Simulating a variable-gap inductor

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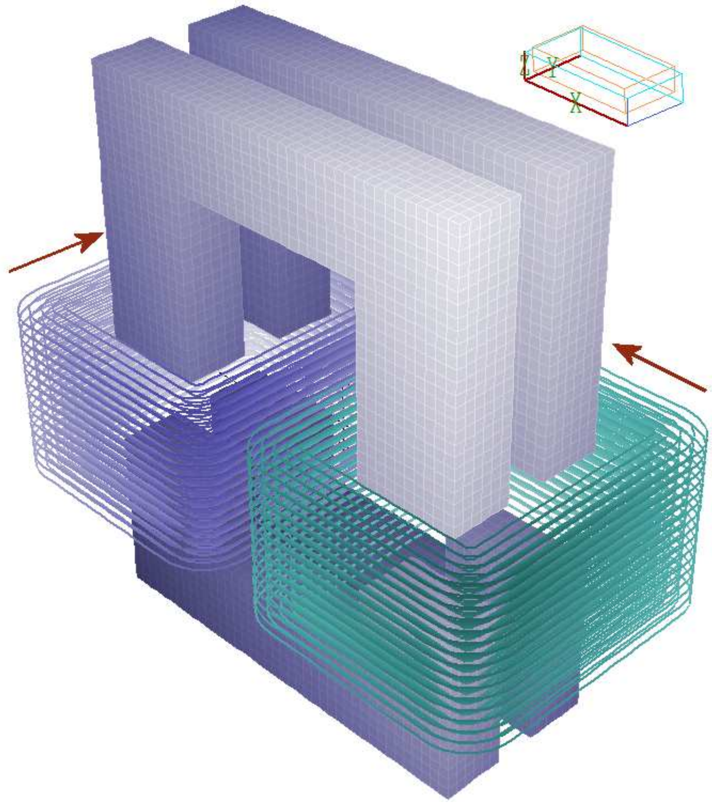

Figure 1: High-voltage, variable-gap inductor. Two coils in series encircle the gaps between upper and lower ferrite poles. Arrows show the relative direction of current flow. The figure was prepared by loading both coil and 3D mesh information in **MagWinder**.

Magnum, our three-dimensional software suite for magnetic devices, accepts two types of input information: 1) the geometry and physical properties of magnetically active structures (*e.g.*, permanent magnets, soft iron poles,...) and 2) the geometry and currents of drive coils. Magnetic structures are defined by **Geometer** and **MetaMesh** and drive coils by **MagWinder**. This tutorial reviews techniques for integrating the data and intoduces the new *COILBOX* model of **MagWinder**. We will follow the steps in a solution for the device shown in Fig. 1, a high-voltage variable-gap inductor. Two coils connected in series encircle the gaps between ferrite poles to form a magnetic circuit. Each coil has 7440 turns. With reference to the coordinate system of Fig. 1, the coils were fabricated on a rectangular mandrel with lengths $L_x = 17.0$" and $L_y = 20.0$". The windings have thickness $W = 5.0$" with height $L_z = 16.0$". The gap between the poles has width 4.0".

To begin, we will create a file to define the drive current elements. Run **Magwinder** and click the *New coil assembly* tool (or choose the menu com-

