Using Magnum to find forces in a latching solenoid

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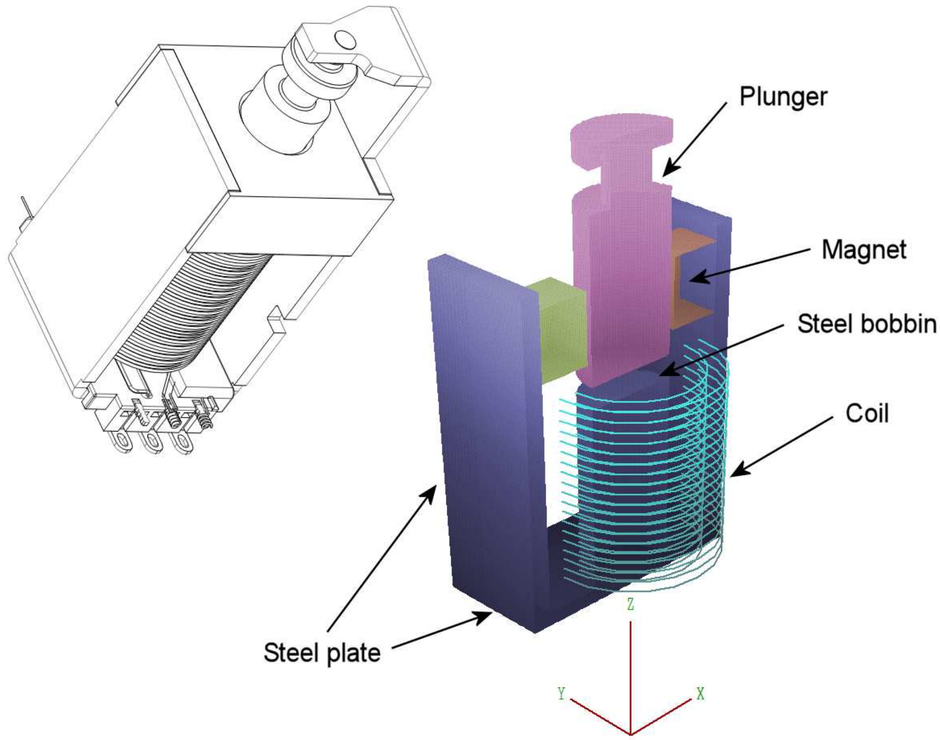

Figure 1: Latching solenoid assembly – drawing and three-dimensional mesh. The parts are displayed in the space $y > 0.0$ mm and the coil in $y < 0.0$ mm. The plunger has diameter 10.0 mm and length 28.0 mm.

I was recently asked by a manufacturer to prepare a demonstration showing how to use **Magnum** to characterize forces in a latching solenoid. This provided a good opportunity to exercise the force calculation capabilities of MagView. Input files with the prefix `LATCHING_SOLENOID` are included in the example library.

Figure 1 shows a drawing of the solenoid assembly and the mesh created by **MetaMesh**. The neodymium-iron permanent magnets are magnetized in the direction pointing toward the plunger. They provide a resting holding force to keep the plunger in contact with the steel bobbin. Depending on the current polarity, the coil may work in opposition to the permanent magnet to unlatch the solenoid or it may assist the permanent magnet to pull in the plunger.

Construction of the mesh was was straightforward. The `BOX` model was used to represent the steel plates and the magnets. The bobbin was a `CYLINDER` and the plunger was a `TURNING`. I picked the direction of plunger motion along z so it was not necessary to rotate the part. The `SHIFT` command was used to move the plunger back and forth. The coil definition

Table 1: Contents of the file LATCHING_SOLENOID.CDF to define the drive coil

```
* File: LATCHING_SOLENOID.CDF
GLOBAL
  DUnit:   1.0000E+03
  Ds:   2.0000E+00
END
COIL
  Name: Solenoid
  Current:   -1.0000E+03
  Part
    Name: PART0001
    Type: Solenoid
    Fab:   6.0000E+00  1.0000E+01  2.7000E+01     2    20    20
    Shift:   0.0000E+00  0.0000E+00 -9.5000E+00
  End
END
ENDFILE
```

file LATCHING_SOLENOID.CDF used the SOLENOID model to create 800 applied current elements. Table 1 shows the file contents with a coil current of -1000 A-turn. The negative value gives a coil field inside the bobbin in the same direction as the permanent magnet field.

