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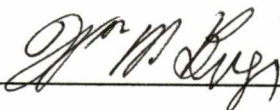
I am submitting herewith a thesis written by Jeremy Myers entitled "Two Stage Solenoid Design." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.



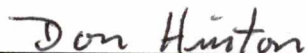
Dr. Frank Speckhart, Major Professor



Dr. Chris Pionke, MAES Dept.



Dr. William Bugg, Physics Dept.



Dr. Don Hinton, Math Dept.

Accepted for the Council:



Interim Vice Provost and
Dean of The Graduate School

Two-Stage Solenoid Design

A Thesis Presented for the Master of Science Degree
The University of Tennessee, Knoxville

Jeremy Myers
May, 2001

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Abstract

Solenoid use and design is limited by the fact that as the gap increases, the force greatly decreases. However, by using a solenoid that contains three cores instead of one, it is possible to greatly increase this force. In such a design, the 3 cores interact as follows: Core 1 is rigidly attached to core 3. At the beginning of the motion, core 3 is in a hole in core 2. Core 2 remains stationary until core 1 reaches it. When this occurs, all cores move until core 3 reaches the shell. To prove this design creates better results, models are created and compared against an equivalent regular solenoid. Models are created in MATLAB using an equivalent resistor circuit to model the solenoid. In this model all flux paths are assumed to be perpendicular to the surfaces they enter and exit. This method shows an improvement of 29 % in the best case scenario. Models are also created in Maxwell 2D Field Solver by Ansoft, a finite elements program. Both models calculate the force that the solenoid can produce as it moves from the open to closed position. Data is collected when various parts of the geometry are varied. It is found that the diameter of core 3, the geometry of core 3, and the length of the connector rod connecting core 1 and core 3 have the greatest impact on the force output through the entire motion. Also it is found that the area with the greatest increase in force can be moved, by changing the initial gap between core 2 and the shell. The best results from the finite element code were found for a solenoid with a 10 mm gap. The results showed an average improvement of 48%. A smaller total stroke yields better results. This is because most of the improvement is localized to area only one area of the stroke path.

Preface

In determining my thesis project I worked with my major professor Dr. Frank Speckhart in finding an appropriate subject. He has worked several years with the design of solenoids, and their application. His idea of a two-stage solenoid led to the investigation presented within. The following is an overview of each chapter.

Chapter One gives an overview of why a new solenoid design is desirable. It brings attention to the limitations of current design

Chapter Two gives the basic equations used in modeling a linear model of a solenoid. It shows the relation between these.

Chapter Three explains the basic design of the new two-stage solenoid design. This includes a description of the necessary geometry and the motion such a solenoid performs. It also describes the patent checks performed.

Chapter Four explains how the MATLAB code was written. This code is for a model of a solenoid using the equivalent resistance method. It explains also the output of the code.

Chapter Five describes how different parts of the geometry were investigated to find their effect on the force output.

Chapter Six describes how the findings in chapter five were implemented into an indexing system to determine the best geometric setup. It also shows the results of the MATLAB code written to find this setup.

Chapter Seven explains why the MATLAB code is not the best model. Justifying the finite element approach

Chapter Eight describes the validity of the finite element model. This is done by comparing results and with those from MATLAB

Chapter Nine speaks of how changes in geometrical parameters effect the force. It shows different indexes used to validate which design is best. It concludes with the best geometric setup.

Chapter Ten describes modifications made to core 3 in order to obtain better results.

Chapter Eleven describes a group of design tables to allow creation of solenoids for certain applications.

Chapter Twelve is the conclusion, giving a recap to important findings and steps to be taken.

The Appendix contains the charts referred to in the text. It also includes the MATLAB code written, and the raw data collected using the finite elements program. Finally a short user guide to using Maxwell 2D Field Solver is presented. With this guide one can quickly begin using this finite element package.

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Chapter 1

Introduction/Objective

Solenoids find their use in areas such as fluid control, automation, the automotive industry, and everyday appliances. The simplicity of their design has led to their mass production and use. However, solenoids have a certain relation between force and displacement that limits their usefulness. When extended, with a small air gap, solenoids can exert a rather large force; when fully retracted the force is noticeably smaller. To have a solenoid that creates a larger force for large air gaps could open up new applications for solenoids. This would open new areas in which solenoids could be employed.

Before improvements can be made, the basics of magnetic fields and the operation of a solenoid must be understood. A current passed through a wire creates a magnetic field around the wire. When the wire is wound into a coil, the magnetic fields produced by each turn add to form a larger magnetic field. Therefore, the current (I) and the number of turns in the coil (N) determine the magnetic field. The product of these values is referred to as amp-turns (NI). The magnetic field lines of a coil flow through a closed path, passing through the center of the coil and down the exterior of the coil, figure 1 (Siemon, 539).

Some materials have properties that give them the capacity to concentrate magnetic lines of force. In fact, a material such as iron or steel performs better at this on a magnitude of a few thousand times. Therefore, if a shell of steel is placed around the coil, as seen in figure 2, it is much easier for the flux to travel around the closed path shown in the figure. There is still a very large resistance to carrying a magnetic flux,

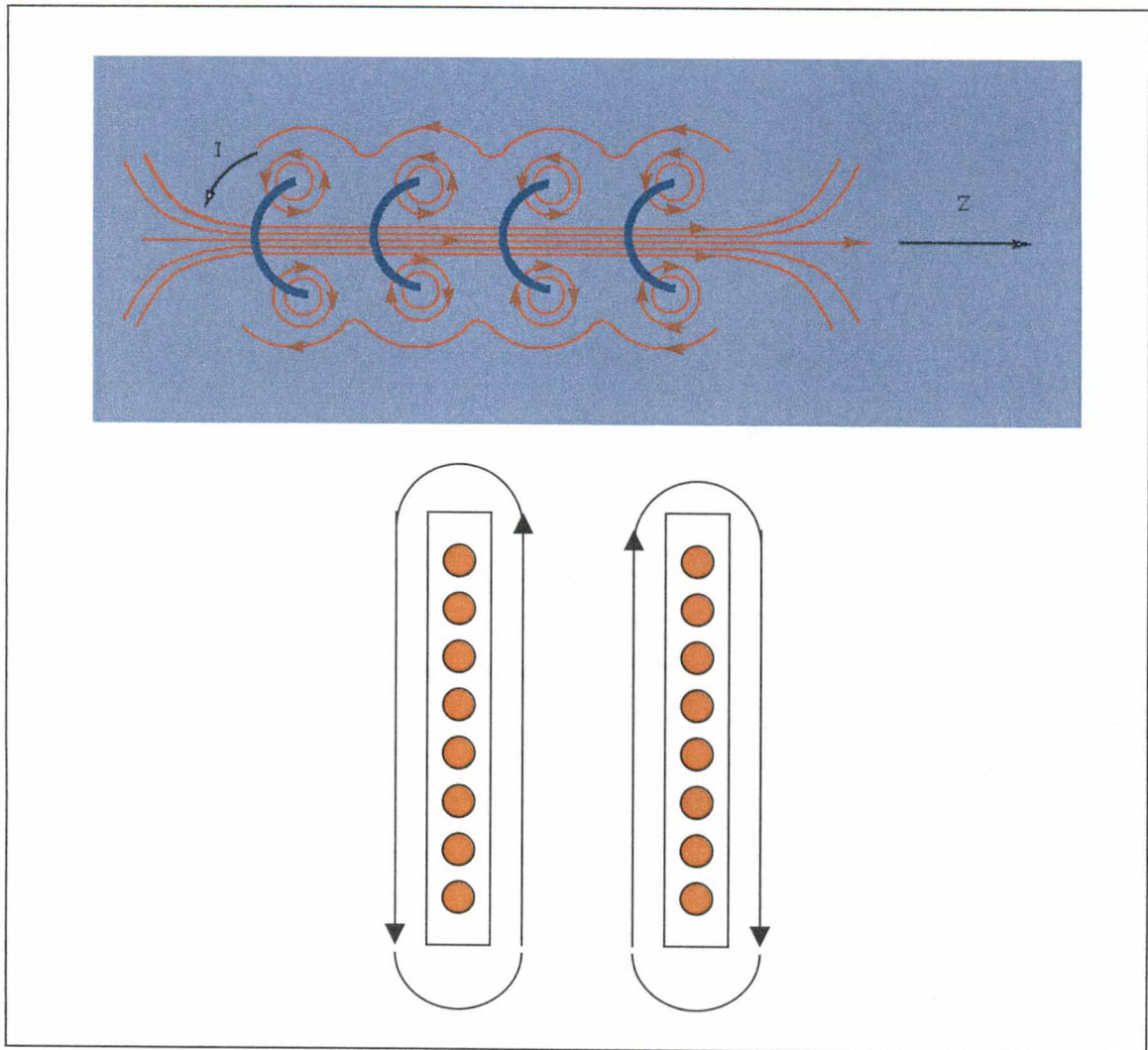


Figure 1: The wires carrying current, shown in blue, create a magnetic field around them. A cross section of a coil shows a simplified path that the flux travels. This path is through the center of the coil and around the outside of the coil.

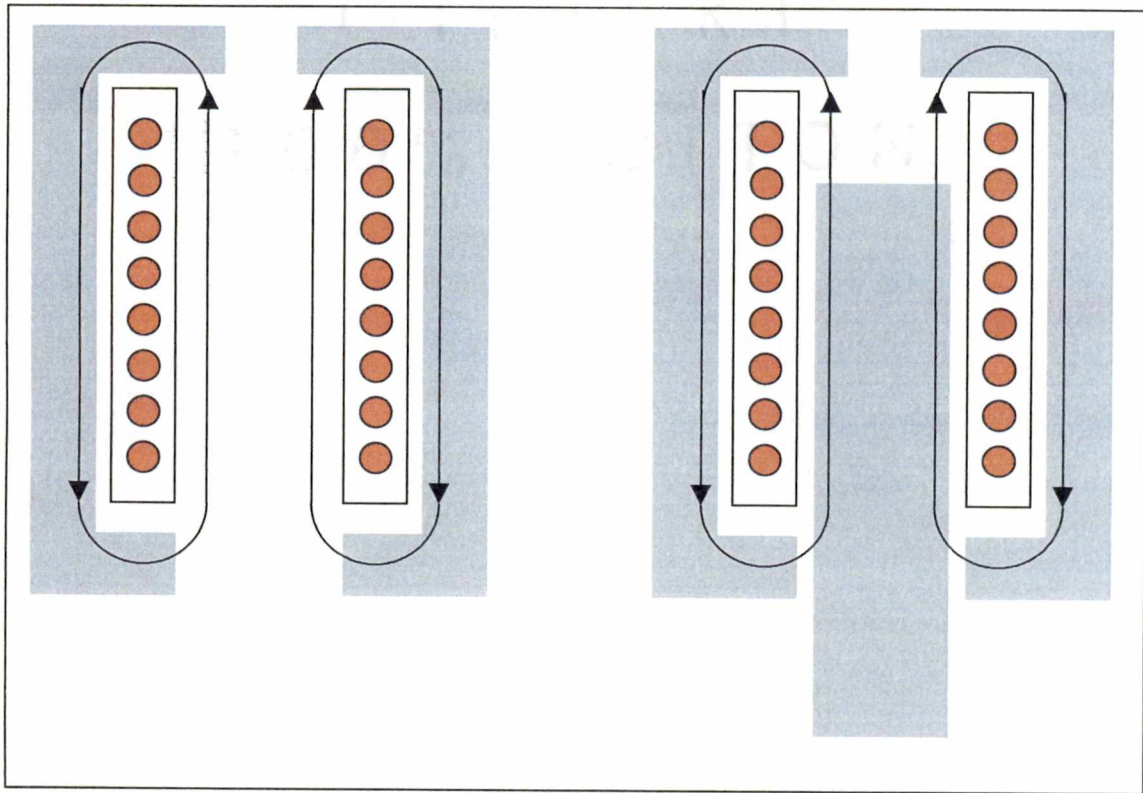


Figure 2: The path followed when steel is added as a shell, figure to left. The figure to the right shows the path followed when a core is added in the middle. This makes it easier for the flux to travel around the coil. Since the core can move, this is what produces motion.

reluctance, in the air gap. If a core of magnetic material, which is free to move, is placed in the middle of the coil, the path of the magnetic flux would have less reluctance.