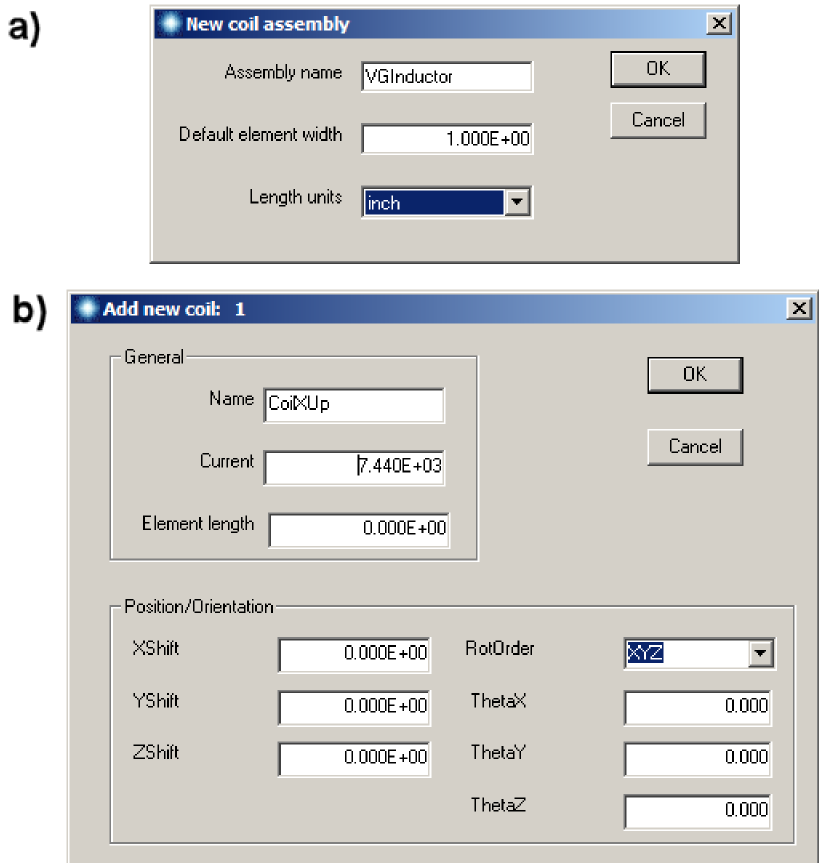

Figure 2: *a*) Dialog to start a new coil assembly. *b*) Dialog to add a coil to the assembly.

mand *File/New coil assembly*). Fill in the values shown in Fig. 2*a*. The quantity *Default element width* ($D_s = 1.0$") is the length and diameter of the cylindrical elements that represent the coil. The quantity will be used in the *COILBOX* model to determine how many model filaments are used to approximate the 7440 turn coils.[1] Next, click the *New coil* tool (*Build/New coil*) and fill in the values of Fig. 2*b*. We will start with the coil on the right side of Fig. 1 and then duplicate it, changing the position and current direction of the new coil.

Coils are composed of part models carrying equal current. Ideally, the models are geometrically connected to form a circuit. Click the *Add part* tool (*Build/Add part*) to open the dialog of Fig. 3. With the *COILBOX* model,

[1]Individual values of D_s may be assigned to coils to override the assembly default. The assembly is regenerated when global or local values of D_s are changed in the interactive environment.

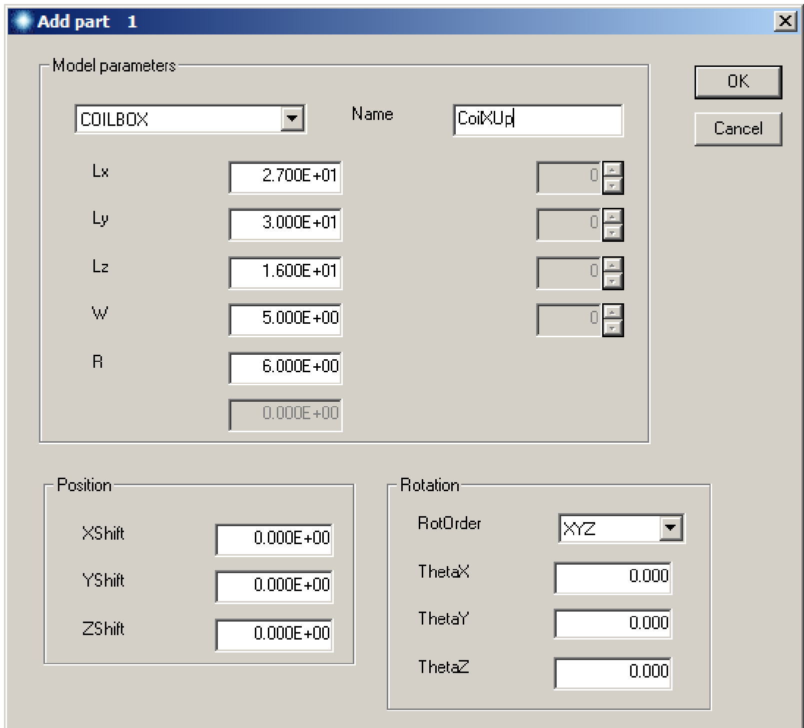

Figure 3: Dialog to add a *COILBOX* part to the first coil.

only a single part model is needed to define the complete coil. Figure 4 shows the dimension parameters for the model. In this case, the outer width L_x equals 27.0", the mandrel length plus $2W$. Similarly, $L_y = 30.0$". The width W is 5.0". When $R = W$, the innermost windings make a sharp 90° bend. We will use $R = 6.0$" to radius the mandrel. Fill in the values shown in Fig. 3 and click *OK* to exit the dialog. Use the *Save coil file* tool (*File/Save coil file*) to back up the work under the name `VGInductorSingle.CDF`.

Figure 5 shows the state of the program before we displace the coil and add another one. Before proceeding, click the *Grid control* tool (*Plot/Grid control*) to open a dialog. By default, the coordinate system origin is set to the center of mass of the current set of elements. Instead, we will clamp the origin at (0.0,0.0,0.0). Check the *Fix origin* box, accept the current values of the original position and click *OK* to exit the dialog. The next step is to move the coil 15.0" in the $+x$ direction. Click the *Edit part* tool (*Build/Edit part*) and select the single available part. The dialog appears with the values you have already entered. Change the value in the *XShift* box to 15.0" and click *OK* to exit.

