

Optical Communications Group (332-D): Deep-space Optical Terminal (DOT) and Active Isolation Steering Element (AISE) design

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I. Abstract

The JPL Optical Communications Group is developing an actively stabilized vibration isolation platform for a potential optical communications transceiver. Such a platform will use electromagnetic actuators including voice coils. When designing voice coil actuators for a vibration isolation platform for optical communication, we strive for acceptable performance at the smallest possible mass. The bulk of the mass of the actuator is in the magnetic assembly. The optimization of the system requires that we satisfy certain performance requirements while reducing the overall mass. The process of mass reduction is an iterative process by which we reduce dimensions in the magnetic assembly and analyze the force exerted on the voice coil for a given driving current.

II. Introduction and Motivation

RF deep-space communication methods have been successful since the late 1970's in spacecraft such as Jet Propulsion Laboratory's (JPL's) Voyager, Pioneer and in the more recent Cassini mission to Saturn. However, it has become apparent that new methods will be needed to accommodate the larger data volumes produced by increasingly complex missions. One way in achieving this was to optimize and increase the capability of current radio systems and antennae. However, it became clear that sooner or later there would be physical restrictions on the antennae size needed to also allow room for the specific mission payload thus affecting the limit of the data volumes and data rates with which we could successfully transmit information. These are just a few of the reasons for the research and development into optical or laser communication systems at JPL.

One of the key problems in deep space communication is the spreading of the beam from transmitter to receiver. This divergence follows a square-distance law. As a result, transmissions as distances increase can become much wider spreading from an area on the order of one Earth diameter to several thousand. For example, at geosynchronous Earth orbit (GEO) where the distance is some 40,000 km, transmissions between satellite and Earth stations are reliably maintained at the gigabits per second (Gbps) data rate. However, as we approach distances at Neptune some 4 billion km away, the total beam signal would have spread over an area 10 billion times larger than it did from GEO to ground. Given a system capable of data rates at 10 Gbps in GEO, for the equivalent transmission to Neptune, we would have a data rate of 1 bit per second (bps). Another problem in the current implementation of RF communication as mentioned earlier is the physical size of the transmitting antenna. The Voyager spacecraft has an antenna that is 3.7 meters in diameter. Obviously, launching larger devices adds to cost as well as trying to account for the resultant energy demands, power consumption and waste heat. Finally, one of the key improvements in data rate that can be made is by the

increase of the carrier frequencies due to the frequency-squared effect of increasing gain. The current choice of deep space communications is in the X-band or 8 GHz range and will soon be moved to Ka-band or 32 GHz where there is an improvement of 6-10 dB gain. With optical communication, the benefits of the frequency-squared effect are even greater since the carrier frequencies in the optical range operate in the 300 THz range.

The advantages of laser communication become evident in a few different ways. First off, we have the higher frequencies available in the optical band with which to transmit a carrier frequency. This gives us the needed improvement in data rate. Next, we have the reduced size of a telescopic antenna of only 10 cm as compared to a nearly 4 m antenna. Taken together we can estimate that a comparable transmission with an optical wavelength transmission of 1 μm from a 10 cm antenna from Saturn would have a beam spread of about 1 Earth diameter as compared to a Voyager transmission antenna of 3.7 m resulting in a beam spread of 1000 Earth diameters.

Laser communication can solve the problem of beam divergence, increase the data volumes, increase data rates and allow for a more economically sized package. One of the current projects for the JPL Optical Communications group is the DOT or Deep-space Optical Terminal mission where we wish to demonstrate a two-way laser communication system from ground station to Mars. Of the sub-systems involved, research has been focused on the acquisition, tracking and pointing (ATP) of the laser transceiver. A software package known as FEMM or Finite Element Method Magnetics is used for the design and analysis of the Active Isolation Steering Element (AISE) sub-system with the data analysis done by Excel.

III. DOT AISE

An important part of the DOT sub-systems is the vibration isolation platform (VIP). This is the device which is the buffer between the optical transceiver system and the spacecraft structure.