Magnetic flux follows the path of least reluctance. Therefore, a force is produced tending to move the core in such a way as to minimize the reluctance. Nearly all of the reluctance is due to the air gap. As the core moves toward the shell, decreasing the air gap, the reluctance decreases.

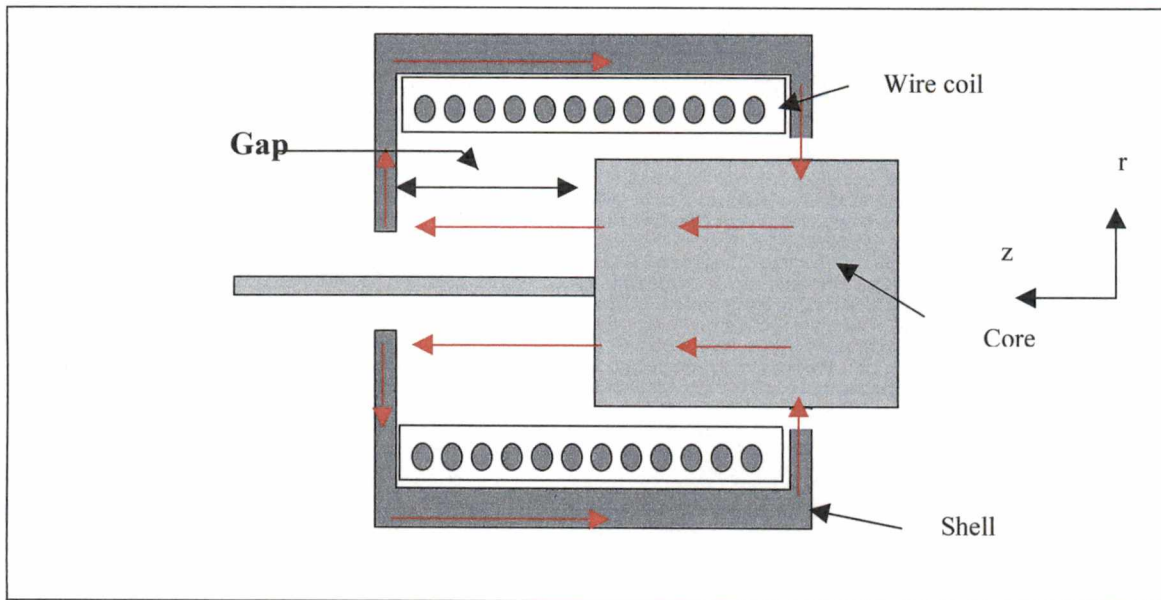


Figure 3: A cross section of a basic solenoid. Here, the plunger travels to the left until the end of the core reaches the end of the shell. The red arrows represent an approximate example of the path of the magnetic flux.

All figures are cross sections of the solenoid. While the solenoid is a three-dimensional object, it can be modeled in two-dimensions because the geometry and flux are axially symmetric. Figure 3 shows a cross section of a basic solenoid.

The force exerted by a basic solenoid is often the limiting factor for its use. This force is smallest when the air-gap is large, and largest when the air-gap is small. Figure 4 shows a typical force-displacement curve for a solenoid like the one shown in figure 3.

As is seen in figure 4, the force decreases rapidly as the air-gap increases, thus limiting the range for viable use. Solenoids of this design are only effective in producing small strokes. Increasing the amp-turn value of the coil can increase the force; but due to space and power limitations, increasing NI is not always possible.

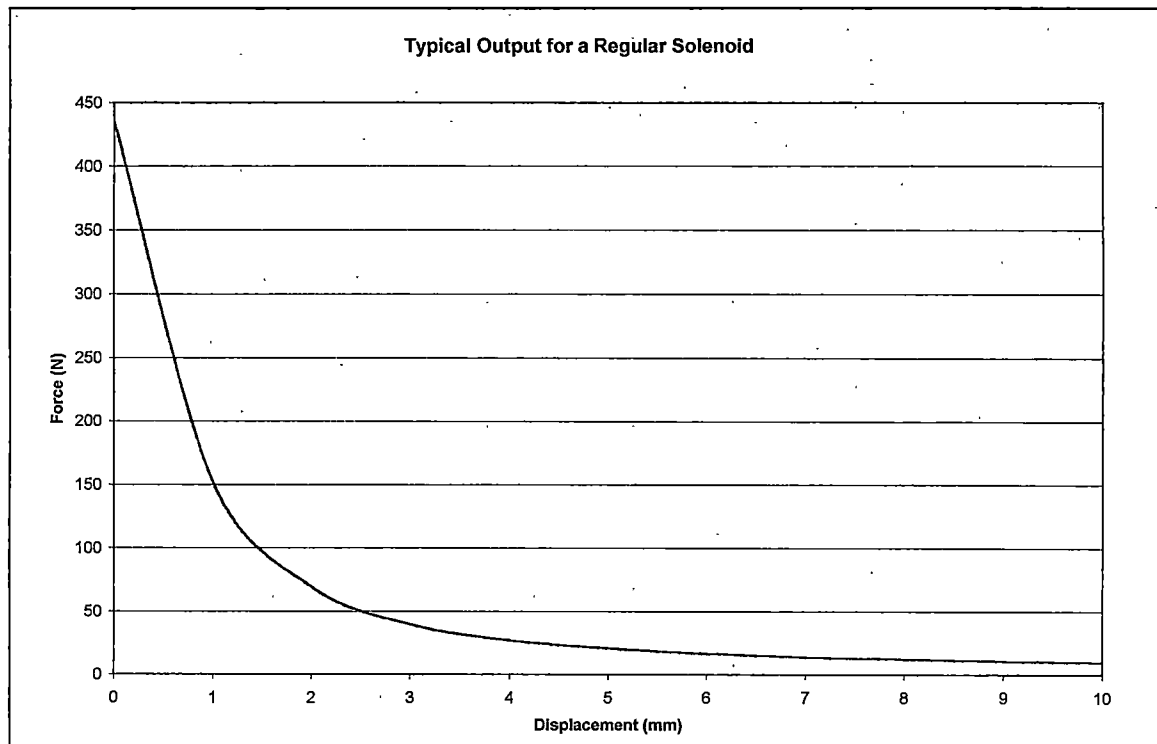


Figure 4: The relation between force and displacement for a regular solenoid. It is clear that force decreases greatly with an increase in displacement (gap).

The objective of this paper is to present a solenoid design that will provide greater force when the air-gap is large, without changing the size of the solenoid or increasing the amp-turns. A few basic principles must be understood to properly model the magnetic system, namely those equations governing the force. (This will be addressed at greater length in the subsequent chapter).

Magnetic circuits will be used to model the solenoid system. This modeling is analogous to an electric circuit. Just as it is easy for electric current to flow through low resistance materials such as copper, it is easy for magnetic flux, to flow through low reluctance materials such as steel. Also, just as in a circuit, high resistance materials impede the flow of electric current, in a magnetic circuit, high reluctance elements, such

as air gaps, impede the flow of magnetic flux. In an electric circuit, current flows through the path of least resistance. Similarly, in a magnetic circuit magnetic flux travels through the path of least reluctance, the magnetic equivalence to resistance. The greater the flux in a gap, the greater the force it can produce (Siemon 2-5).

There is a significant difference between magnetic and electrical circuits. In electric circuits the flow of current is confined to the conductors. Insulators stop the flow of electrical current. In contrast, magnetic flux will travel through all materials, including air. There is no material that will serve as an insulator, stopping the flow of magnetic flux. However, some materials make it more difficult for this flow of magnetic flux because of their reluctance.

Using the magnetic circuit model and the fact that the smaller the gap, the greater the force, it is possible to design a solenoid with improved force output. The basic concept is to use multiple parts to provide multiple flux paths. These paths ensure that the total flux remains large. However, they must also ensure that flux passes through gaps so that forces are produced. The design presented in figure 5 does provide multiple paths. Figure 6 shows this design in three different stages of the stroke. In these figures the basic operation of the three-core design is demonstrated. The following section describes these three main parts of the motion.

Case 1) When the gap between core 1 and 2, and the gap between core 2 and the shell are large: Since the flux takes the path of least reluctance, flux will pass through core 3. Core 2 remains stationary because the attraction between core 1 and core 2 is greater than the forces in the opposing direction, and the stops prevent core 2 from moving toward core 1.

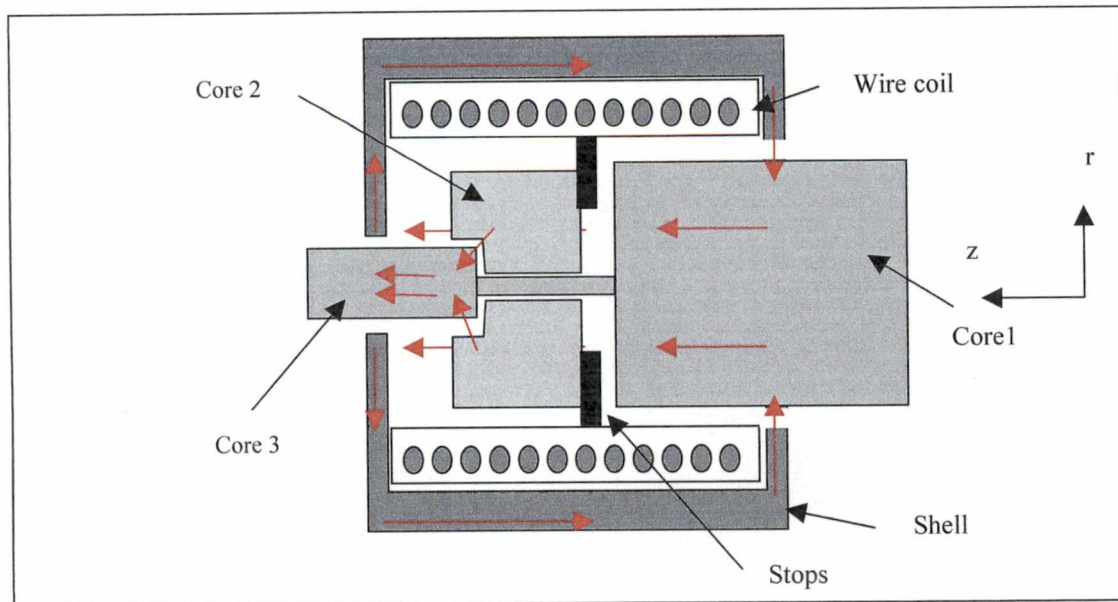


Figure 5: A cross section of the two-stage solenoid design. Core 1 is rigidly attached to core 3. Core 1 moves toward core 2 until they are touching. Core 2 is held in place until this time by the magnetic force, and the stops. After this, the whole assembly moves left until core 2 is touching the shell. The red arrows represent a crude example of the path the magnetic flux travels, this path varies through the motion of the solenoid.

