Optimizing an Electromechanical Device with Multidimensional Analysis Software

White Paper

June 2013

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Abstract

Modern CAE software allows engineers to investigate a multitude of design variations that could not possibly be considered using conventional physical prototypes. In this paper we will first illustrate parametric methods for automatically creating virtual prototypes of electromechanical actuators (in our case simple electromagnetic solenoids) using the **AMPERES** and **MAGNETO** programs from **Integrated Engineering Software**. We will then use a specific case study to show how the **Tecplot Chorus** program can assist in determining optimal design choices.

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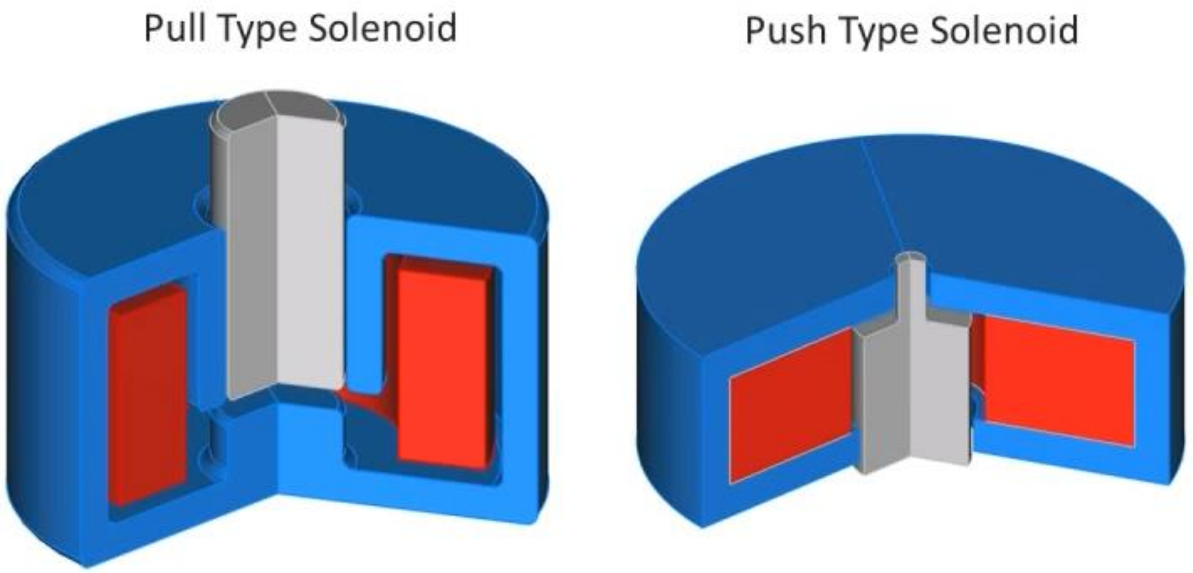
Solenoid Basics

In engineering, the term “solenoid” usually refers to an electromagnetic linear actuator. For simulation purposes they can be reduced to three component parts. The first is a ferromagnetic moving armature, (sometimes called a “core” or “plunger”) which provides force over a range of motion. The second component is an electrical coil that generates a magnetic field when energized (in fact the term solenoid originally meant only a cylindrical coil). And the third is a ferromagnetic yoke or case which guides the motion of the armature and completes the path for the magnetic flux.

Solenoids can be configured to provide either pushing or pulling actions as shown in the picture below. In both types the armature moves in a direction that decreases the reluctance of the magnetic path.

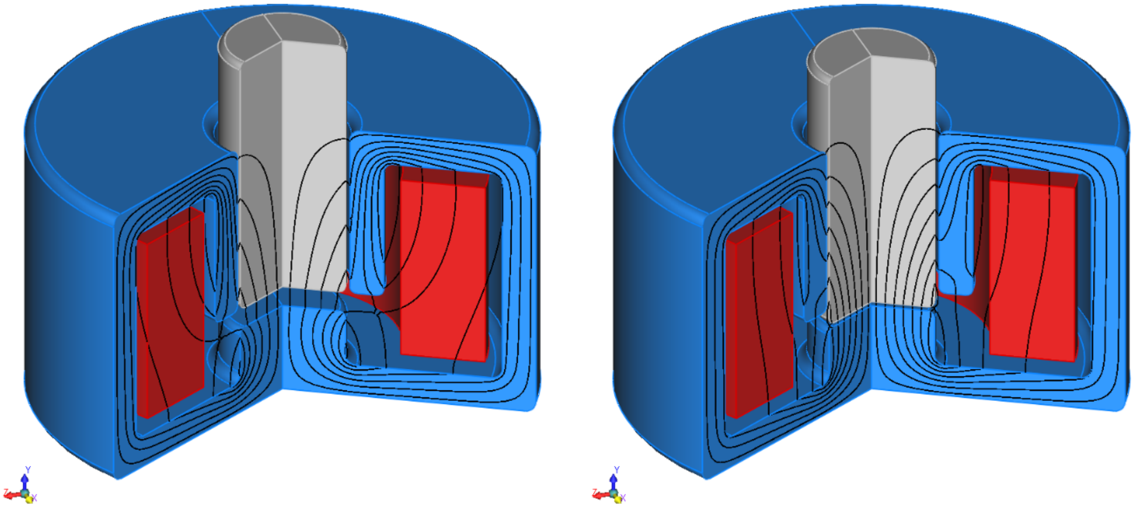


Cutaway views of **Pull** and **Push** type solenoids. In the picture above, the armatures are colored gray, the coils red and the yokes blue

In the preceding picture we have not shown any mechanical linkages or springs since they are not part of the magnetic analysis.