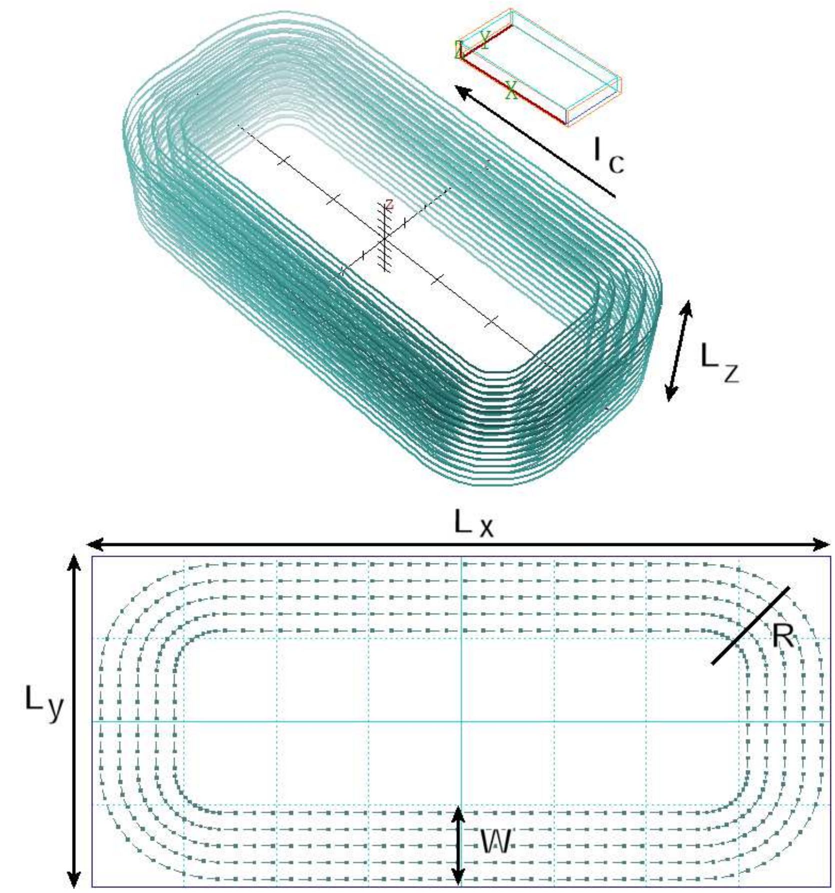

Figure 4: Parameter definitions for the *COILBOX* part model.

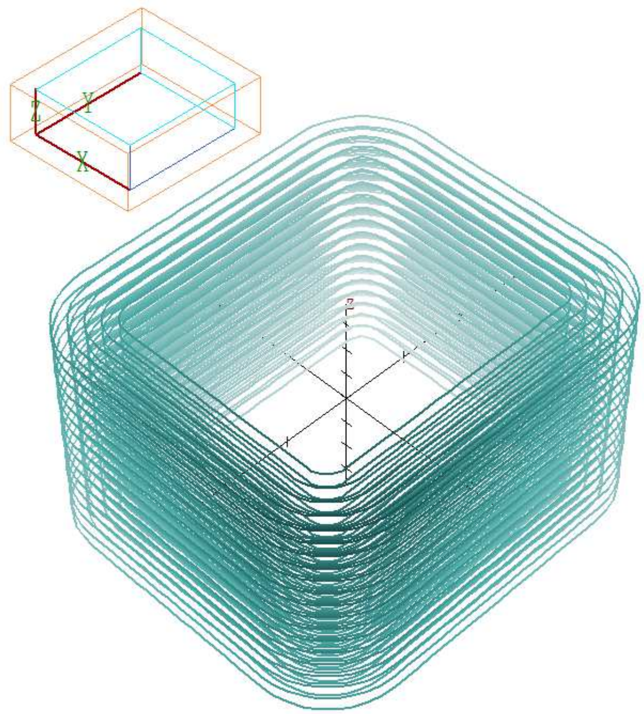

Figure 5: Elements of the first coil before addition of a displacement.

To build the second coil, click the *Coil management* tool (*Build/Coil management*) to open the dialog of Fig. 6. Push the *Duplicate coil* button and pick Coil 1. When the entry for the second coil appears, change the name to CoilXDn. As shown in Fig. 1, the current for Coil 2 flows in the direction opposite to that of Coil 1. One way to accomplish this is to set the current to -7440.0 A. When you exit the dialog, the display shows the two coils overlapped.

The next operation is to move Coil 2 into position. The two options are 1) to add a global shift to the coil or 2) to shift the position of *COILBOX* model in Coil 2. We will choose the latter to preserve the symmetry of the setup. The status bar at the bottom of the window shows that Coil 2 is the *current* coil. Therefore, part editing operations are applied to this coil. Click the *Edit part* tool and select the *COILBOX*. Change the part name to *CoilXDn* and set $XShift = -15$". Both coils are displayed in their proper positions when you click *OK* to exit the dialog.

