **Prefix and suffix** subsection. In the **Prefix** text field, type `Flat BL Optimization`.

5 In the **BL Factor** toolbar, click **Plot**.

Line Graph 3

1 Right-click **Line Graph 2** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Study 3 - Flat BL Validation/Solution 3 (sol3)**.

4 Locate the **Selection** section. From the **Selection** list, choose **Voice Coil Center Possible Locations (Import 2)**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `int_BL2(BL_integrand*coil_location_z)`.

6 Locate the **Legends** section. Find the **Prefix and suffix** subsection. In the **Prefix** text field, type `Flat BL Validation`.

7 In the **BL Factor** toolbar, click **Plot**.

Annotation 1

1 In the **Model Builder** window, right-click **BL Factor** and choose **Annotation**.

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

3 Clear the **Show point** check box.

4 In the **BL Factor** toolbar, click **Plot**.

Table Graph 1

1 Right-click **BL Factor** and choose **Table Graph**.

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

3 From the **Table** list, choose **Traditional Design BL Curve**.

4 In the **BL Factor** toolbar, click **Plot**.

5 Click to expand 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
`Traditional Design`

8 Locate the **Coloring and Style** section. Set the **Width** value to **3**.

9 In the **BL Factor** toolbar, click **Plot**.

Point Graph 1

1 Right-click **BL Factor** and choose **Point Graph**.

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

3 From the **Selection** list, choose **Voice Coil Center at Resting Position**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `int_BL(BL_integrand*coil_location_z)`.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `(z-z_coil)`.

7 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

8 From the **Color** list, choose **Cycle (reset)**.

9 Set the **Width** value to **6**.

10 Find the **Line markers** subsection. From the **Marker** list, choose **Diamond**.

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

12 In the **BL Factor** toolbar, click **Plot**.

Point Graph 2

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

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

3 From the **Dataset** list, choose **Study 2 - Flat BL Optimization/Solution 2 (sol2)**.

4 Locate the **Selection** section. From the **Selection** list, choose **Voice Coil Center Measuring Points**.

5 In the **BL Factor** toolbar, click **Plot**.

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

7 Click **Define custom colors**.

8 Set the RGB values to 85, 200, and 103, respectively.

9 Click **Add to custom colors**.

10 Click **Show color palette only** or **OK** on the cross-platform desktop.

11 In the **BL Factor** toolbar, click **Plot**.

Iron Volume

1 In the **Results** toolbar, click **Evaluation Group**.

2 In the **Settings** window for **Evaluation Group**, type `Iron Volume` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **None**.

Surface Measurement 1

1 In the **Iron Volume** toolbar, click **Measure** and choose **Surface Measurement**.

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

3 From the **Dataset** list, choose **Filter - Max BL at Rest Optimization**.

4 Locate the **Measurement Settings** section. From the **Unit** list, choose **cm^3**.

5 Select the **Description** check box.

6 In the associated text field, type `Max BL Opt`.

7 In the **Iron Volume** toolbar, click **Evaluate**.

Iron Volume

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

Surface Measurement 2

1 In the **Iron Volume** toolbar, click **Measure** and choose **Surface Measurement**.

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

3 From the **Dataset** list, choose **Filter - Flat BL Optimization**.

4 Locate the **Measurement Settings** section. From the **Unit** list, choose **cm^3**.

5 Select the **Description** check box.

6 In the associated text field, type `Flat BL Opt`.

7 In the **Iron Volume** toolbar, click **Evaluate**.

Iron Volume

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

Surface Measurement 3

1 In the **Iron Volume** toolbar, click **Measure** and choose **Surface Measurement**.

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

3 From the **Dataset** list, choose **Study 3 - Flat BL Validation/Solution 3 (sol3)**.

4 Locate the **Selection** section. Click to select the **Activate Selection** toggle button.

5 Select Domains 3 and 10 only.

6 Locate the **Measurement Settings** section. From the **Unit** list, choose **cm^3**.

7 Select the **Description** check box.

8 In the associated text field, type `Flat BL Validation`.

9 In the **Iron Volume** toolbar, click **Evaluate**.

Geometry Modeling Instructions

If you want to create the geometry yourself, follow these steps.

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 Click **Done**.

GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

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 Click **Load from File**.

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

GEOMETRY 1

Air

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

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

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

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

5 Locate the **Position** section. In the **z** text field, type `z_design+h_design/2-h_air/2`.

6 Click **Build Selected**.

Design Space with Magnet and Coil Gap

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

2 In the **Settings** window for **Rectangle**, type `Design Space with Magnet and Coil Gap` in the **Label** text field.

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

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

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

6 In the **z** text field, type `z_design`.

7 Click **Build Selected**.

Voice Coil Gap

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

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

3 Locate the **Size and Shape** section. In the **Width** text field, type `w_coil+w_gap_i+w_gap_o`.

4 In the **Height** text field, type `h_coil+2*z_offset`.

5 Locate the **Position** section. In the **r** text field, type `r_coil-w_gap_i-w_coil/2`.

6 In the **z** text field, type `z_coil-h_coil/2-z_offset`.

7 Click **Build Selected**.

Design Space with Magnet

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 In the **Settings** window for **Difference**, type `Design Space with Magnet` in the **Label** text field.

3 Select the object **r2** only.

4 Locate the **Difference** section. Find the **Objects to subtract** subsection. Click to select the **Activate Selection** toggle button.

5 Select the object **r3** only.

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

7 Click **Build Selected**.

Magnet

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

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

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

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

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

6 In the **z** text field, type `z_magnet`.

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

8 Click **Build Selected**.

Voice Coil Possible Locations

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

2 In the **Settings** window for **Rectangle**, type `Voice Coil Possible Locations` in the **Label** text field.

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

4 In the **Height** text field, type `h_coil+2*z_offset`.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

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

7 In the **z** text field, type `z_coil`.

8 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (mm)
Layer 1	h_coil/2

9 Select the **Layers on top** check box.

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

11 Click **Build Selected**.

Voice Coil Center Possible Locations

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

2 In the **Settings** window for **Line Segment**, type `Voice Coil Center Possible Locations` in the **Label** text field.

3 Locate the **Starting Point** section. From the **Specify** list, choose **Coordinates**.

4 In the **r** text field, type `r_coil`.

5 In the **z** text field, type `z_coil-z_offset`.

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

7 In the **r** text field, type `r_coil`.

8 In the **z** text field, type `z_coil+z_offset`.

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

10 Click **Build Selected**.

Lowest Voice Coil Center Point

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

2 In the **Settings** window for **Point**, type `Lowest Voice Coil Center Point` in the **Label** text field.

3 Locate the **Point** section. In the **r** text field, type `r_coil`.

4 In the **z** text field, type `z_coil-z_offset`.

5 Click **Build Selected**.

Voice Coil Center Measuring Points

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

2 In the **Settings** window for **Array**, type `Voice Coil Center Measuring Points` in the **Label** text field.

3 Select the object **pt1** only.

4 Locate the **Size** section. In the **z size** text field, type `n_points`.

5 Locate the **Displacement** section. In the **z** text field, type `2*z_offset/(n_points-1)`.

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

7 From the **Show in physics** list, choose **Point selection**.

8 Click **Build Selected**.

Voice Coil Center at Resting Position

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

2 In the **Settings** window for **Point**, type `Voice Coil Center at Resting Position` in the **Label** text field.

3 Locate the **Point** section. In the **r** text field, type `r_coil`.

4 In the **z** text field, type `z_coil`.

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

6 Click **Build Selected**.

Form Union (fin)

1 In the **Model Builder** window, click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, click **Build Selected**.

Mapped Domains

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

2 In the **Settings** window for **Union Selection**, type `Mapped Domains` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Add**.

4 In the **Add** dialog box, in the **Selections to add** list, choose **Magnet** and **Voice Coil Possible Locations**.

5 Click **OK**.

Design Space

1 In the **Geometry** toolbar, click **Selections** and choose **Difference Selection**.

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

3 Locate the **Input Entities** section. Click **Add**.

4 In the **Add** dialog box, select **Design Space with Magnet** in the **Selections to add** list.

5 Click **OK**.

6 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.

7 Click **Add**.

8 In the **Add** dialog box, select **Magnet** in the **Selections to subtract** list.

9 Click **OK**.