When the solenoid coil is not energized, the armature is normally held by springs in a position where there is a maximum air gap and maximum reluctance. Energizing the coil produces magnetic forces that moves the armature until it hits some physical stop, at which point both the air gap and reluctance are at their minimum. The range of motion of the armature is often referred to as the stroke of the solenoid. The performance of a solenoid is characterized by its force versus stroke curve.

The picture below shows the range of armature motion for the Pull type solenoid.



Cutaway views of the **Pull** type solenoid at maximum gap (left) and minimum gap (right) positions.

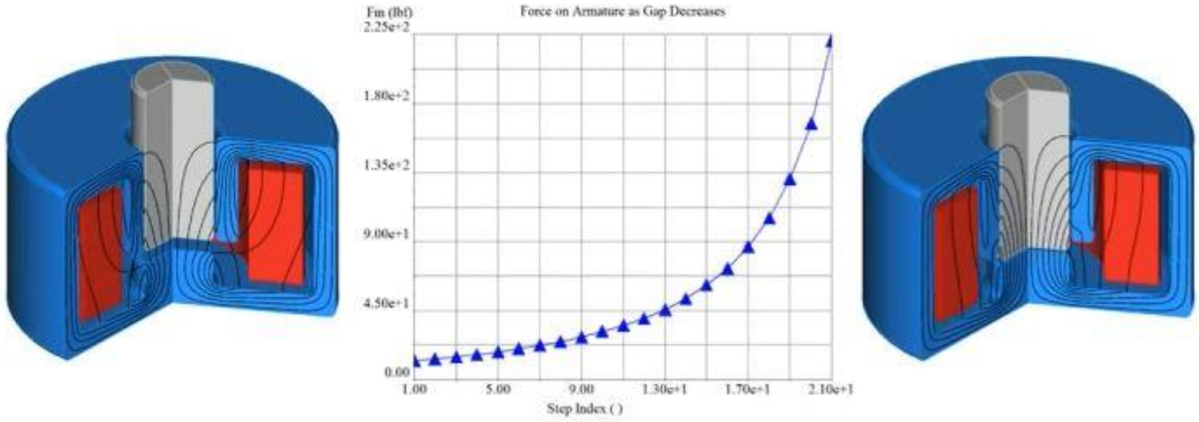
It is possible to manually calculate the force versus stroke curve by creating and solving models at multiple gap conditions and recording force values for each variation. Fortunately this procedure can be automated using **Parametric Analysis**.

Parametric Analysis as a Tool for Performance Testing

A parametric analysis is essentially a batch run that automatically creates and solves multiple models which are variations of a single basic design. In addition, post processing can be defined that will be executed for each model variation and saved after each solution.

The simplest Parametrics studies are those which are used to simulate the performance of designs over their normal range of operation. In our case, we can use parametrics to calculate the variation of armature force as a function of stroke from maximum to minimum air gap positions. Here the movement of the armature would be defined as the variable parameter used to create the individual model variations. The key desired result of the parametric study is the force produced for each armature position. The force is obtained by specifying it as a postprocessing setting to be calculated for each step of the parametric run.

The picture below shows the results of a parametric analysis for a Pull type solenoid model simulated in **AMPERES** which is a **3D** magnetic field solver from **Integrated Engineering Software.**



Parametric results for the **Pull** type solenoid. Graph shows armature force versus stroke characteristic.

Note that as the gap within the solenoid decreases, the force on the armature increases dramatically. At the minimum gap position, the force is maximum and is called the **hold force**.

In the above analysis, the force was calculated for **21** air gap positions, and this required the solution of **21** individual **3D** models. If an engineer wished to experiment with alternate designs, each case could theoretically require a similar number of solutions, and it is easy to see that both the simulation time and amount of data collected could become cumbersome. In fact we will present a case study that involved the solution of **864** individual solenoid models.

To make the simulation time more manageable, we will take advantage of the cylindrical symmetry of the solenoid models and use **Rotational Symmetric** (as opposed to full **3D**) models for the remainder of this paper.

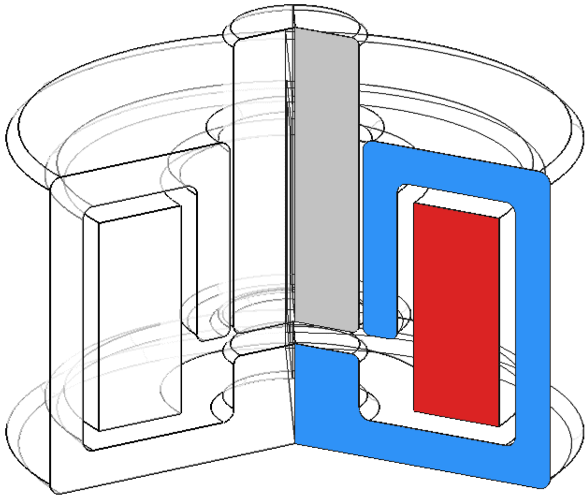
Rotational Symmetric Models

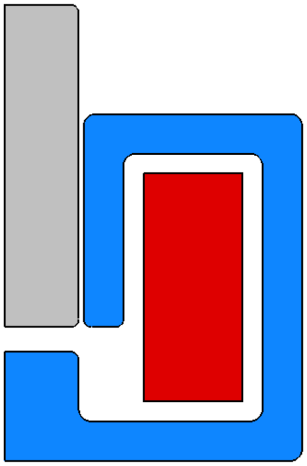
The solenoid models we will consider in this paper consist of components which are **solids of revolution**. In addition, the components are assembled in such a way that they share a common axis. Models that have these two characteristics can be described as **Rotational**

Symmetric (the term we will use in this paper) or **Axisymmetric**. We will use the abbreviation **RS** to indicate a Rotational Symmetric model.