Before saving the coil and element files, we can check that the currents are in the correct direction. Click the *Toggle 2D/3D* tool (*Plot/Toggle 2D/3D*). If necessary, click the *Z normal* tool and to obtain the view of Fig. 7. Then click the *Arrow plot* tool to show the current flow. The figure confirms that B_z points out of the page on the right and in to the page on the left.

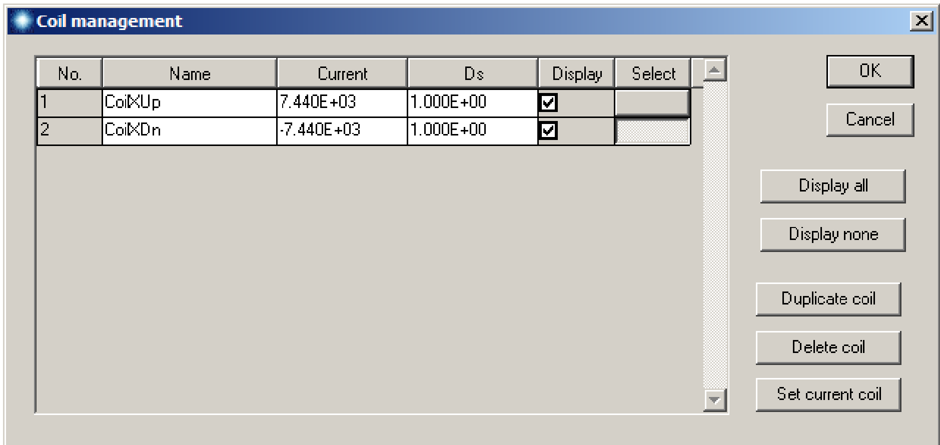

Figure 6: Coil management dialog.

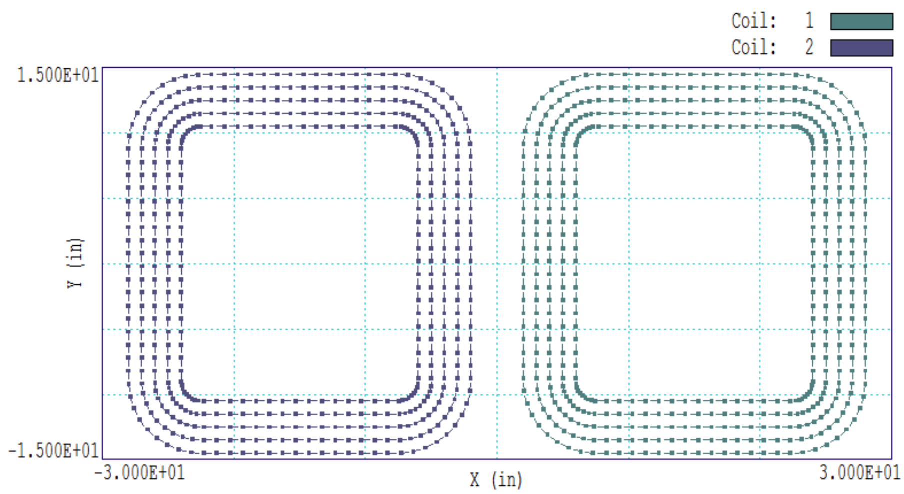

Figure 7: Checking current flow directions in a 2D view.

To conclude this section of the work, click the *Save coil file* tool to create the file `VGInductor.CDF` and the *Save element file* tool to write the file `VGInductor.WND`. The first file saves information from the interactive session and can be modified to change the solution parameters. The second file serves as input to the **Magnum** solution.

For information, we will explore an alternative to the interactive environment. Click the *Load coil file* tool and reload the file `VGInductorSingle.CDF` that you created earlier. Next, pick the menu selection *File/Edit coil file*. In the editor window, select and copy the coil section (between the entries *COIL* and *END*) and paste it before the *ENDFILE* command. Change the name to *CoilXDn* and the current to -7440.0 A. Add the line

```
Shift: 15.0 0.0 0.0
```

to the first coil and

```
Shift: -15.0 0.0 0.0
```

to the second. Then save the results as `VGInductorAlt.CDF`. Load this file into **MagWinder** to confirm that the resulting elements are the same as those of `VGInductor.CDF`. It is not necessary to use the internal program editor. Script modifications may be performed with any text editor or even a Python script for automated runs. They offer a quick way to make small changes in a calculation.

We next turn to the second task, definition of a 3D mesh for the **Magnum** calculation. The required data are the boundaries of the solution volume and the indentification of elements to represent the large ferrite cores. Because the emphasis of this tutorial is on **MagWinder**, we will keep the discussion brief. The ferrite cores can be represented as extrusions of thickness 6.0" with the outlines shown Fig. 7. They can be conveniently represented in **Geometer/MetaMesh** using the *EXTRUSION* model. The default orientation for the model is to associate the vertical direction with y and the horizontal direction with x. Therefore, we need to rotate the parts about the x axis to match the orientations of the Fig. 1. Run **Geometer** and click the tool *Start a new MetaMesh script* to open the dialog of Fig. 9. Fill in the name and mesh dimensions as shown. The mesh dimensions give sufficient clearance so that the boundaries have negligible effect on the fields near the gaps.