One of the components of the VIP, is a magnet assembly and voice coil that constitutes the actuators. This is the mechanism by which the laser transceiver will point and track. Six actuators for exerting forces on the platform are connected between the spacecraft and the platform at six separate locations. Due to the inherent background noise of the spacecraft and transient random vibrations, to successfully point and track the device these actuators must be made to fulfill some minimum requirements. With FEMM, we can analyze a 2D model of an actuator subject to these requirements. These requirements are:

1. to maintain a 1mm clearance of the voice coil to the cup and assembly unit
2. to overcome the minimum force from the springs of the VIP
3. to keep the magnetic springs weak so that they don't couple vibrations to the platform
4. to overcome the centripetal forces (though these are negligible)

5. to not exceed the maximum operating temperature of the voice coil by driving current

In order to meet these requirements, several design parameters come into play such as:

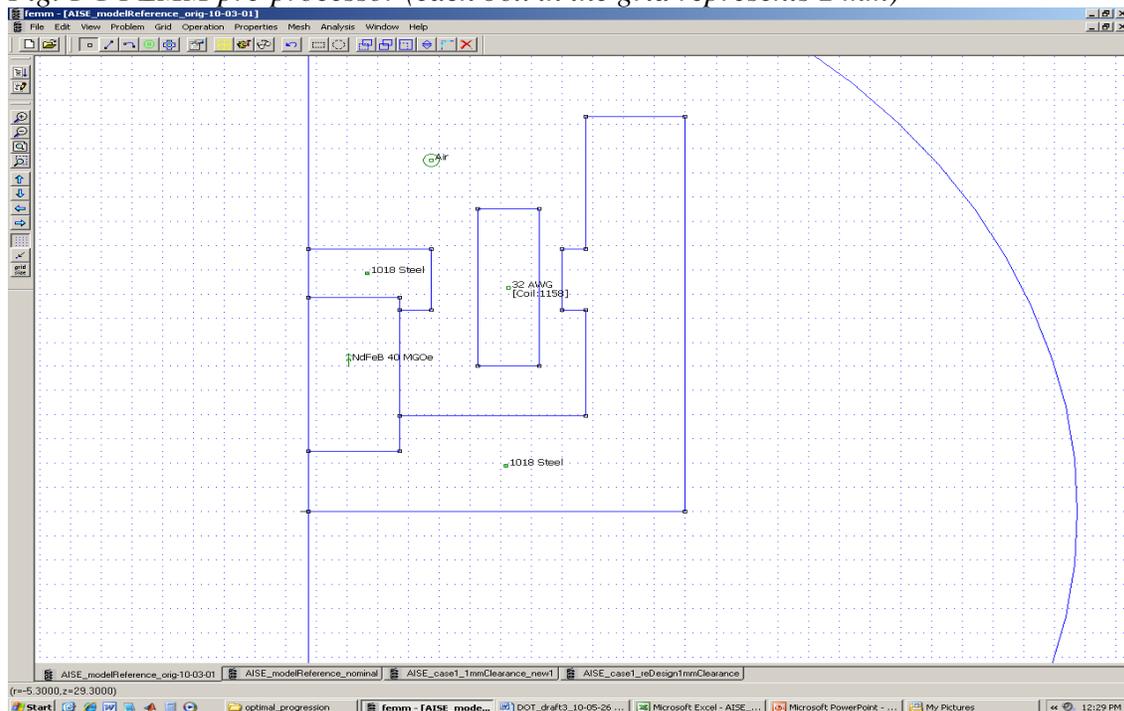
1. dimensions of the magnet assembly and voice coil
2. material properties of the cup and coil
3. the value of the driving DC current
4. number of wire turns in coil and the voice coil wire gauge

As a result we obtain the forces, tabulate the values of both magnetic and mechanical effective spring constants, calculate the coil temperature and obtain a mass for the assembly. Obviously there is significance in reducing the mass for the equivalent performance of a larger unit.