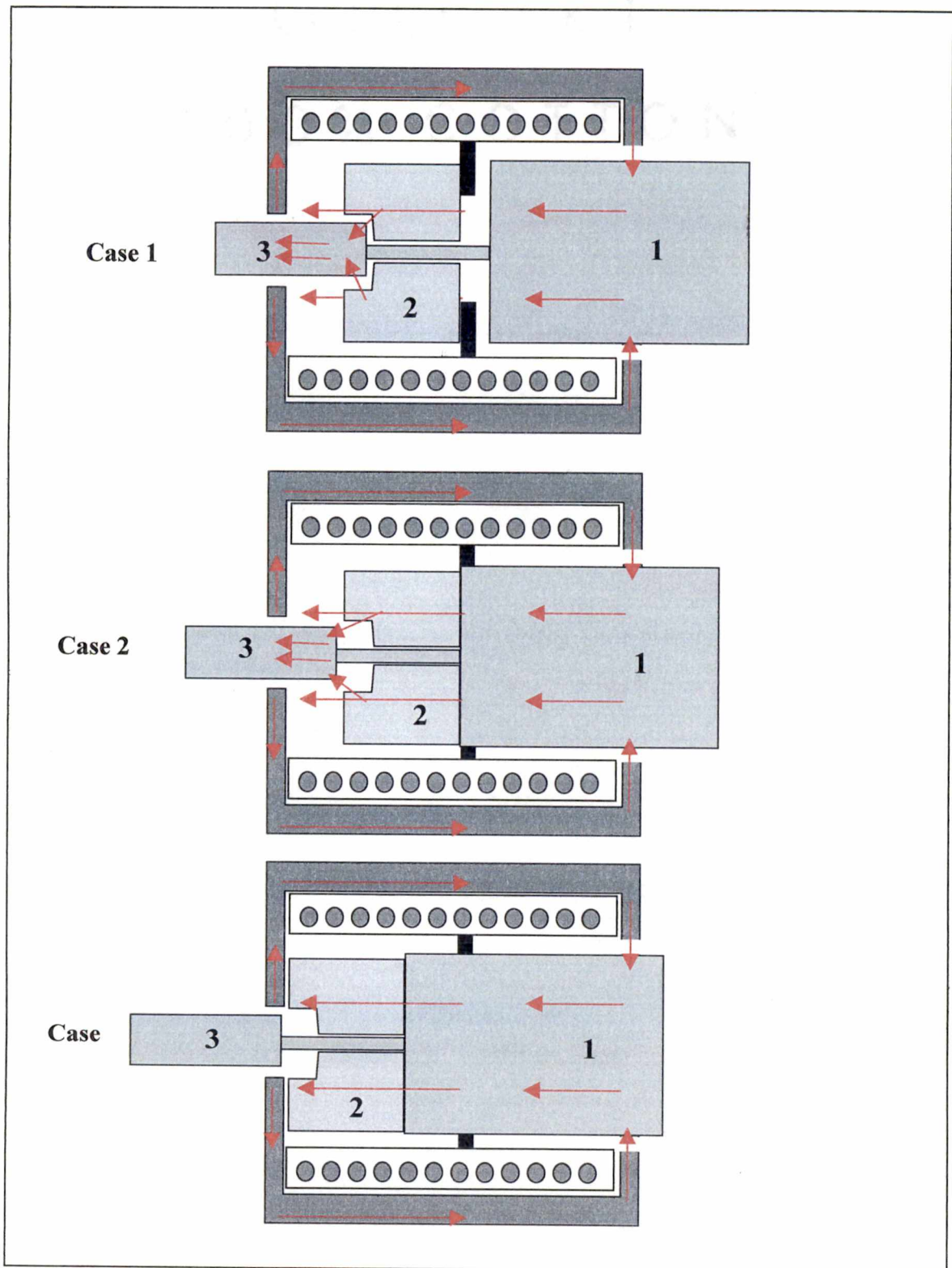


Figure 6: The motion of the two-stage solenoid design. This figure shows how there are two available paths for the magnetic flux to travel.

Case 2) When core 1 reaches core 2: At this point it becomes less advantageous for the flux to travel through core 3. Therefore, more flux passes through the gap between core 2 and the shell. The net force is such that all three cores move together.

Case 3) When core 2 reaches the shell: At this point and just before core 2 reaches the shell, flux flows almost exclusively from core 2 to the shell.

In the above design, reluctance of the system is reduced throughout the stroke. Therefore, the force is improved. With this basic understanding of solenoids, and the basic concept of the new design in hand, a quantitative study of the design can be performed.

In chapter 2 the basic equations governing solenoids are described. MATLAB and finite element models are created to model the design and results are discussed in later chapters. Also, a conventional solenoid is modeled for comparison. After demonstrating the overall effectiveness of the new design, geometrical parameters are varied in order to optimize the force output of the two-stage solenoid.

Chapter 2

Theory

To model a solenoid, the basic design equations must be understood. Four equations are used in determining the force output of a solenoid. Figure 3 is of use to better understand the components of a solenoid and the explanation of the given equations.

Basic Equations

First to be considered is the reluctance due to gaps in the path (follow the arrows in figure 1). Reluctance is measured in amps/Weber. This is described as:

$$R = \frac{Gap}{Area (\mu)}$$

In the equation, μ is the permeability of free space $= 4 \pi \times 10^{-7}$ Wb/A*m (All units are presented in the metric system). The reluctances are summed to determine the total flux, ϕ , measured in webers. The following equation is used to calculate flux:

$$\phi = \frac{NI}{\sum R}$$

NI is the current multiplied by the number of turns in the winding (amp-turns) (Siemon 3). Given the flux, the force, in Newtons, on the solenoid is given by:

$$F = \frac{1}{2} \frac{\phi^2}{Area (\mu)}$$

The units work out to be Newtons since $1 \text{ Wb} = 1 \text{ N}\cdot\text{m}/\text{A}$. Area in each equation is the area of the smallest surface in the location that the value is being calculated. The MATLAB model of the solenoid is based on these equations.

Another important quantity is flux density, B , measured in $\text{Webers}/\text{m}^2 = \text{Tesla}$.

$$B = \frac{\phi}{A}$$

In every material there is a maximum allowable flux density. The flux density increases with magnetic field intensity. However, a point is reached when this increase stops and the flux density remains approximately constant.

The existence of the flux density property of materials is important because it limits the total flux of the magnetic system. When a material is saturated, at the maximum allowable flux density, no more flux can be carried. Therefore, an increase in amp-turns will not yield additional flux, thus limiting the force produced by the system.

Chapter 3

Basic Design

The equations in chapter 2 show that if the total gap could be reduced, a larger force is possible. The equations are approximate since the assumption is made that all flux lines are perpendicular to the surfaces that they enter and exit. Using this assumption and noting that the gap should be minimized, a model can be produced that will increase the force for large gaps.

By varying the reluctance during the solenoid stroke, it is possible to improve the net force. Upon first consideration this may appear impossible. However, by providing multiple paths for the flux to travel, it will follow the path of least reluctance. It must be insured that the different paths vary through the motion, so that a benefit is gained. It would be desirable that these results be obtained by a simple change in geometry instead of complex mechanisms or circuits. Choosing geometrical parameters that achieve greater force over a longer distance optimizes the basic design shown in figure 5.

Geometry

Figure 5 shows the basic design geometry explored to create the desired results. A detailed drawing is presented in figure 7, which shows the different variables used in the analysis. Figures are presented for both the new solenoid and a standard solenoid. However, before the calculations used to model the system are considered, the desired performance characteristics of the solenoid are discussed.

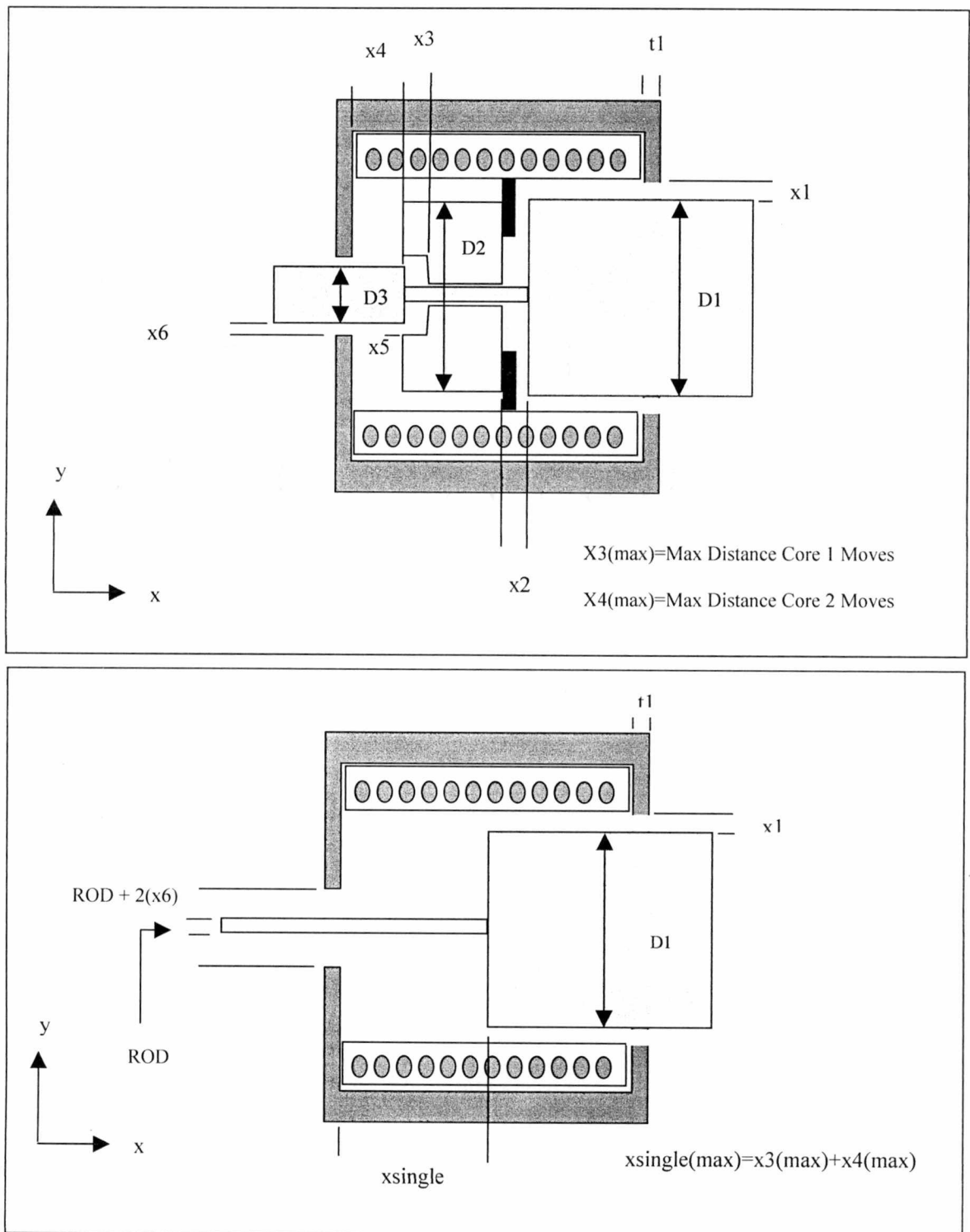


Figure 7: Various variables used in the MATLAB code. It also shows how the different variables for a 2-stage solenoid are compared to a regular solenoid. All gap distances are measured from the left.