The field solution for Rotational Symmetric models can be greatly simplified by using cylindrical coordinates. The resulting system will have only two degrees of freedom, so a full 3D solution is not required. Instead the model can be set up using a 2D cross section from a radial cutting plane extending from the common axis.

The picture at left below shows the 3D cutaway model of our Pull type solenoid in wireframe with solid shading on the cross section surfaces. Below right we show the equivalent **RS** model.





When the RS formulation can be applied, it has three significant advantages:

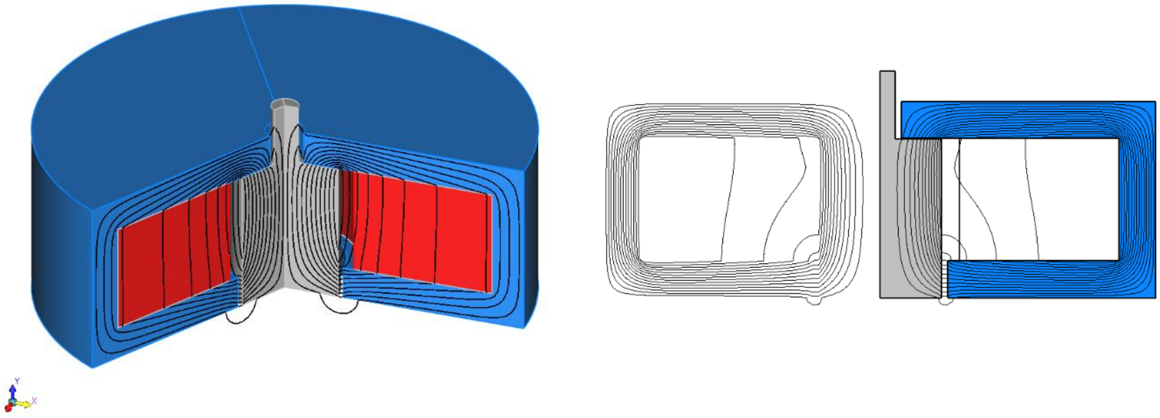
- It will produce exactly the same results as a full 3D simulation.
- The RS models will be easier to build and modify since all the geometric objects are on a 2D plane.
- RS models will solve significantly faster than full 3D models. This is particularly important when trying to optimize models.

Because of these advantages we will use **RS** models for our optimization case study. The parametric models will be created using the **MAGNETO** program from **Integrated Engineering Software**. **MAGNETO** can be configured to solve both **2D** and **RS** cross section models.

Solenoid Actuator Design Case Study

Part 1: Problem Description

We will now consider an actual case study of a Push type solenoid for use in aerospace applications.
The picture below shows the 3D cutaway model of the initial solenoid design and the equivalent **RS** model.



The objective of the case study was to determine the right shape of the solenoid components to guarantee a certain minimum hold force F_0 at the minimum air gap position. Acceptable designs were required to be within a maximum weight limit less than W_0

Furthermore, in order to limit thermal rise to an acceptable level, it was decided that the current density in the coil would be set at $J = 2{,}000$ A/in^2 assuming a 50% fill factor.

Finally, the stray magnetic fields (or "leakage" fields) around the actuator were required to be less than a value B_0.

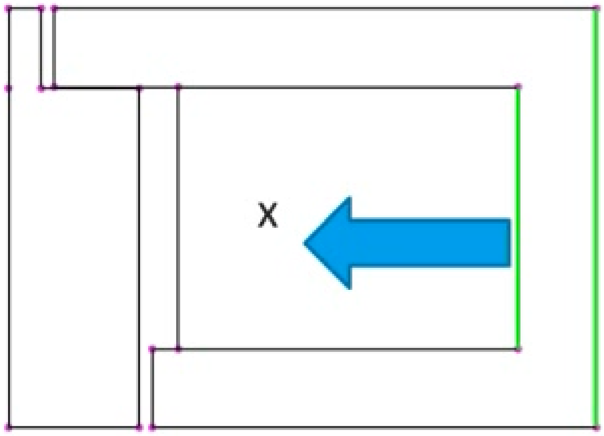
Part 2: Variable Design Parameters

The optimization search strategy was to create a range of trial prototypes by varying three parameters:

- Parameter **x** which reduces the outside diameter of both the yoke and coil
- Parameter **y** which reduces the axial length of all three components of the solenoid
- Parameter **z** which reduces the outside diameter of all three solenoid components

Before presenting the case results, we will first examine the effects of each of these parameters individually.