Design Parameters and Progression

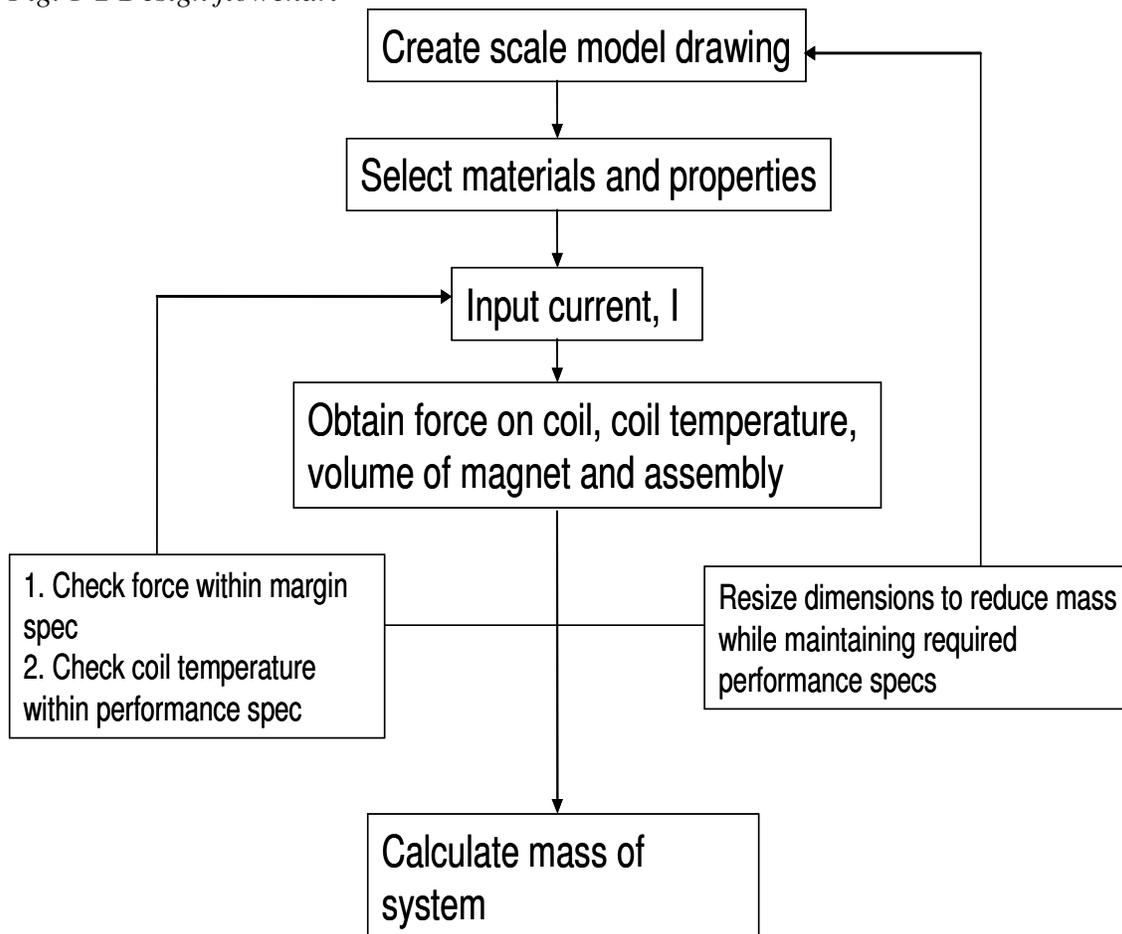
The dimensions of the magnetic assembly and cup are the physical properties that fulfill the AISE optimization requirements. The significance here is that all the mass is contained within this parameter of the magnet and assembly structure. The FEMM program allows for the user to assign different materials and includes those material properties of interest used in computations. This is done through the *FEMM pre-processor* (Figure 1-1).