Motion

When the solenoid is fully retracted, core 2 will be resting on the stops. Core 3 will be as close to core 2 as it will be at any point in the stroke. Core 1 will be as far away from core 2 as at any point in the stroke. The objective is to get core 1 to move toward core 2 without core 2 moving. Since core 3 is rigidly attached to core 1, core 3 will be moving away from core 2. It is imperative that the sum of the attractive force between core 2 and core 3 and the attractive force between core 2 and the shell never exceed the force between core 2 and core 1. This ensures that core 2 will remain at rest on the stops until core 1 reaches core 2. At this point, all cores move together, until core 2 reaches its final position; the solenoid is now in its most extended position.

Patent Check

A patent search was performed at www.uspto.gov. This site allows a search of patents by keywords in titles. A search on "solenoid" returned many results. This was refined to reject titles containing the word "valve". This removed most of the entries and left 200 patents. In this group the only idea similar to the present design was patent number 5,999,073, entitled "Tri-Core, Low Reluctance Tubular Solenoid". However, this design operates on a completely different premise; therefore, it appears that study of the presented design is justified.

Chapter 4

MATLAB Model

The objective of this study is to create a geometry that will allow the above-mentioned motion and create the largest force possible. To determine this, a model was created in MATLAB. (The Appendix contains the actual code).

Equivalent Resistance

The model is implemented by a series of steps. First, the total flux of the system is determined by finding the equivalent resistance of the system. Each gap is modeled as a resistance, and the equivalent system is found. Basically two systems exist, because as the solenoid moves, a point is reached where core 1 and core 2 are together. Figure 8 shows the gaps that will be modeled as reluctances, when core 1 is not touching core 2.

This model is of the solenoid presented at the top of figure 7. R_2 will approach zero when core 2 and core 1 touch. Also, R_5 will approach infinity when core 3 exits core 2. However, as has already been mentioned and as is presented in figure 9, the flux is assumed to travel in straight paths perpendicular to each surface. Logically, this is a poor approximation since fringing occurs, curving of the flux path.

After the basic model of the system was created, using the equivalent resistance method, the model was stepped through various positions. This gives the force vs. displacement curve.

Oversaturation Check

A MATLAB Code was developed to calculate quantitative results for this model of the system. In determination of the total flux, a check is made to make sure that the

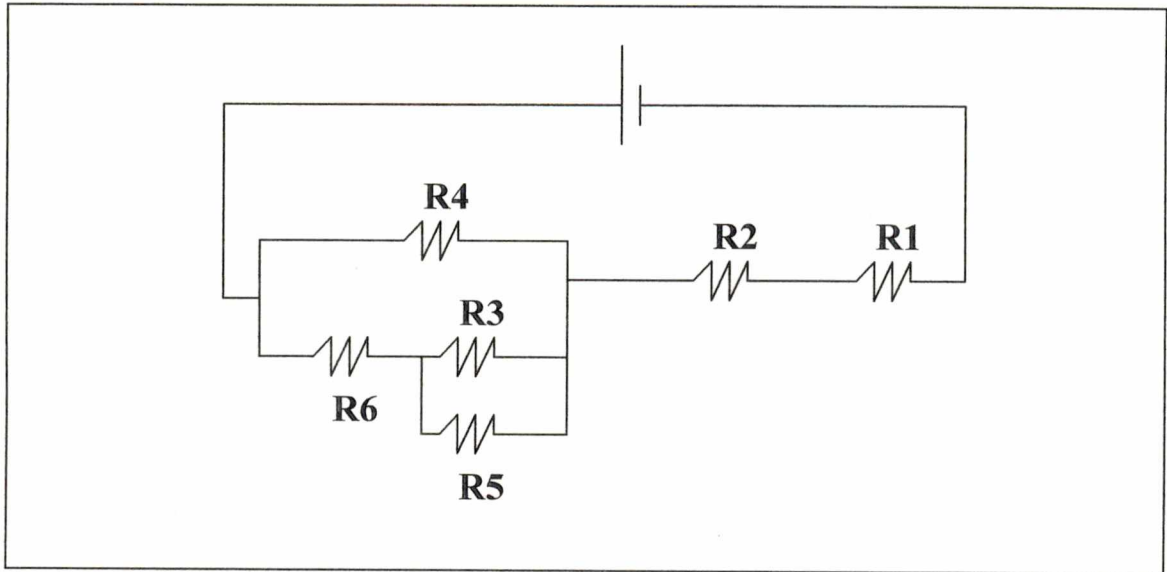


Figure 8: The equivalent resistance model for the solenoid modeled in MATLAB.

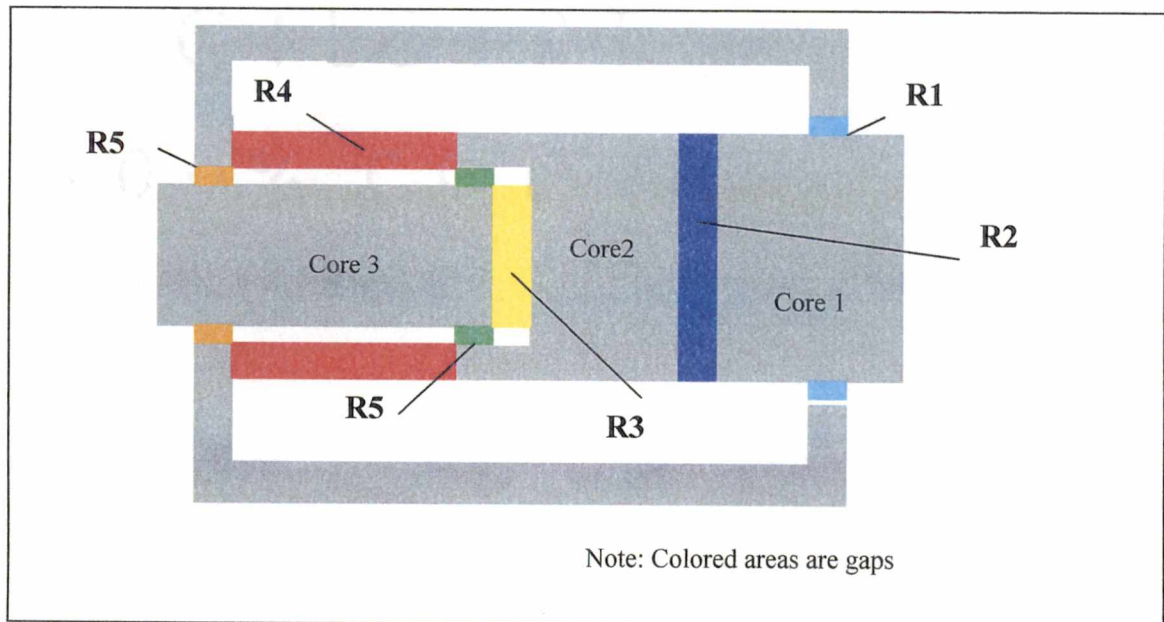


Figure 9: Different areas modeled as resistances in the MATLAB model. Notice that all areas are strait paths, not allowing for fringing of the flux path as would really be expected.

magnitude of flux density does not exceed the saturation value of typical materials. For example, a material such as nickel-iron, has a limit of 1.25 Tesla. The value of flux density is checked at the location with the smallest surface area in the path of the magnetic circuit. Therefore, it is found whether the above equations should be used in determining the total flux, or if the constant value of 1.25 Tesla should be used.

Force Check

The code is also set up to ensure that the net force between core 3 and core 2 and core 2 and the shell is not larger than that between core 1 and core 2. This ensures that core 2 remains resting against the stops for the time period it should. The program creates an error plot, which returns a one instead of a zero when an invalid situation occurs. Geometries that create this situation are not considered as options.

Program Output

With the total flux of the system found, the force created at each gap can be calculated using the previously mentioned equations. The program determines force versus displacement for the three main forces: force between core 1 and core 2, force between core 2 and core 3, and force between core 2 and the shell. The net force is equal to:

$$F_{net} = F_{1-2} + F_{2-Shell} - F_{2-3}$$

This net force is then compared with a regular solenoid with equivalent dimensions. Figure 10 shows the results of one such calculation.