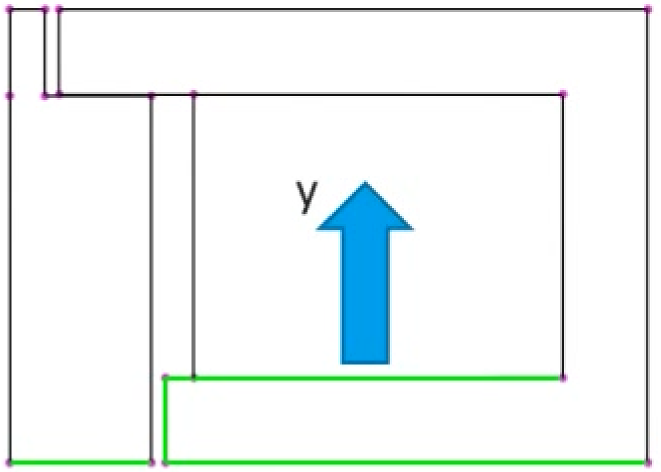
The picture below shows the geometric properties of the **x** parameter. The segments highlighted in green will move in the direction indicated by the arrow.



The picture above shows the maximum diameter condition, which in this case is **4.5 inches**. The **x** parameter was defined to reduce the diameter to a minimum of **2.1 inches** over a series of **12 steps**.

Note that reducing the coil outside diameter also reduces the coil area, and since we are assigning a fixed current density this automatically reduces the available magnetomotive force (**MMF**). However, the weight of the coil and yoke will also be reduced which is desirable as long as the hold force requirements are met.

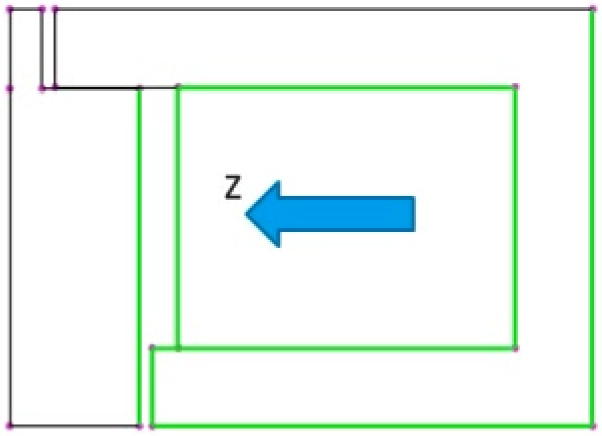
The next picture shows the geometric properties of the **y** parameter. The highlighted segments show that all three solenoid components will be affected.



The **y** parameter was defined to reduce the axial length from an initial maximum value of **1.6 inches** to a minimum value of **0.7 inches** over a series of **9 steps**.

Here again the coil area and MMF are reduced, but the so are the weight of all three components. Though not a consideration for this case study, the reduction of the mass of the armature would have the added benefit of reducing the operating time for the solenoid.

Finally, we show the geometric properties of the **z** parameter. The highlighted segments show that here again all three components will be affected.



The **z** parameter reduces the outside diameter of all 3 components by **0.7 inches** over a series of **8 steps**. This corresponds to a **70%** reduction in armature diameter, but only an **18%** reduction for the coil and less than a **16%** reduction in yoke diameter.

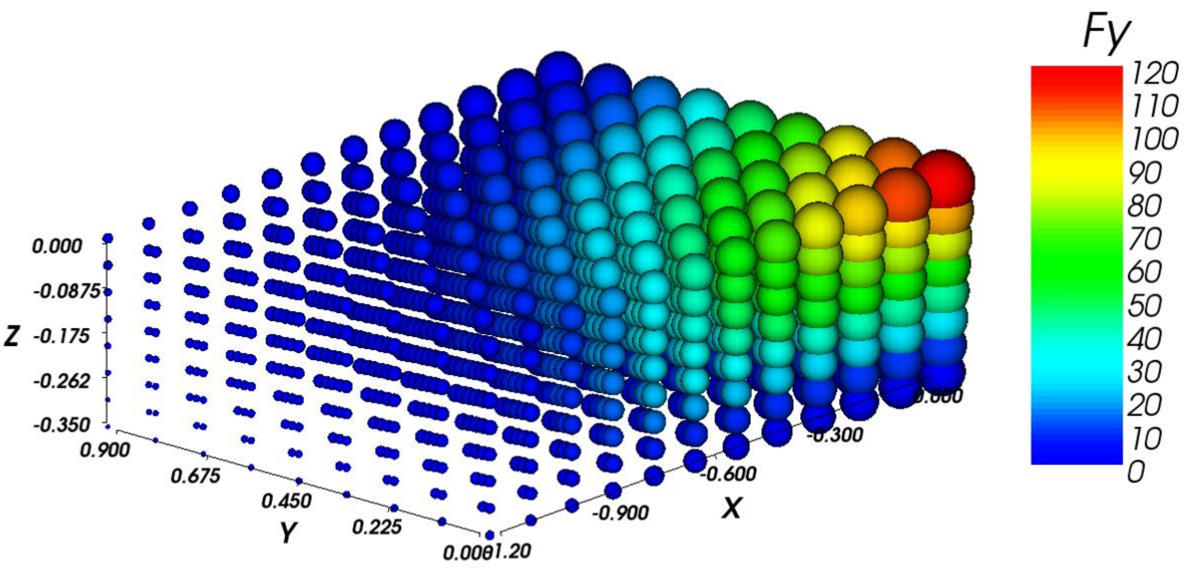
Note that since the coil cross section area is maintained, the **z** parameter does not reduce the available MMF. However since the coil outside diameter is reduced, so will its weight.