Fig. 1-1 FEMM pre-processor (each box in the grid represents 2 mm)



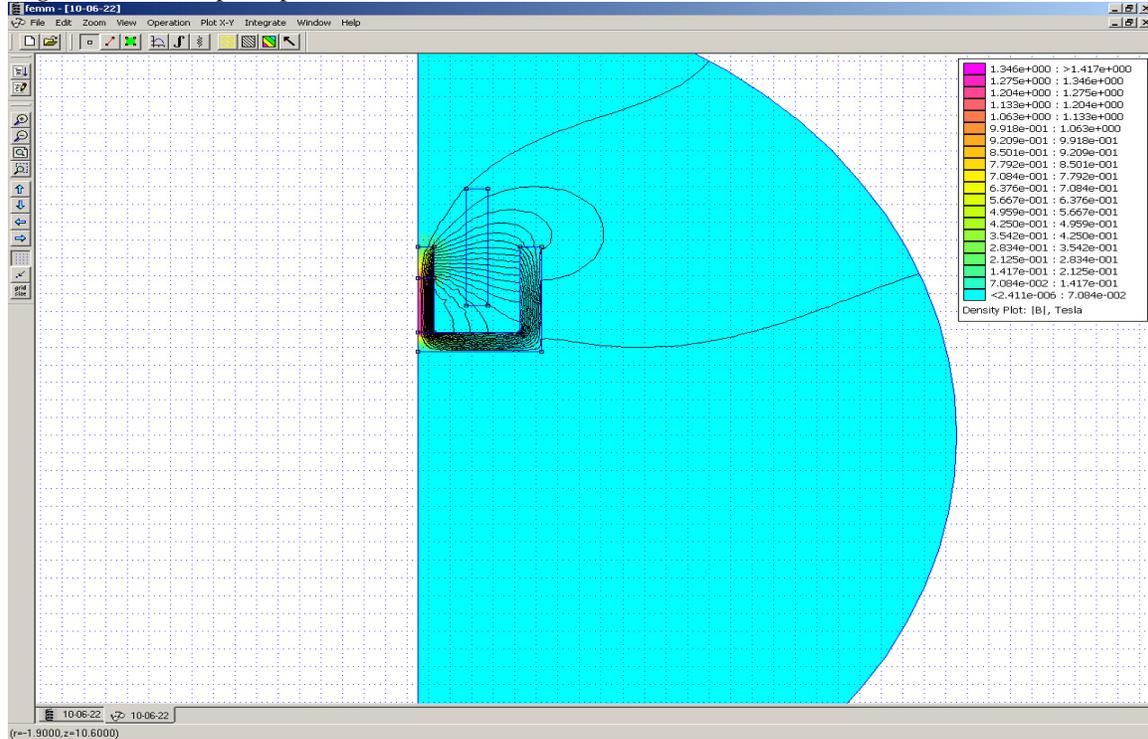
For example, the material used in our model for the cup is 1018 Steel and the magnet is NdFeB. Starting from an original model of the system, we have a computed mass of approximately 306 grams. After several iterations in the course of optimizing the system, we get a result of approximately 10 grams. This is an overall reduction of 97% in mass. The material properties of the cup and coil will have obvious physical effects on the thermal properties of the voice coil, the conduction of current, the strength of the magnetic field and the containment of said field. The required current has to be chosen such that one is able to satisfy the force requirements of the actuator within an allowed margin in addition to meeting the other thermal and performance properties. The number of wire turns is used in the calculation of the total current. It is computed from the knowledge of the dimensions on the coil and the wire gauge. For the voice coil, we simulated a 32AWG copper wire with an approximate diameter of 202 μm . Assuming that the wires are closely packed and wound about each other, we calculated within a space of 4 x 13 mm allowed for the coil that there are 1100 turns of wire. We can use FEMM to input the materials, wire type, number of turns and an arbitrary current to obtain the forces acting on the voice coil. The process in selecting the required parameters to meet design specifications is an iterative process. A sample flowchart is found in Figure 1-2.

Fig. 1-2 Design flowchart



After successive iterations, we take the output values and put them through Excel to tabulate the results and to analyze the trends that lead to an optimal design. By this process, we can determine which parameters to maintain for performance requirements and scale the cup dimensions to reduce the mass of the system. The numerical values of the computed forces, power output and volumes are found in the *FEMM post-processor* (Figure 1-3).