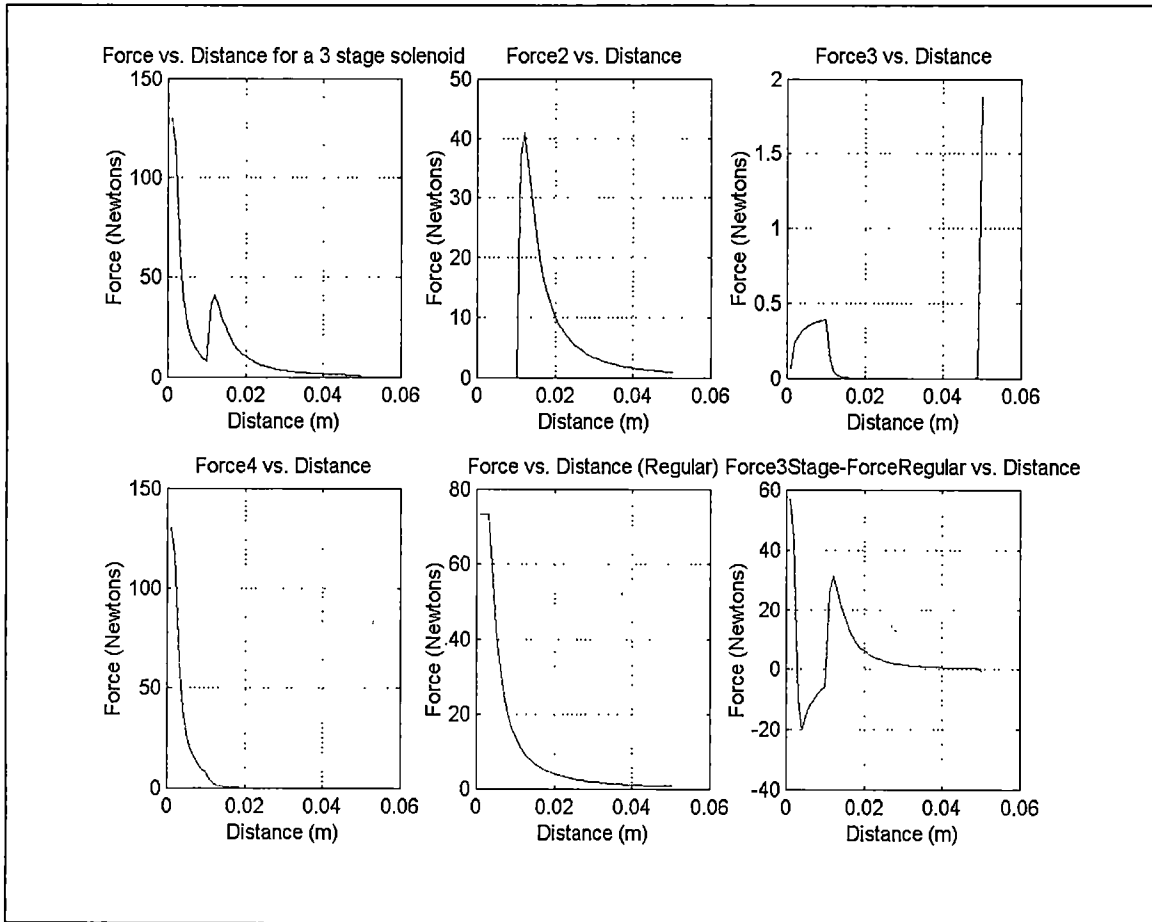


Figure 10: Sample output of the MATLAB code.

In this figure, force 2 is the force between core 1 and core 2, force 3 is the force between core 2 and core 3, and finally Force 4 is the force between core 2 and the shell. All forces are in the z-axis.

Force 4 has the basic shape of a normal solenoid. Force 3 increases slightly until it is inside the hole. When core 3 is inside core 2, the force decreases, until it is about to touch core 2 at which point the force is much greater. This shows that the hole is important so as to minimize force3, which detracts from the net force, and also makes

sure that core 2 remains in place until it should move. Force 2 increases until core 3 is in core 2, at which point the force decreases drastically.

This figure shows also, the results for a solenoid with an equivalent diameter (The diameter of the regular solenoid is the same as the diameter of core 1 in the two-stage solenoid). Also, the total distance traveled by the solenoid is identical to the total distance traveled by the two-stage solenoid. Figure 7 shows how these two solenoids are equated ensuring proper dimensions for an equivalent regular solenoid.

From the graphs it is possible to determine if the new design is better or worse. Also, it is possible to determine how changes in geometry change each force. This allows optimization of the geometric arrangement for certain force outputs.

Chapter 5

Refinement of Design Using MATLAB

Now that a model has been created, one can attempt to maximize the benefits from the new solenoid design. To study the importance of different parameters, changes are made to different parts of the geometry and the results compared. The following is a summary of the changes tried and the results.

Varying Gap between Core 2 and Core 3

First of all, the gap between core 2 and core 3 was minimized. This increased the value of force 2 by a noticeable amount, while not changing the value of the other forces. Therefore, the net force will increase, thus showing that this gap must be minimized.

Varying Gap between Core 3 and the Shell

Next, the gap between core 3 and the shell was minimized. This too created an increase in force 2, with no change in force 3 or force 4. Since it is force 2 which is the cause of the second hump in the net force graph, and this is the main benefit of the new design, it is very desirable to minimize this gap.

Varying the Diameter of Core 3

The diameter of core 3 was next varied; as this increases, the value of force 2 increases. However, force 4 decreases greatly. As the diameter decreases, Force 4 increases, but force 2 greatly decreases. Therefore, a value must be found which maximizes the results for both forces. This is a critical dimension.

Varying the value of x_4

Next, the maximum value for x_4 was decreased, which resulted in the first hump, the greatest value at the left of the figure, and second hump, the middle hump, moving

closer together. These results are notable since, our goal is to maximize force 2, the second hump. By having the two humps move closer together, force 4, creator of the first hump, and force 2, creator of the second hump, are more likely to overlap. This results in a higher net force in the area of overlap.

Varying the Diameter of Core 1 and Core 2

Next, the diameter of core1, as compared to core2, was varied. No benefit was found by changing the value of these two cores. Simply making them the same size is the best choice.

Varying the Amp-Turns

Finally, the number of amps running through the system was doubled, this created a great change in the results. More clipping occurred for both force 2 and force 3. This is because the solenoid becomes oversaturated in this setup. Therefore, in the final design, a change in the voltage could be used to refine the results.

Chapter 6

MATLAB Comparison of Performance Indexes

As can be seen changing the dimensions of various parts of the geometry has profound effects on the results. Therefore a computer code was created to compute many different setups and determine which is best. To do this, performance indexes are setup, to make the judgement.

Index Types

We can not compare the entirety of the curves with one another. Instead, we must set up performance indexes that numerically describe the benefit of each setup. Three different comparison indices were set up to determine this. The first criterion is the average value of the difference between the force of a single stage solenoid and the two-stage solenoid.

The second was the sum of the average value of the difference between the two solenoids and the average of the negative values. This basically puts twice the weight on all negative values. Since a negative value represents a performance that is poorer than that of a normal solenoid, this method is logical.

Finally, a difference between the two was found that looked only at the difference after the minimum value had been reached. Since the maximum force occurs when a solenoid has the smallest gap, it was felt that it would prove beneficial to ignore this area. This location does not create problems in the operation of a solenoid. However a focus is made on the portion which creates the most problem for a solenoid, when the gap is largest. This index is called the special average on chart 2.

Variables

A program was set up that would change various parameters. When the indices were maximized the parameter values were stored. Basically from the above results it was determined that a total of four quantities should be varied. Constant values of 20 mm were set up for the diameter of core 1 and core 2. All gaps that did not involve a change from the motion of the cores had a value of .5 mm. The total stroke of the system was also fixed at 50mm. This represents the sum of the two gaps which decrease with core motion. However, the initial gap between core 1 and core 2, called x3, and the initial gap between core 2 and the shell, called x4, were varied. These values are referred to as x3max and x4max. The following relationship governs this:

$$X_{total} = X_{4 \max} + X_{3 \max}$$

Also varied, were the depth of the hole in core 2, and the diameter of core 3. Table 1 gives the initial values entered for the system. Refer to figure 3 for a description of the location of each of these points. (All tables are found in the appendix).

Results

The results of these studies are seen in table 2. As can be seen, when one index is maximized, the values of the other comparison indices are not at their maximum. The best geometry for each situation is different. It is notable though that x3max always has the same value as xhole.

A decision was made as to which of the indices to use. This was done by choosing the index which, when at its maximum, would not make the other two indexes

excessively small. This proved to be the index that was the sum of the average value and the negative average value.

After determination of the best design, the data is input into the original program to obtain plots of the force for this arrangement. Figure 11 shows the results of this. It can be seen that improvement has been made as compared to a regular solenoid.

The plot shows the actual force created by the system. This appears as the first graph on the figure. The final plot on this figure shows the difference between the new solenoid and the regular solenoid. The new design follows closely the output of the old design, yet increases sharply at the second hump. Through this whole motion the average value for the two-stage solenoid is 8.9915 N and that of an equivalent regular solenoid is 6.9867 N. This represents a 29% increase in the average force through the stroke.

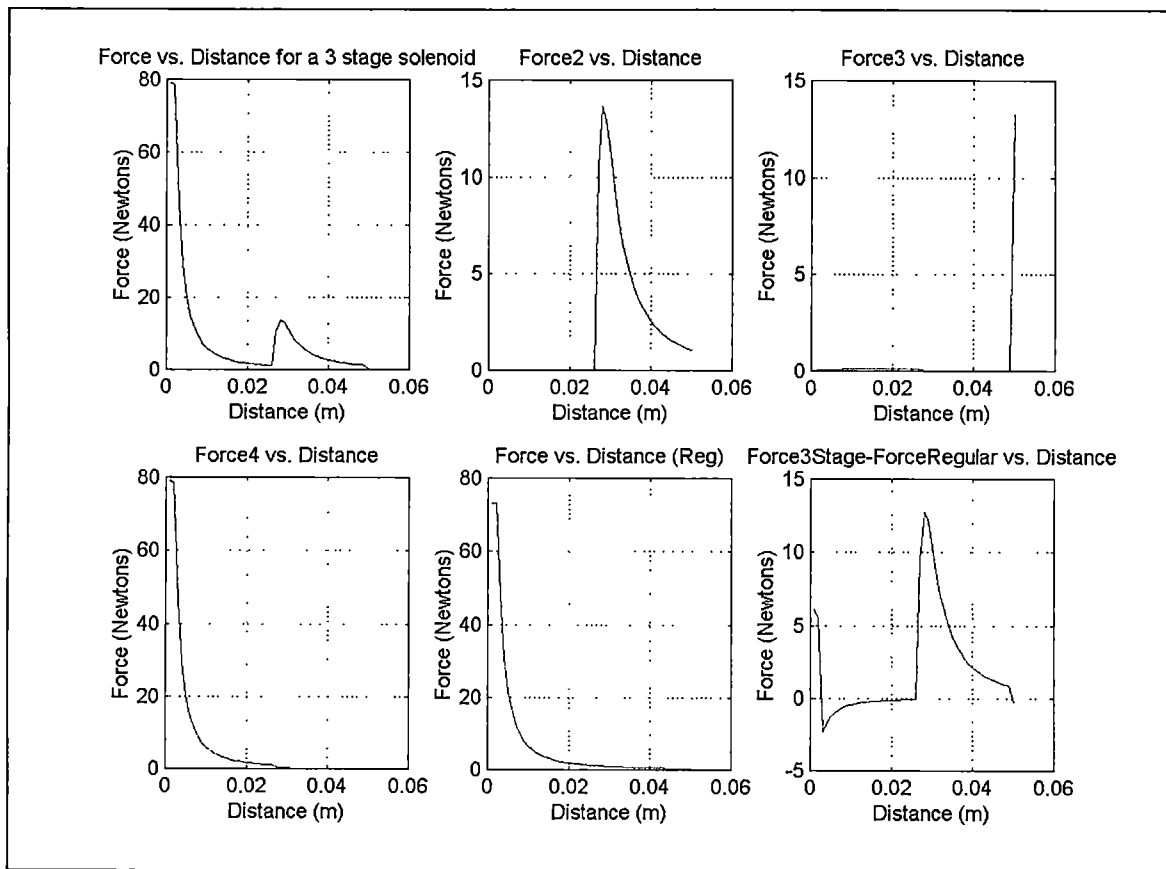


Figure 11: Matlab output for the best setup for a total travel of 50mm.