Extrusions are based on *outlines*, representations of the cross-section boundary by a series of line and arc vectors. The **Geometer** *Outline Editor* is an easy way to create one. It features an easy-to-use 2D CAD environment with automatic checks of validity. The **MetaMesh** manual reviews operations with walk-through examples. Figure 10 shows creation of the upper pole outline. Once an outline is complete, it can be saved as a file for future use. For brevity, we will continue under the assumption that you have followed the procedure at the end of this tutorial to create two outline files. Run **Geometer** and click *OUTLINE* in the main menu to enter the *Outline Editor*. Click the *Load outline* tool and load the file `UpperPole.OTL`. Then load the file `LowerPole.OTL`. The two outlines are now available in the program to define extrusions or turnings. Then click *Return* to close the editor and return to the main menu.

For clarity, pick *Edit/Edit region names* and change the name of Region 2 to *Ferrite*. Now click the *Add part* tool to open the dialog of Fig. 10 . Fill in the values shown (Part type: *Extrusion*, Part name: *UpperPoleUp*, Height: 6.0", Path: *UpperPole*, YShift: 5.0 and XRotation: 90^o) and exit

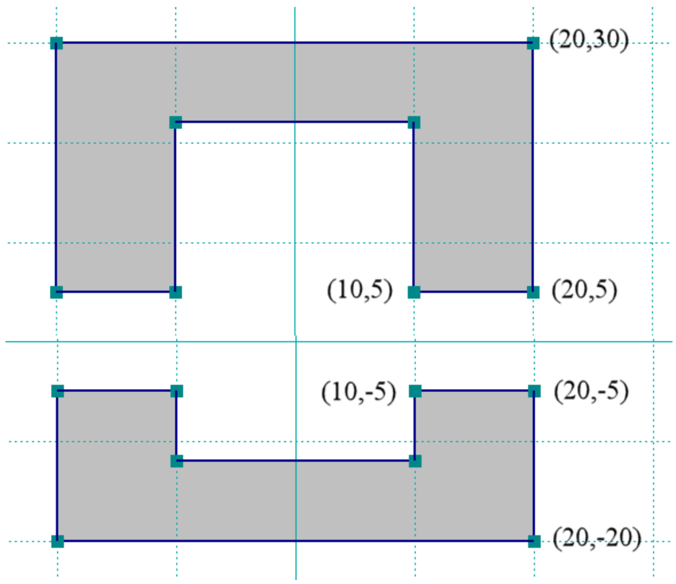

Figure 8: Outlines of the extruded ferrite cores in the x-y plane with coordinates.

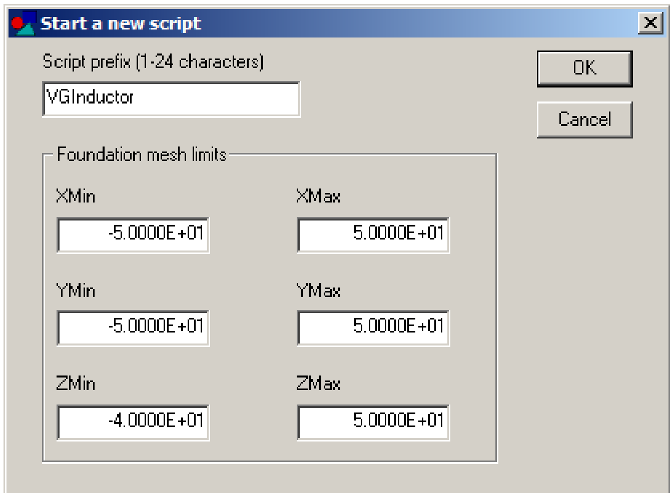

Figure 9: **Geometer** dialog to initiate a new **MetaMesh** script.