Fig. 1-3 FEMM post-processor

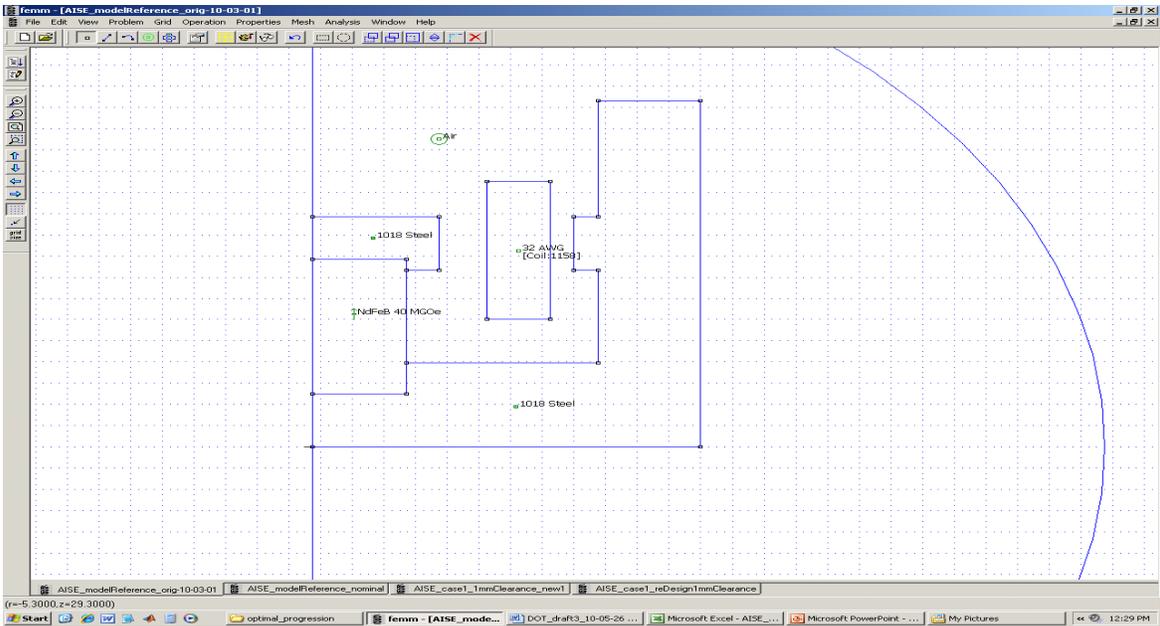


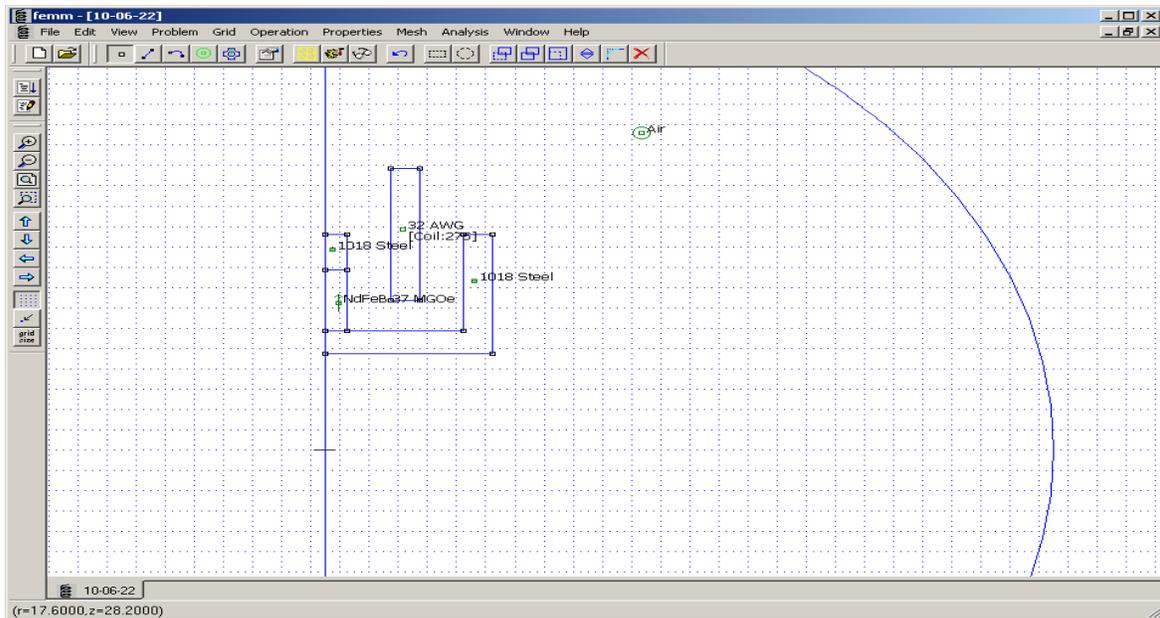
Results

The process to obtain an optimal design for the AISE system lends itself to many variations that may be promising (see Figure 1-4). One of the preliminary results we have obtained is a system that is capable of producing more than 3x the necessary marginal force to overcome the mechanical spring constants, further compensating for any negligible centripetal forces, as well as keeping the operating temperature to within 60 degrees Celsius of the maximum tolerable operating temperature of the voice coil. Given these constraints, we have also achieved as previously noted, a 97% reduction in overall mass of the system. Table 1-1 summarizes some of the results.

Table 1-1 Original design compared to optimized design after FEMM

Force Requirement =	4.8 mN	
Parameter	Original	Improved
Current	200 mA	100 mA
Turns	1158	275
Cup + Disk volume	37.73 cm ³	1.189 cm ³
Magnet volume	1.389 cm ³	0.0424 cm ³
Lorentz force	1.35 N	17.2 mN
Magnetic Spring Constant	0.06 N/m	0.05 N/m
Coil Temperature	286.22 °C	94.70 °C
Mass	306.6 g	9.7 g





IV. Using FEMM

FEMM can be found at <http://www.femm.info/wiki/HomePage>

The program does a two-dimensional analysis of physical problems in magnetics, electrostatics, heat flow and current flow. It can cast these problems in planar or cylindrical symmetry. For the purposes of the DOT project, we have used cylindrical symmetry.

Creating a FEMM Model of the AISE