Chapter 7

Need for A New Model

At this point it is obvious that the proposed design does provide a better force output. However, a few problems exist with our model. First of all, the MATLAB model is approximate in that it assumes that all flux paths are perpendicular to the surface they exit. This inaccuracy exists because fringing occurs. Secondly, approximations were only made for the effect of oversaturation of the materials. Third, the models looked at so far were for solenoids with very long strokes (50 mm); however, a typical solenoid only has a stroke of a few millimeters (5-10 mm).

A more refined model was obtained by the finite element method, utilizing Maxwell 2D Electromagnetic Software, a magnetic fields finite element modeler (A user guide is found in the appendix). A starting point for the proper geometry to use is gained from the MATLAB results. This approach is only an approximation because the solutions found represent magnetostatic solutions, which does not take in account the motion of the system. A solution for a dynamic system depends upon the loads applied to the solenoid. This problem is beyond the scope of this paper.

Starting Point

Some basic design parameters have been taken from the MATLAB program. For example, the MATLAB results showed that for best results the third core should just barely be out of the hole when all cores are moving ($x_{3\max}=x_{\text{hole}}$). However, with the fringing factor, different results may be expected. Too, it was found that the third core's size should not be excessively large. Finally, the distance traveled by core 1 and 3 while core 2 is not moving, should be approximately the same as the distance traveled when all

cores are moving. These assumptions will be used for the initial look at the finite element models. A closer look at their accuracy will be made later.

Chapter 8

Finite Element Model

Check of Model Error

An important issue is how fine a mesh the finite element code uses. The Maxwell program uses the energy method to determine the error in the calculation. This method compares the total energy of the system based on input information with the total energy found by the finite element method. For this problem the program recommended a maximum allowable error of 1%. The error goal should be small enough so that a constant force value is arrived at for the problem, but large enough to minimize the number of iterations required to reach the error goal.

Figure 12 and 13 show convergence plots. The plots show that the value of the total energy of the system, the error of the systems energy, and the force level off after about 10 passes. Each pass represents a refinement of 15%. Figure 13 also shows that the number of triangles increases greatly after 10-15 passes. The number of triangles is the number of small areas into which the drawing is split to perform the calculation. The greater the number of triangles, a finer mesh, the greater the accuracy. As the allowable error is decreased the number of triangles required increases. Since the more triangles, the greater the number of equations, and thus an increase in calculation time, it is obvious that 1% error (which almost always happens in less than 10 passes), is a good choice.

Throughout the rest of the studies, this allowable error is used. The validity of this assumption was checked a few times in different geometries, and all showed similar results.

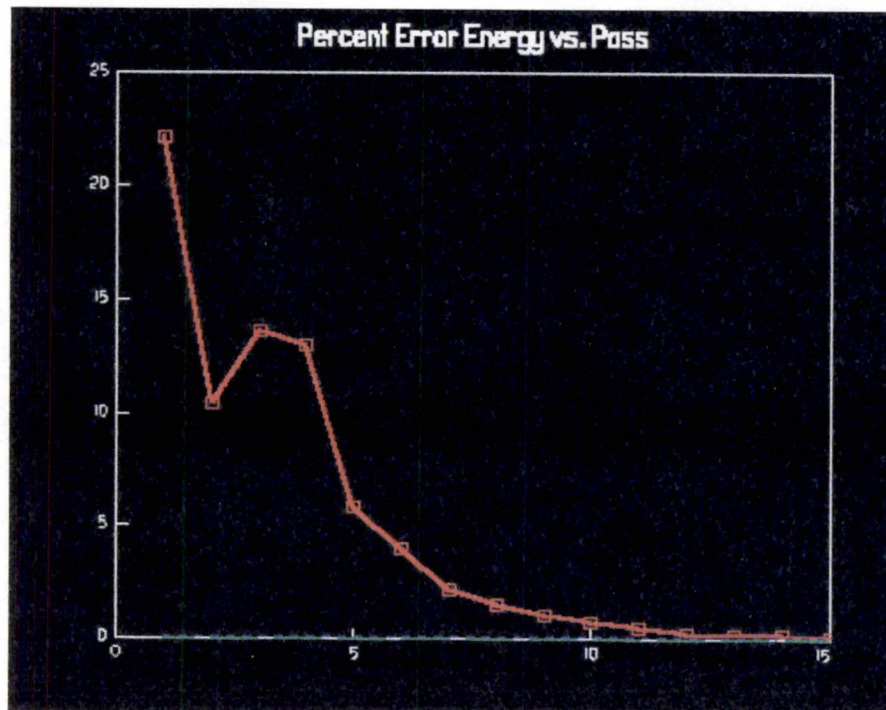
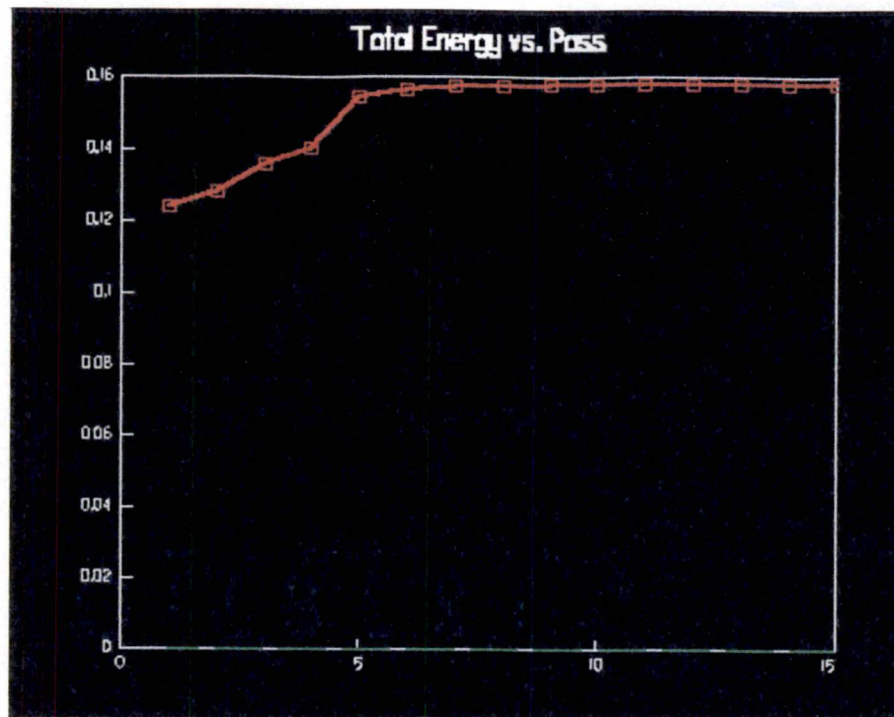


Figure 12: Energy refinement for the system after consecutive passes. It is obvious that a point is reached when more passes are not beneficial for the time invested. This is for the system described in the previous figure.

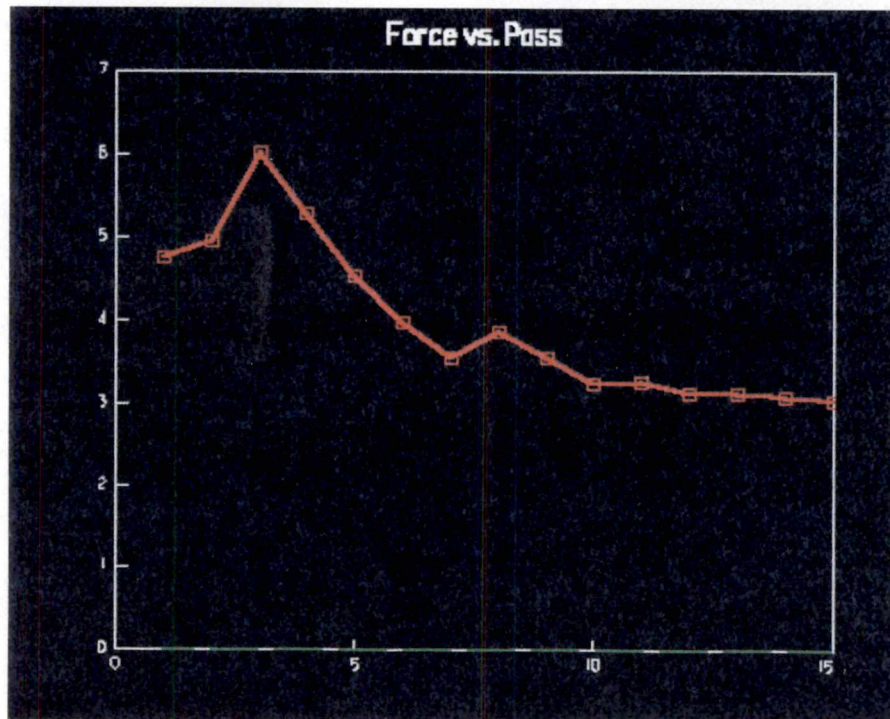
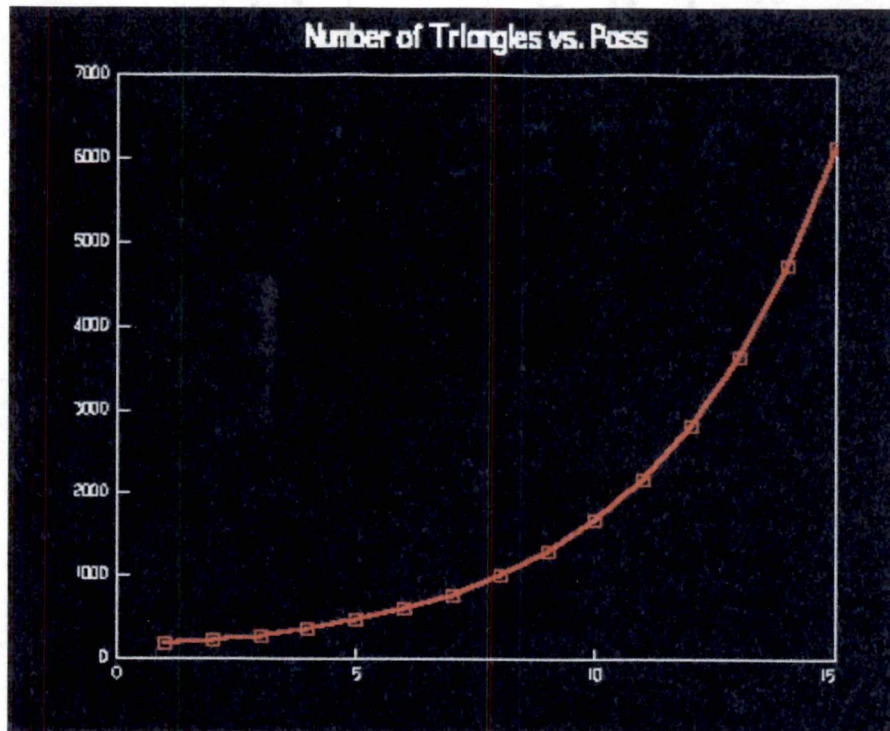


Figure 13: Force Refinement and Number of Triangles increase. The top figure shows the number of triangles in the calculation increasing exponentially, detracting from having too many passes. The lower figure shows that the calculated value basically levels off when a certain point is reached.