When all possible combinations are considered the total number of model solutions required comes to **864**. On commonly available desktop computers this would be a formidable undertaking if full **3D** solutions were required. Fortunately, the **RS** models solve on the order of forty times faster than full **3D** models. As a result, the total solution time was just over one half hour using a computer with 12 threads.

Part 3: Initial Analysis of Results using Tecplot Chorus

The parametric data from **MAGNETO** was exported to a **.csv** file, which was then used to create a project in the **Tecplot Chorus** program. **Tecplot Chorus** is a software package specifically designed for the analysis and visualization of large data sets.

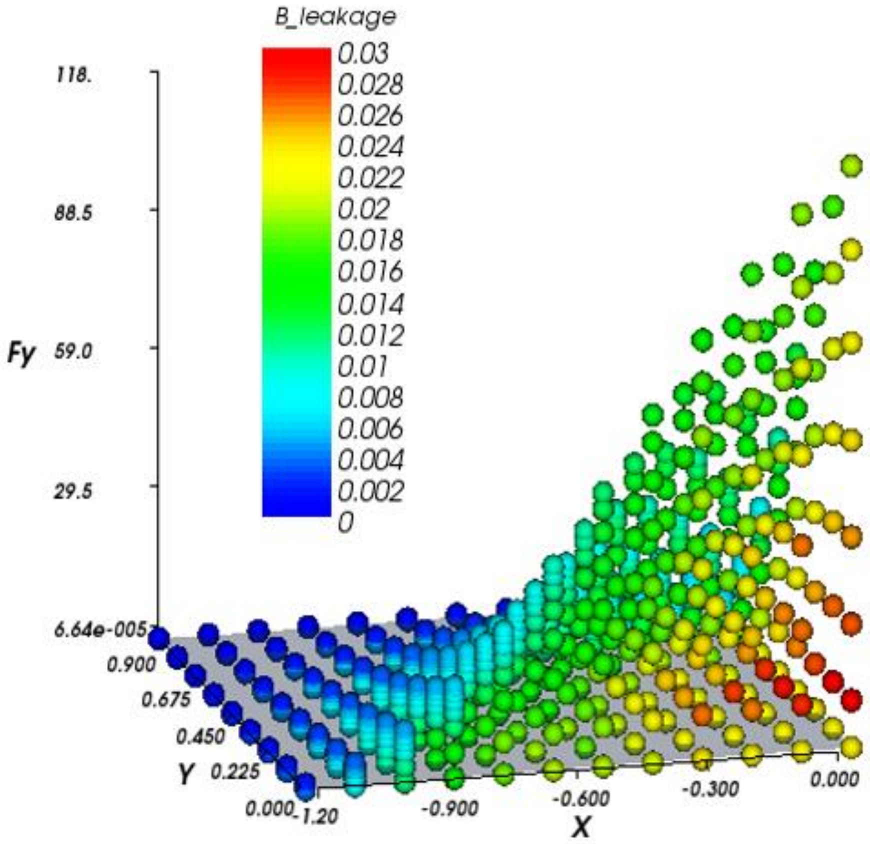
For our first visualization, we show a 3D scatter plot of the 864 results where the axes represent our three parameters. In the plot below the spheres are color coded according to the armature force, with the highest force colored red, and the lowest colored blue. Also the spheres are scaled in size according to the total weight of a prototype.



From this plot it is apparent that there is a correlation between the weight of a prototype and the force it can produce. However, note that there are some fairly large spheres which are colored blue; these indicate models which are heavy but have inferior force capabilities compared to some lighter models.

In order to get a more quantitative feel for the range of force variation, we can create a second scatter plot using armature force as the vertical axis.

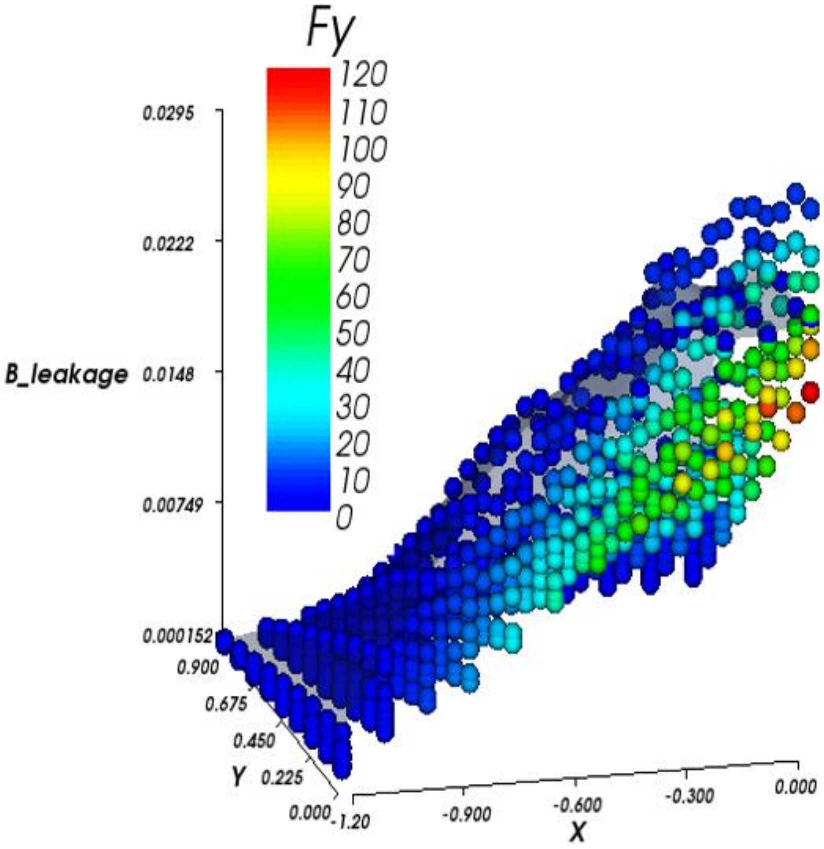
In the plot below the spheres are constant in size, but colored according to the magnitude of the leakage fields.