The FEMM program is divided between what is called the pre-processor and post-processor. The pre-processor is where the problem to be modeled is defined. FEMM has many options associated with how to create a model of a system and how to analyze the results. Go to the FEMM website and find the documentation for FEMM 4.2. Refer to Chapter 2 pgs. 16-46 for an in-depth discussion on using the FEMM magnetics pre and post processor.

Pre-Processor

The Pre-processor, as seen in Figure 1-4, is used to draw the problem. The toolbars on the pre-processor don't support tool tips, but the status bar at the bottom of the window will display button names when the mouse is hovered over a button.

Select File > New, "Magnetics Problem" from the drop-down menu

Select Problem,

Problem Type: Axisymmetric

Length Unit: Millimeters

Select Grid > check “Show Grid”
Select Grid > Set Grid
Grid Size: 0.5 (for ½ mm grid)
Select Operation > Node

This has the same effect as clicking the first of the four buttons shown here:



After selecting the node operation, we draw a perimeter around our work area. The area inside the perimeter is the area within which FEMM will solve the electromagnetics problem. The perimeter must be sufficiently far from other parts of the problem that the presence of this boundary won't have a significant effect on the solution. So we select two points along the z-axis (at $r = 0$) and at $z = 30$ and $z = -30$. Next we draw a line segment (using Operation > Segment, or the corresponding tool bar button) to connect the two points.