With the parameters known for the finite element software, it is now possible to construct an actual model. A solenoid was drawn in Maxwell using the same dimensions that proved to be the best results for the solenoid that travels 50 mm. However, when modeled in Maxwell, the distance traveled was only allowed to be 25 mm. Also created was an equivalent regular solenoid model. The same method for equivalence was used as used in the MATLAB program.

Observations

The first observation is that flux lines do not travel in straight lines perpendicular to the surface they exit. This is just as expected. Figure 14, a regular solenoid, shows the flux output of the system. The main thing that should be observed is the curved path of equivalent values of flux. Note: In these plots half of the cross section is observed. This is because the solenoid is axially symmetric.

The second observation is that magnitude of B varies throughout the assembly as expected. However, the value is not necessarily a constant at any given cross section as is modeled in the MATLAB code. Figure 15 shows the magnitude of B for the same solenoid presented in figure 14.

Equivalent Regular Solenoid Model

We will now look at the actual force output of the three-core solenoid through its entire motion. First we create a model of a regular solenoid to have a basis of comparison of results. The flux carrying material is chosen to be 1008 steel, which has an effective range of use from 1.5 to 2.1 Tesla. This solenoid has a main core diameter of 20 mm and travels 25 mm. The force for different gap amounts is found by changing the gap and performing the magno-static finite element calculation on the configuration.

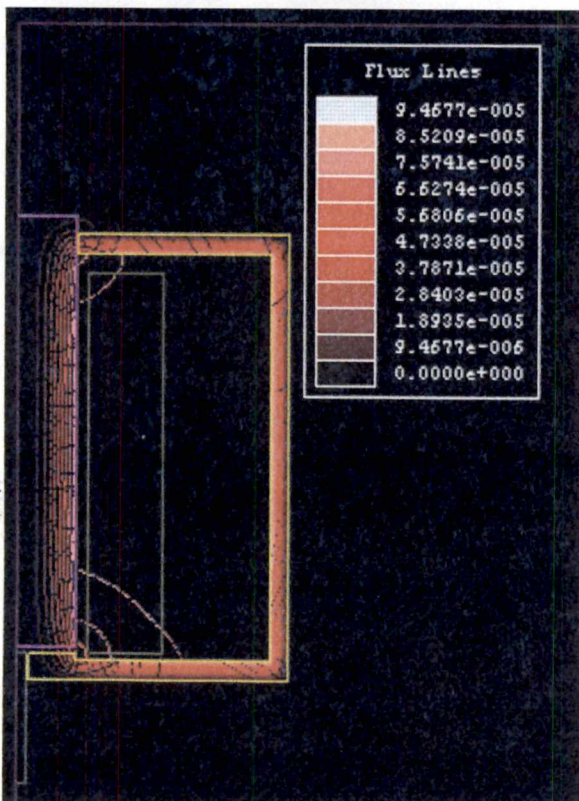
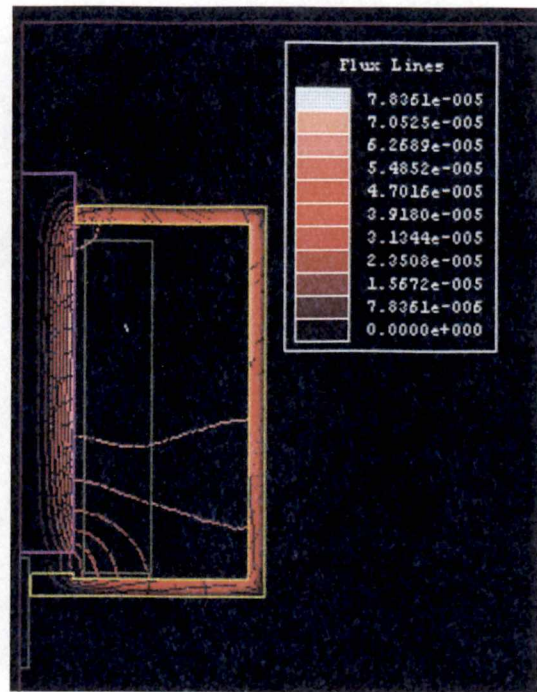
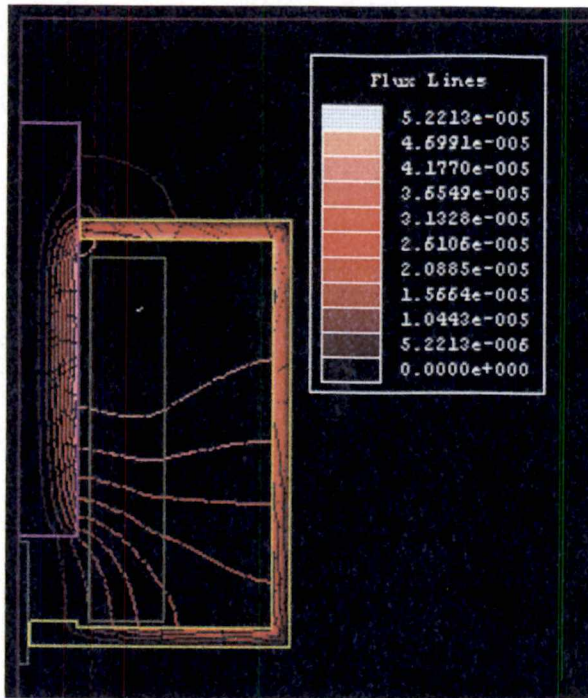


Figure 14: Flux lines for a regular solenoid with the core in various locations. The main thing to observe is that more straight paths occur the closer the solenoid is to the shell.

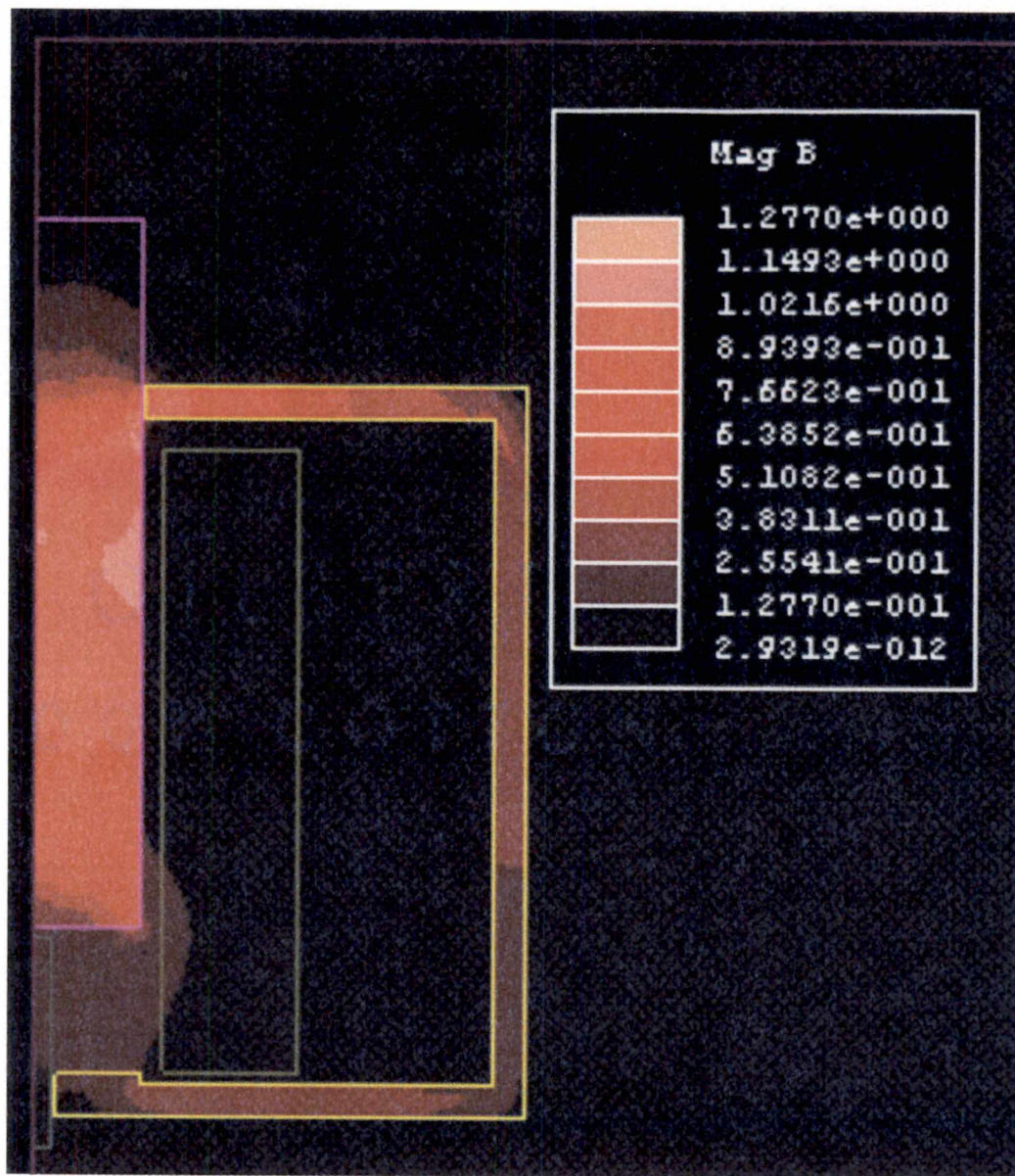


Figure 15: Magnitude of B (Measured in Tesla) in a solenoid. It should be noted that the magnitude of B is not the same in any given cross section. In fact it is quite complex in its description, thus requiring something such as a finite element code to describe it.

Results from the finite element code are presented in Figure 16. Here also is seen the results for the same solenoid using the MATLAB code. It is obvious that a similar trend is followed by both. While they are similar in shape, the finite element results give higher force values, which could be due to the fringing effect.