It is encouraging to see that prototypes with the highest force capabilities are colored green indicating they fall in the midrange of leakage fields.

As an alternate way of viewing the relationship between force and leakage fields, we can use the magnitude of the leakage field for the vertical axis, and color according to force.

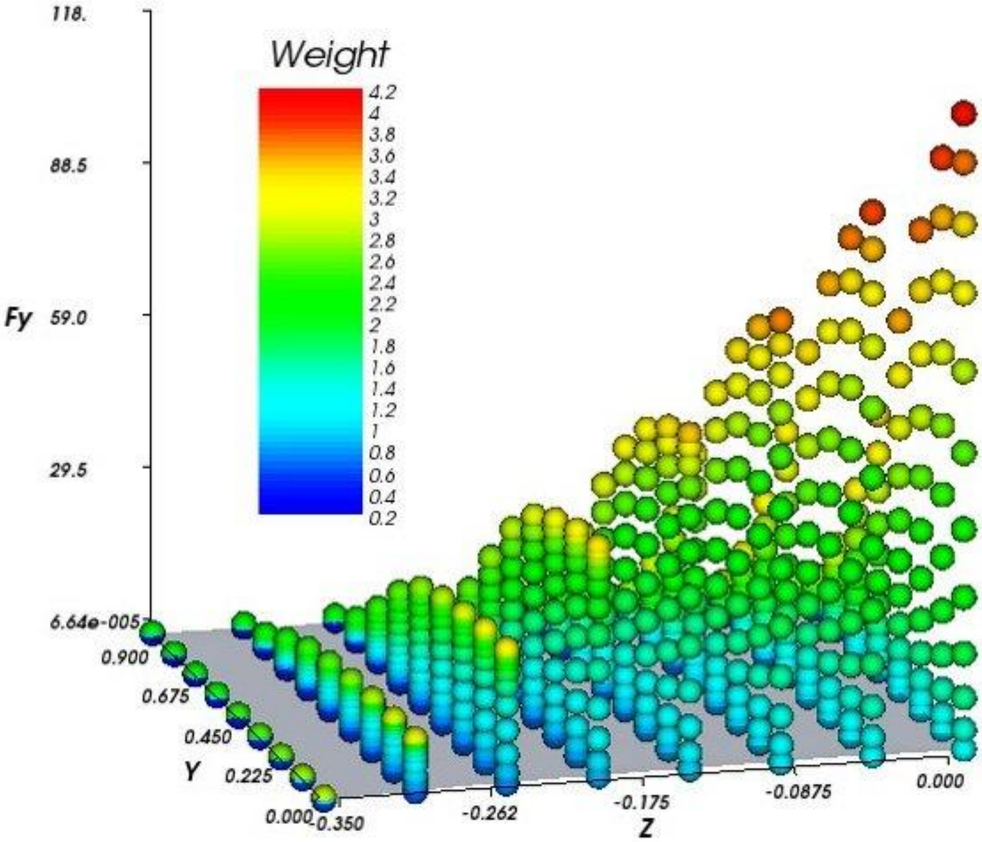
In the plot below the lowest force models are represented by blue spheres, and it can be seen that they span the full range from lowest to highest leakage values.



Part 4: Using Tecplot Chorus to Select Optimal Designs

So far we have used **Tecplot Chorus** to display the results for the entire 864 parametric run. In this section we will show how limiting the range of dependent variables can be used to locate optimal design configurations.

We begin with a scatter plot of armature force as a function of the **y** and **z** parameters, with spheres colored according to weight as shown below.