Left-click one of the two points and then select the other in turn. Now we create an arc and Mirror the curve into the right-half plane, deleting the original arc by right-clicking and pressing Delete. To mirror:

Select arc by right-clicking > select Edit > select Mirror > Input points along line of symmetry in x,y coordinates

FEMM will then produce a copy of the arc which is the original mirrored in the line of symmetry that was defined in the previous step.

Now that we have our workspace, we can begin placing nodes at the grid points that conform to the dimensions of our problem and create the physical scale of the model. If we wish to set a node to a grid point, select Grid > Snap to Grid.

Magnet Assembly and Voice Coil

We draw a closed region to represent each distinct piece of uniform material in the problem, and then select the material for each region. FEMM has a materials library in which various materials and their respective physical properties are stored. For example, the cup assembly and disk is labeled with 1018 Steel and the magnet is NdFeB.

Select Properties > Materials Library.

Then drag and drop the materials you want to use from the left, to the right under the “Model Materials.”

To assign a material to a region, Select Operation > Block, or the corresponding toolbar button, then left click to place a label, right click to select the marker (turning it red) and press Space Bar to open the “Properties for selected block” window.

In this window:

select , e.g.,

Block type: NdFeB 37 MGOe for a type of Neodymium Iron Boron magnet,
For a magnet, specify a Magnetization Direction.
For a coil, select e.g., Block Type: AWG 32 and (after adding the circuit, as described below), specify a circuit and then a number of turns (Number of Turns is grayed out until a circuit is selected), and
Uncheck “Let Triangle choose Mesh Size” and select a mesh size if, when FEMM solves the problem, it seems to be using too fine or too coarse a mesh.

Select Properties > Circuits > Add Property > give circuit name e.g. “Coil”
Select Properties > Circuits > Modify Property to specify the current whether the turns in the coil are in series or parallel.

Post-Processor

The post-processor has neither tool tips nor status bar indications of the functions of tool bar buttons. Apparently only the manual can be used to identify their function.

Select Analysis > Analyze or click the “Gear Crank” button on the toolbar.

If the mesh is consistent, there will be no errors. FEMM will give an error message if there are open regions, unassigned regions etc.

After running through the finite element analysis of the problem,
Select Analysis > View Results, or click the “Glasses” button on the toolbar.

The result will be a window showing the same grid and model from the pre-processor with the difference that now, one can view the magnetic field and obtain the quantities of physical interest.

Obtaining the Force on the Voice Coil

There are two methods to obtain the force acting on the voice coil in the post-processor window.

Select Operation > Areas, or click  on the toolbar.
Left-click in the voice coil region, which highlights it green, then

Method One

Select Integrate , Lorentz Force ($J \times B$), Ok

Method Two

Select Integrate, Force via Weighted Stress Tensor, Ok

The differences between the methods are discussed more thoroughly in the FEMM manual. Refer to pgs. 35-46 for the magnetics post-processor information. Regardless, the results are virtually identical within numerical range, as expected.

Obtaining the Resistance of the Voice Coil and the power dissipated:
Select View > Circuit Props

Note the circuit properties of interest that pertain to the labeled circuit, namely “Coil.”

Power Dissipated can also be used by selecting the voice coil and integrating Resistive Losses or Total Losses

Obtaining the Mass

To obtain the mass of the design, one needs to highlight the regions of the assembly structure and magnet and obtain the volume. Having the volume and knowing the density of the material properties of the cup, disk and magnet, means that we can then multiply the density and volume to obtain the mass of the system.

Select Operation > Area

Select and highlight the assembly and magnet

Select Integrate > from drop-down menu select Block Volume

V. Conclusion

It is clear that the optimization process is never truly finished. We may also consider other effects such as:

- further reduction in dimensions of the magnetic cup
- the effect of increased thickness on the surrounding magnet disk on the magnetic spring constant and possible reductions in size as a result
- the effect of reduced thickness of the voice coil on the magnetic spring constant and possible reductions in size as a result

Whatever avenues we choose to investigate, it is clear that the FEMM program is an excellent tool with which we may design, analyze and accomplish our objectives.

VI. Acknowledgements

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