The steel parts had the fixed value $\mu_r = 1000.0$. The remanence field of the permanent magnets was $B_r = 1.25$ tesla. Figure 2 shows the distribution of $|\mathbf{B}|$ in the plane $y = 0.0$ mm with the plunger in contact with the bobbin. The combination of flux from the two magnets produced an approximately uniform field at the contact point of $B_0 = 1.61$ tesla. Note that it was not necessary to surround the assembly with an extended external volume because the flux was well-contained in the magnetic circuit.

Force calculations were easy when the plunger was separated from the bobbin. In this case, the plunger was surrounded by air ($\mu_r = 1.0$) elements. I used the SURFACE INTEGRAL command in **MagView**. With the configuration file MAGVIEW_STANDARD.CFG, the integral gave force components determined from the Maxwell stress tensor. As an indication of accuracy, I found that the force components F_x and F_y were less than $10^{-5} F_z$. With a gap of 3.0 mm, the axial force with no coil current was $F_z = -1.111$ N. The force increased to -7.427 N with a coil current of -1000 A-turns. With a gap of 6.0 mm, the force with both permanent magnet and coil was -1.427 N.

The manufacturer was particularly interested in the holding force in the latched state (*i.e.*, plunger touching the bobbin with no coil current). In this case, a Maxwell stress tensor integral around the plunger does not apply

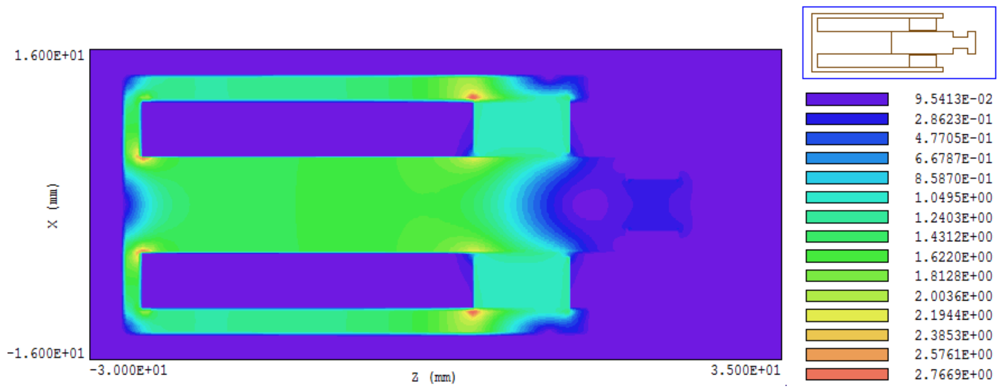

Figure 2: Field distribution in the latched state in the plane $y = 0.0$ mm. Color-coding shows $|\mathbf{B}|$ in tesla.

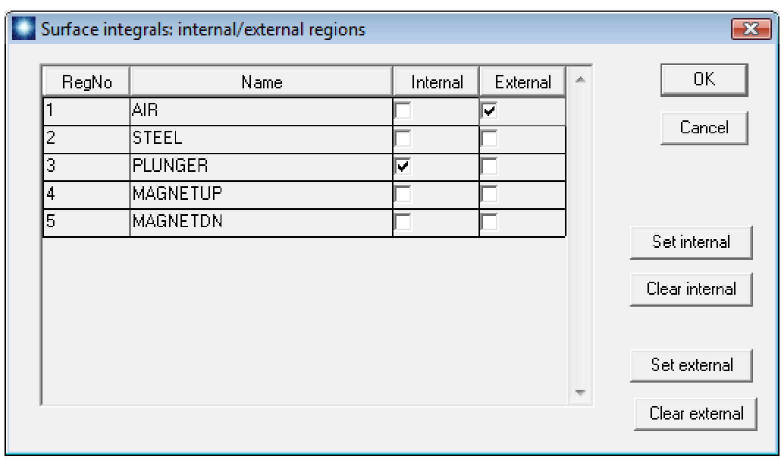

Figure 3: Surface integral dialog. In this case, the integral is taken over all external facets of the plunger in contact with air elements.