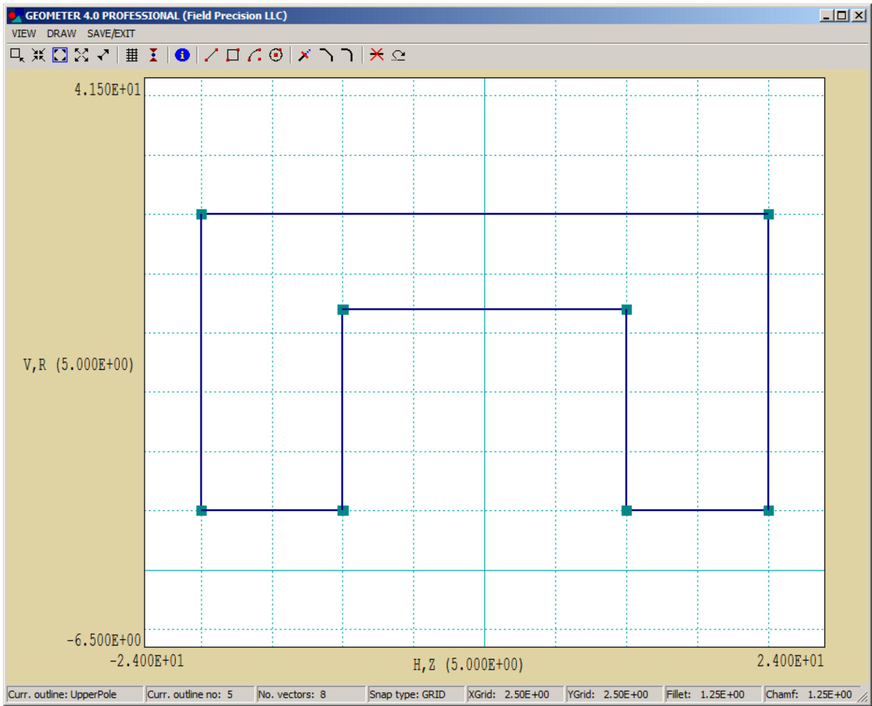

Figure 10: Creating the upper pole cross section in the **Geometer** *Outline Editor*.

the dialog. Next pick *Edit/Select part(s)* and select *UpperPoleUp*. Then pick *Edit/Duplicate selected* to make a copy of the pole. Click on *Edit part* and pick the new part. Change its name to *UpperPoleDn* and set $YShift = -5.0$".Follow similar procedures for the two lower pole parts to complete the assembly. Then save the results as `VGInductor.MIN`.

Run **MetaMesh**, process the script and save the file `VGInductor.MDF`. The script for the **Magnum** run (`VGInductor.GIN`) is simple:

```
SolType = STANDARD
Mesh = VariableGap
Source = VariableGap
DUnit =   3.937000E+01
ResTarget =   5.000000E-09
MaxCycle =   2500
CheckIron = Off
Parallel 4
* Region 1: SOLUTIONVOLUME
  Mu(1) =   1.000000E+00
* Region 2: CORE
  Mu(2) =   5.000000E+02
EndFile
```

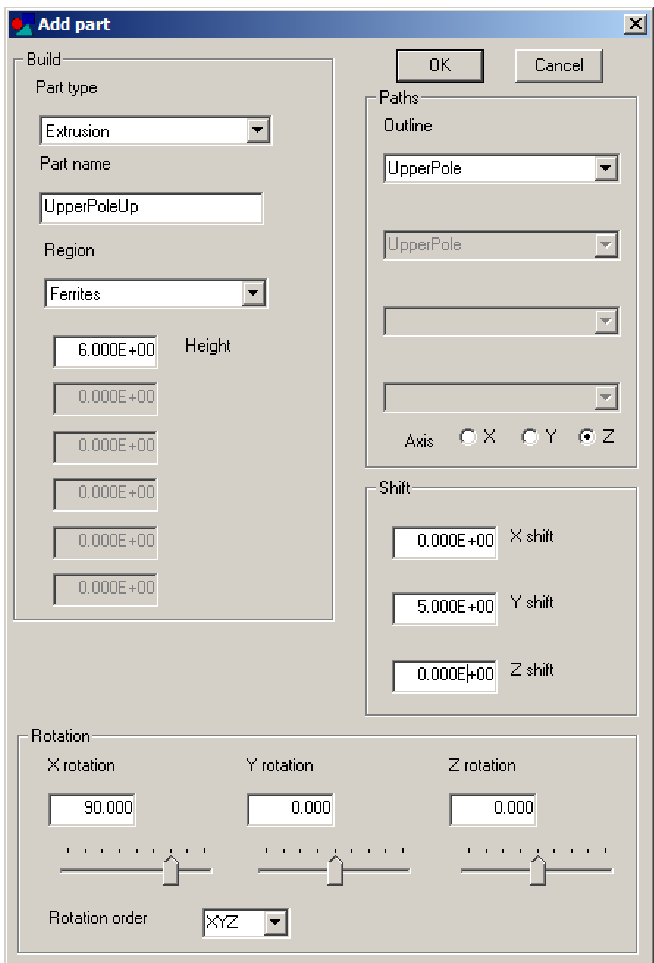

Figure 11: **Geometer** dialog to add a part to the assembly showing parameters for the pole in the $+y$ direction.