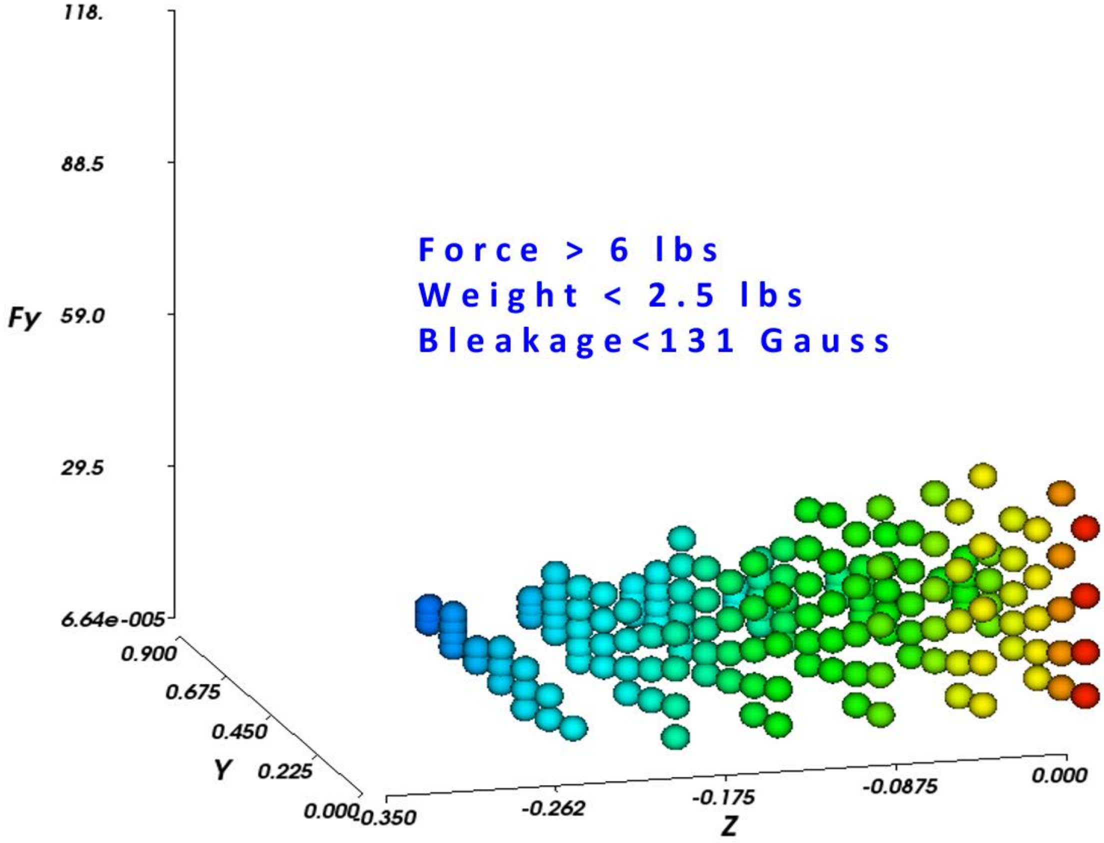
The forces can be as high as **118 lbs.**, and the possible weights as great as **4.2 lbs**.

In fact the actual force requirement was only **6 lbs.**, and the maximum allowable weight was limited to **2.5 lbs**. In addition the leakage fields were required to be less than **131 Gauss**.

Since the initial base design produced far more than the required force (but was also heavier than acceptable), it seemed reasonable to expect that there should be at least some parametric variations that could meet the design criteria.

An outstanding feature of **Tecplot Chorus** is the capability to filter results so that only acceptable prototypes are displayed.

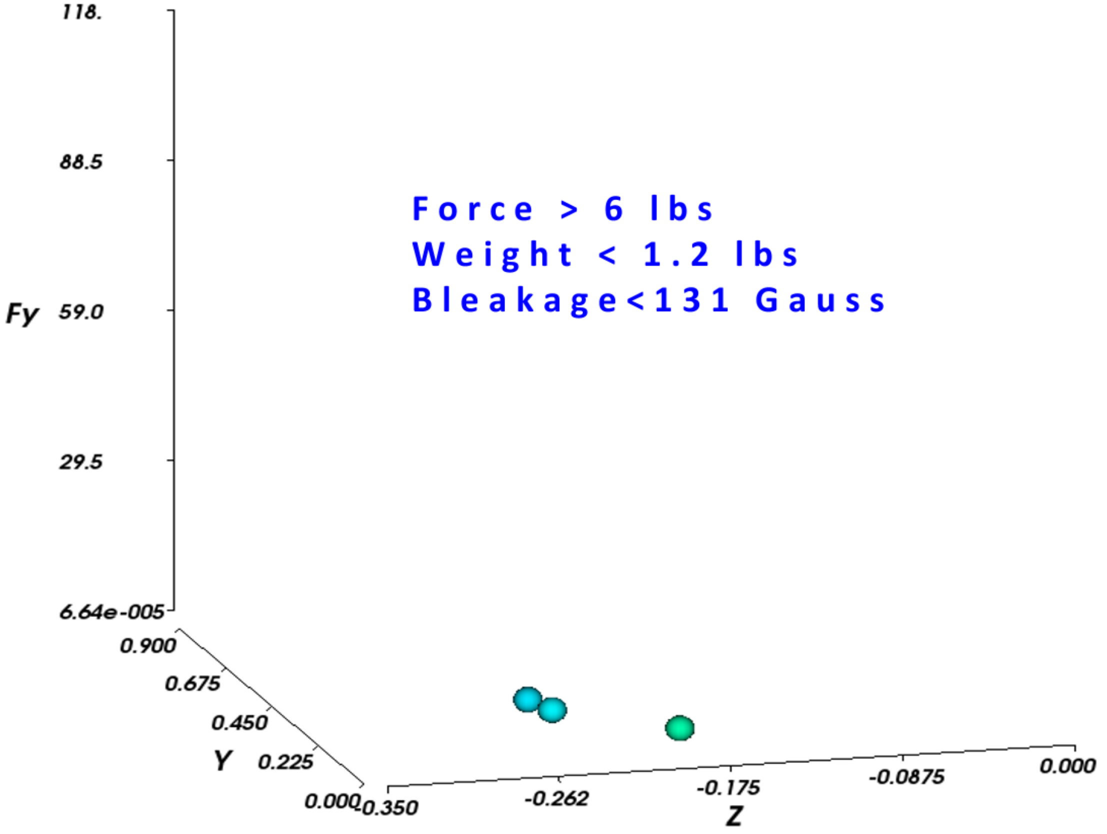
Here we show the reduced set of acceptable designs after the data has been filtered.



Note that there are still a large number or prototypes to select from.