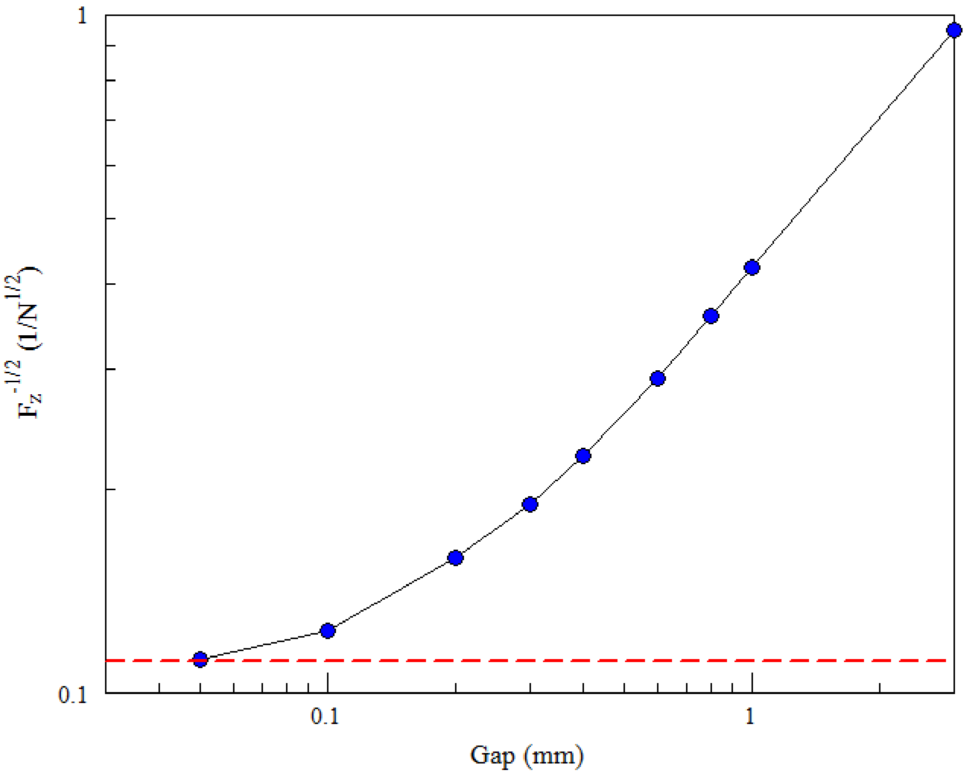

Figure 4: Plot of $F_z^{-1/2}$ as function of the gap between the plunger and the bobbin, where F_z is the force on the plunger in newtons. Blue circles indicate results determined by a surface integral in **MagView**. The dashed red line indicates the theoretical value for zero gap.

because the plunger and bobbin were effectively the same piece of material. My original impulse was to perform a series of calculations with an air gap of decreasing width d_g. The goal would be to fit the force variation with an interpolation function that could be extrapolated to zero gap.

Figure 4 shows results of the calculation. A simple plot is F_z versus d_g would not be particularly informative because the force varies by two orders of magnitude. The strong variation reflects the familiar experience of two magnets snapping together when they are close. I observed that the force scaled as $\sim 1/d_g^2$ for gaps greater than 0.5 mm. Therefore, I constructed Figure 4 as a log-log plot of $F_z^{-1/2}$ versus d_g. The data illustrate that the force would reach constant value at zero spacing. This approach is ineffective, both in terms of the effort involved and the numerical accuracy. It was necessary to go to very small gap widths ($d_g = 0.05$ mm) to observe the inflection toward a constant value. There was a large potential for error in a polynomial fit to the calculated points.

Fortunately, there is a simple way to determine the exact holding force from a knowledge of the flux distribution at $d_g = 0.0$ mm. Suppose we displaced the plunger an infinitesimal distance dx from the bobbin. The field in the air gap would remain confined to the cross section area A of steel parts with a value approximately equal to the zero gap field, B_0. The change in field energy in the magnet circuit is

$$dU \cong \frac{B_0^2}{2\mu_0}\ A\ dx. \tag{1}$$

Using the principle of virtual work, the holding force is

$$F_z = -\frac{dU}{dx} = -\frac{B_0^2}{2\mu_0}\ A. \tag{2}$$

With a plunger diameter of 10.0 mm, the area is $A = 7.854 \times 10^{-5}$ m^2. With $B_0 = 1.61$ tesla, the total force is $F_z = -80.935$ N (plotted as a dashed red line in Fig. 4). The mass equivalent is 8.25 kG. This value should be considered a maximum because the force depends sensitively on the accuracy of the surface contact between the plunger and bobbin. For comparison, the manufacturer reports a value of about 7 kG.