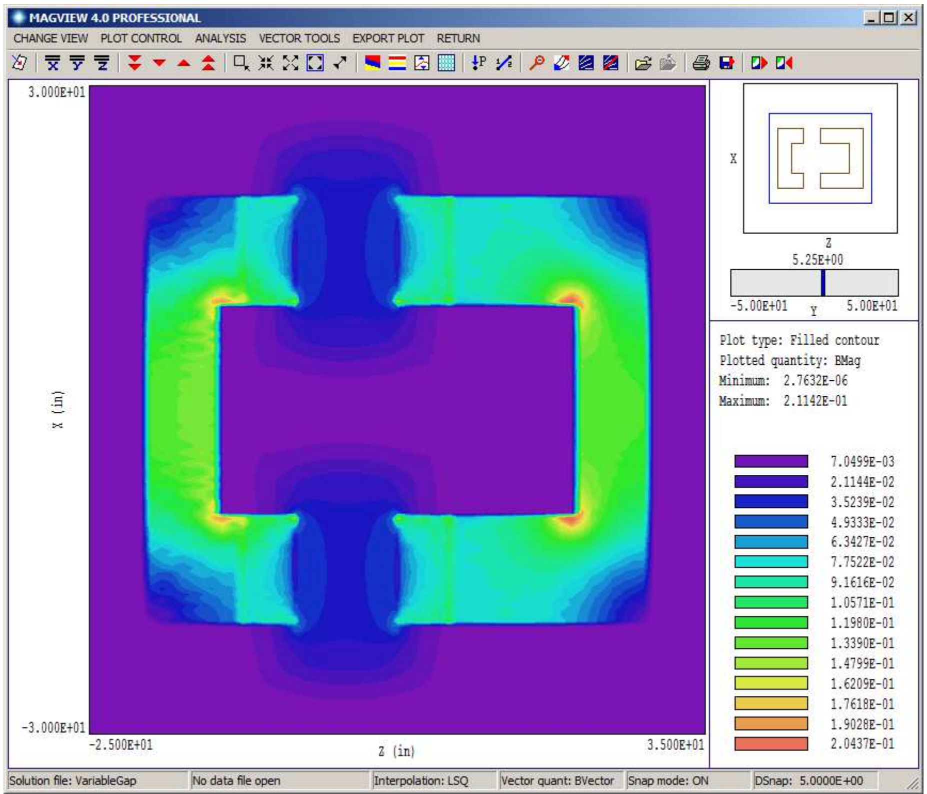

Figure 12: **MagView** display of $|\mathbf{B}|$ in the midplane of one of the pole sets.

The file could be prepared interactively in **Magnum** or directly with a text editor. The command *CheckIron = Off* saves run time when we can be sure that drive current elements do not pass through iron elements (Fig. 1). The *Parallel* command, which functions only in the Pro version of **Magnum**, substantially reduces the run time. The value of $\mu_r = 500$ for the ferrite is a good average for field levels below saturation. The **Magnum** run with 559,440 uniform elements of size 1.0” took 52 seconds. Figure 11 shows field levels through the gap in a plane passing through the center of one gap.

The main goal of the calculation is to find the inductance of the assembly. With a current of 1.0 A through each of the 7440 turn coils, the inductance is related to the total magnetic field energy in the assembly by $L = 2W$. We can use **MagView** to find the energy. Run the program, click the *Load solution file* tool (*File/Load solution file*) and read the **Magnum** output file `VGINDUCTOR.GOU`. In the main menu, pick the entry *Analysis/Volume integrals*. At the prompt, save the data to `VGInductor.DAT`. For the baseline solution with 1.0” elements, the predicted inductance is $L = 124.3$ H, close to a reported measured value of 133 H. We can use the solution setup to make tests of sensitivity of the results to assumed properties of the core and the