To narrow our choices to the best designs, we can set even more stringent filtering criteria. It was found that setting the weight filter down to a maximum of **1.2 lbs.** narrowed the choice to only three acceptable designs.

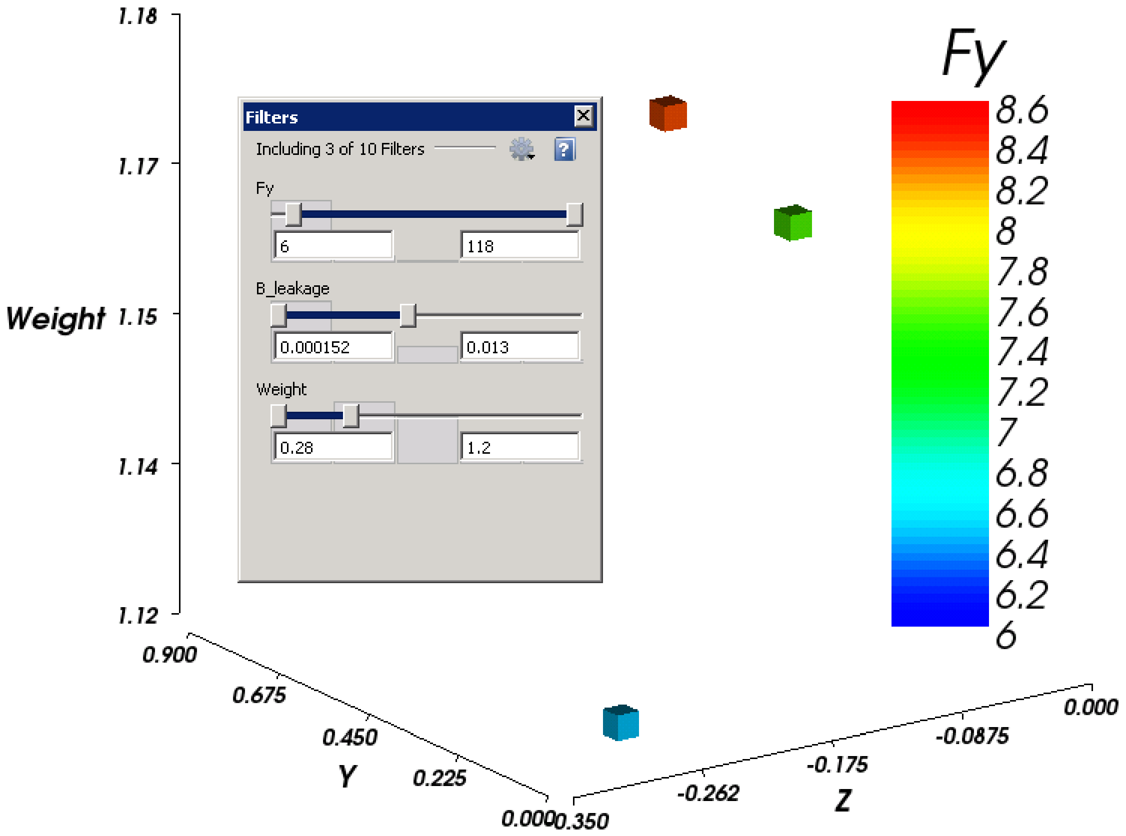
The plot below shows the remaining three candidates for the optimal design.



At this point the original plot scales are too coarse to allow a meaningful comparison of the last three designs.

To get a better feel for the characteristics of the remaining designs, we can replot with weight used for the vertical axis. Also we apply a color coding according to force.

Below we show the new scatter plots using cubes as markers.



Fy: 6 – 118

B_leakage: 0.000152 – 0.013

Weight: 0.28 – 1.2

This new plot reveals that the difference in weight between the largest and smallest is only **5%**. However, the heaviest solenoid is capable of producing **30%** more force than the lightest.

At this point it becomes a matter of engineering judgment as to whether or not the absolutely lightest solenoid capable of meeting the hold force requirement is the best choice, or whether the small **5%** weight penalty is more than compensated by the **30%** gain in force. Since both designs are less than half the specified maximum weight, the higher force solenoid would be the most likely choice.

Part 5: Comparison to Numerical Optimization Techniques

The preceding section demonstrated how the use of the **Tecplot Chorus** visualization tool could quickly locate optimal designs from a large data set. There are of course a number of purely numerical search techniques which can be applied to problems of this type.

For example the **Response Surface Method** could be used by applying the following steps:

- Fit the three key parameters F_y, weight, and field leakage to the independent variables
- Fit these three functions to the three independent variables using a multivariable spline matching subroutine
- Fit the complex function in the region of a point (x,y,z) with a simpler quadratic function within a small region
- Determine the local minimum ($-F_y$) subject to the constraints

However, at the end of any purely mathematical search routine, there is still uncertainty as to whether or not the resulting solution is truly the global optimum or merely a local optimum. For this reason the ability to visualize what the data actually means is of paramount importance.

Summary

The ability to economically produce optimal designs of electromechanical devices is dependent on three prerequisites:

- The engineer must have a thorough understanding of both the design objectives and the parameters that can be varied to meet those requirements.

- The engineer must have the appropriate CAE tools to perform virtual prototyping.

- The engineer must have the means to interpret and visualize simulation results in order to identify optimal designs.

The case study presented in this paper illustrates the practicality of combining parametric analysis with advanced visualization to produce an effective optimization strategy.