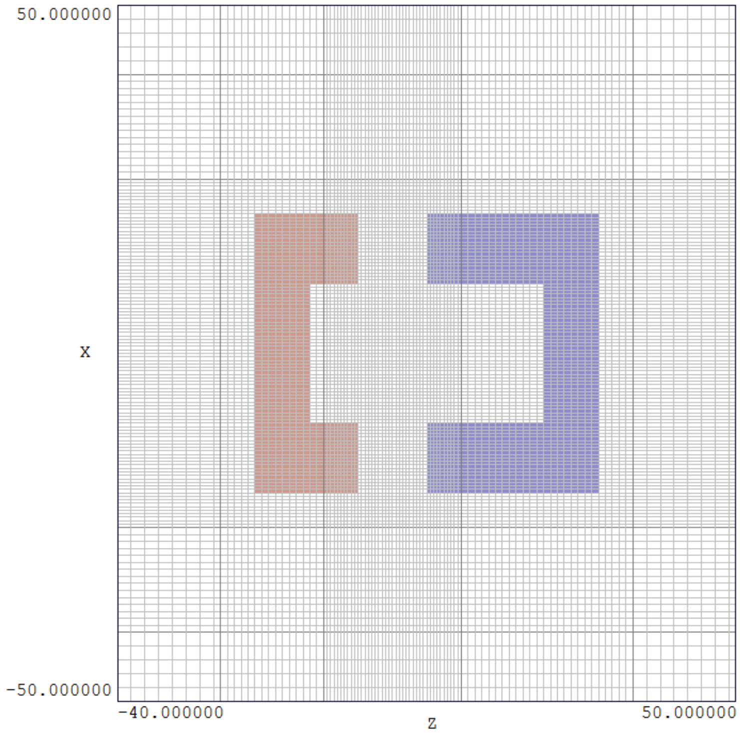

Figure 13: Refined foundation mesh

element size. The inductance drops to 114.4 H when $\mu_r = 100$ and equals 127.8 when $\mu_r = 1000$. A solution with the foundation mesh of Fig. 12 was made to check the effect of element size on the calculated inductance. The fundation mesh had small elements (0.5") around the air gap and large elements (2.0") near the boundaries. In this case, the number of elements was 1,631,840 and the run time was 196 seconds. The correspond predicted inductance was $L = 125.9$ H, a difference of only 0.8% from the uniform element run.

The calculation approximated the geometry of the physical system and showed good absolute agreement with the measured inductance. The prime advantage of simulations is the ability to make changes easily and see the consequences. As a demonstration, the fine mesh setup was used to determine the effect of gap size on inductance. Variations were easily effected by adding shift operations in the z direction to the ferrite poles, either through the interactive environment of **Geometer** or by directly editing the **MetaMesh** input file. For the demonstration, the upper and lower poles were moved to maintain average position of the gap within the coils. Figure 14 shows the results.

To conclude, use this procedure to create outline files for the upper and lower pole pieces for input to **Geometer**. Copy this section, paste it into a

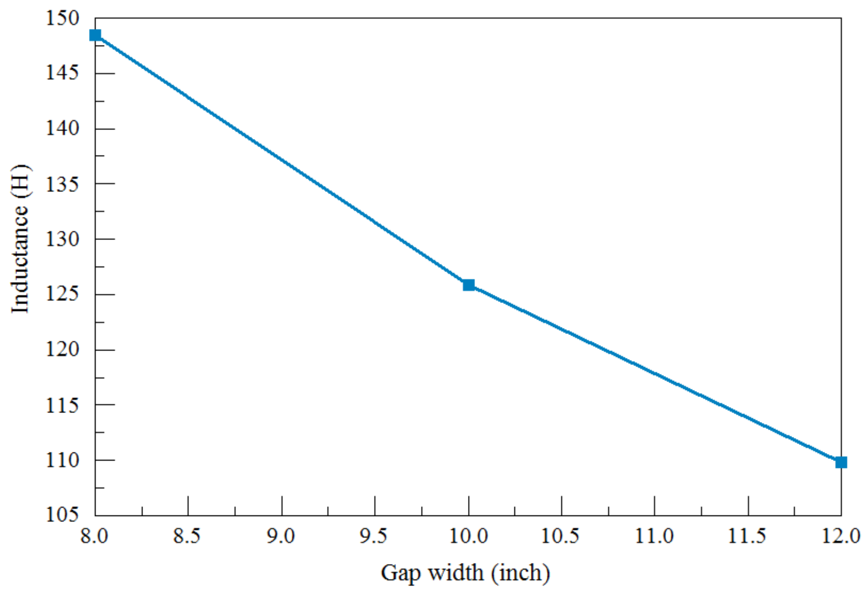

Figure 14: Variation of inductance with gap spacing.

text editor and save the result to your work directory as `UpperPole.OTL`:

```
* Upper pole for the VGInductor example
      L    1.0000E+01  5.0000E+00  2.0000E+01  5.0000E+00
      L    2.0000E+01  5.0000E+00  2.0000E+01  3.0000E+01
      L    2.0000E+01  3.0000E+01 -2.0000E+01  3.0000E+01
      L   -2.0000E+01  3.0000E+01 -2.0000E+01  5.0000E+00
      L   -2.0000E+01  5.0000E+00 -1.0000E+01  5.0000E+00
      L   -1.0000E+01  5.0000E+00 -1.0000E+01  2.2000E+01
      L   -1.0000E+01  2.2000E+01  1.0000E+01  2.2000E+01
      L    1.0000E+01  2.2000E+01  1.0000E+01  5.0000E+00
END
```

Save this information as `LowerPole.OTL`:

```
* Lower pole for the VGInductor example
      L    1.0000E+01 -5.0000E+00  2.0000E+01 -5.0000E+00
      L    2.0000E+01 -5.0000E+00  2.0000E+01 -2.0000E+01
      L    2.0000E+01 -2.0000E+01 -2.0000E+01 -2.0000E+01
      L   -2.0000E+01 -2.0000E+01 -2.0000E+01 -5.0000E+00
      L   -2.0000E+01 -5.0000E+00 -1.0000E+01 -5.0000E+00
      L   -1.0000E+01 -5.0000E+00 -1.0000E+01 -1.2000E+01
      L   -1.0000E+01 -1.2000E+01  1.0000E+01 -1.2000E+01
      L    1.0000E+01 -1.2000E+01  1.0000E+01 -5.0000E+00
END
```