Two-Stage Solenoid Model

The two-stage solenoid model is now created. Figure 17 shows the dimensions of the model. The only problem is that two separate models are required to describe the system. As in the MATLAB model, there are two magnetic circuit designs, one model for the occurrence when core 1 and core 2 touch, and the other for the situation when they

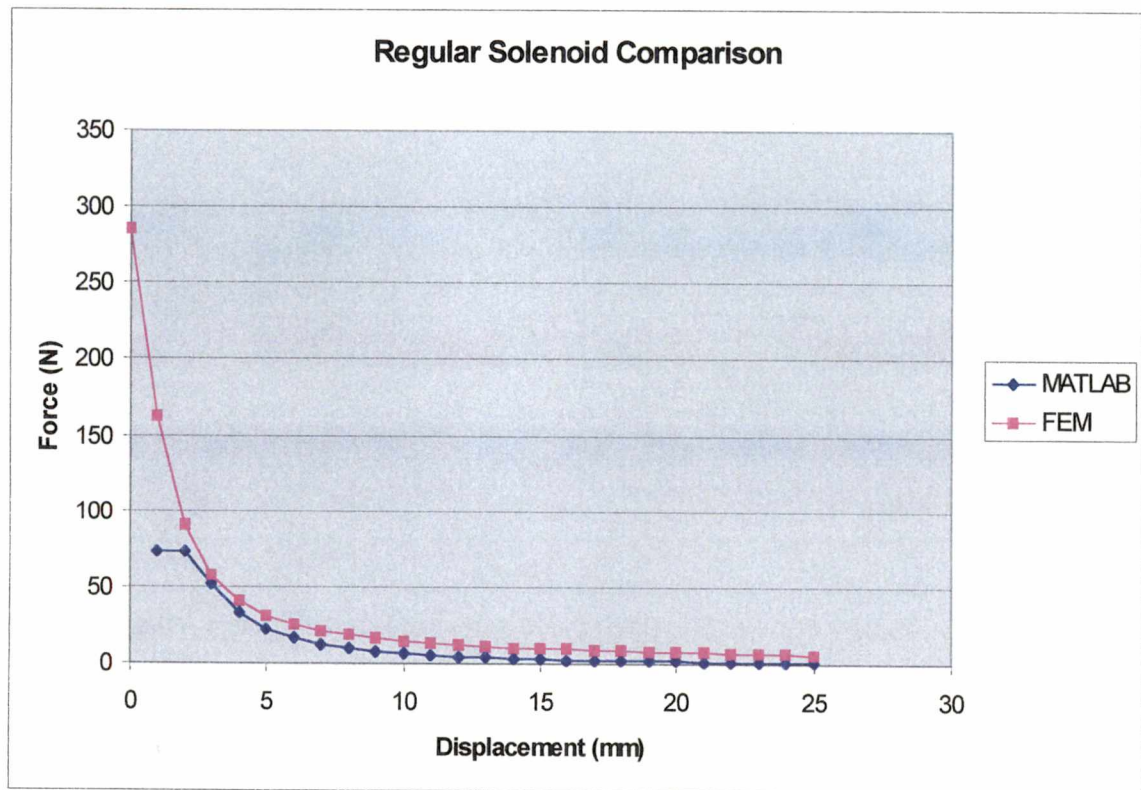


Figure 16: Relation between the Finite Element Code and the MATLAB code for a regular solenoid.

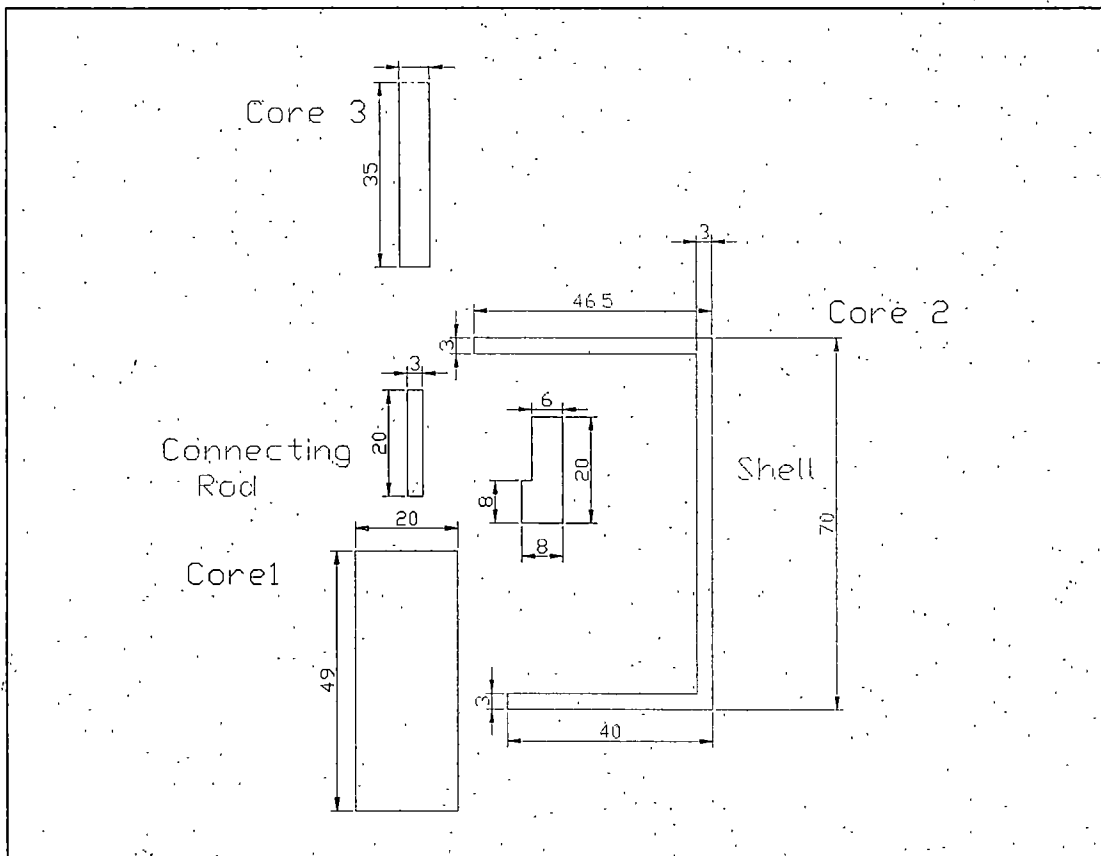


Figure 17: Dimensions of Two-Stage solenoid modeled in finite element program. Units are mm.

are separated.

Figure 18 shows the force output of that system for the part of the motion before core 1 touches core 2. This represents the force on core 1 and core 3, the moving parts of the solenoid. Figure 19 shows the force output for the motion when core 1 and core 2 are touching. This represents the force on all three cores since they are all moving. Notice that these are plots for different amp-turn values for the coil in the solenoid.

For proper operation it is critical that core 2 remains at rest until core 1 reaches it, that is it must remain at rest on the stops. This requires a negative force on core 2 during this time. This is exactly the result, as shown in figure 20.

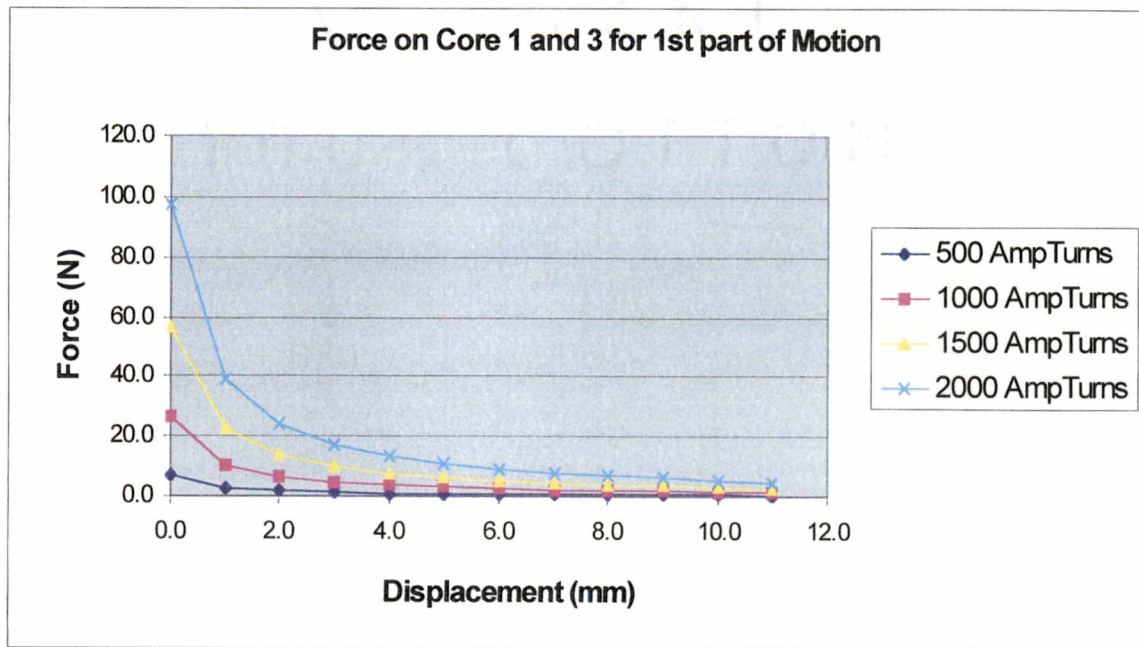


Figure 18: Force output for the first part of the motion, for the solenoid shown in figure 17.

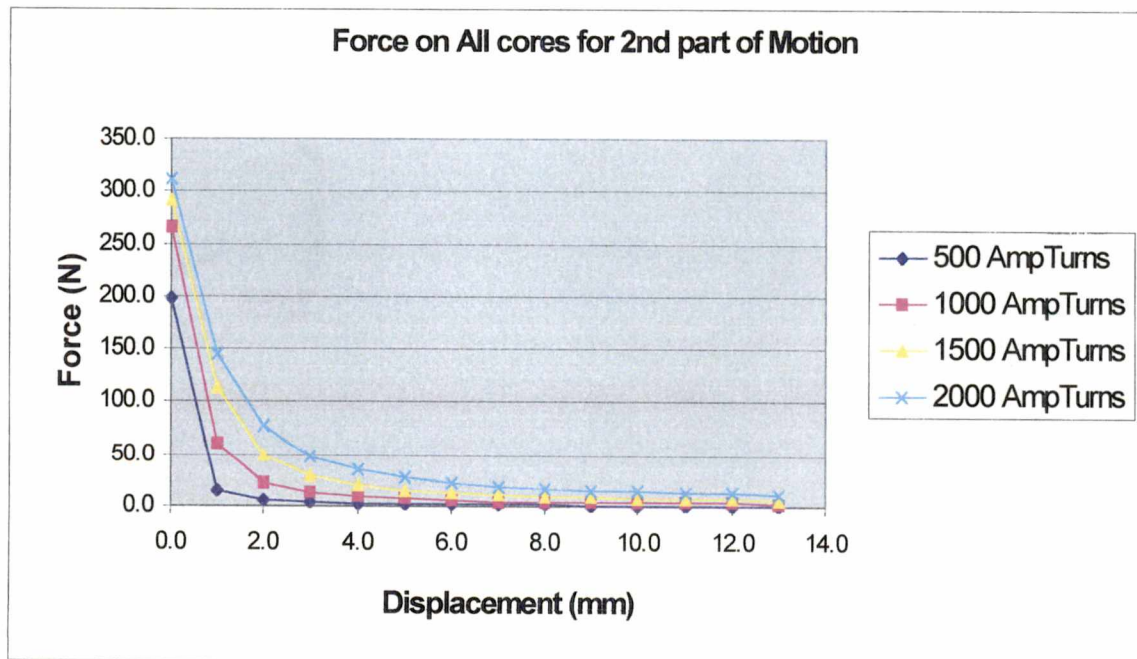


Figure 19: Force output for the second part of the motion, for the solenoid shown in figure 17.

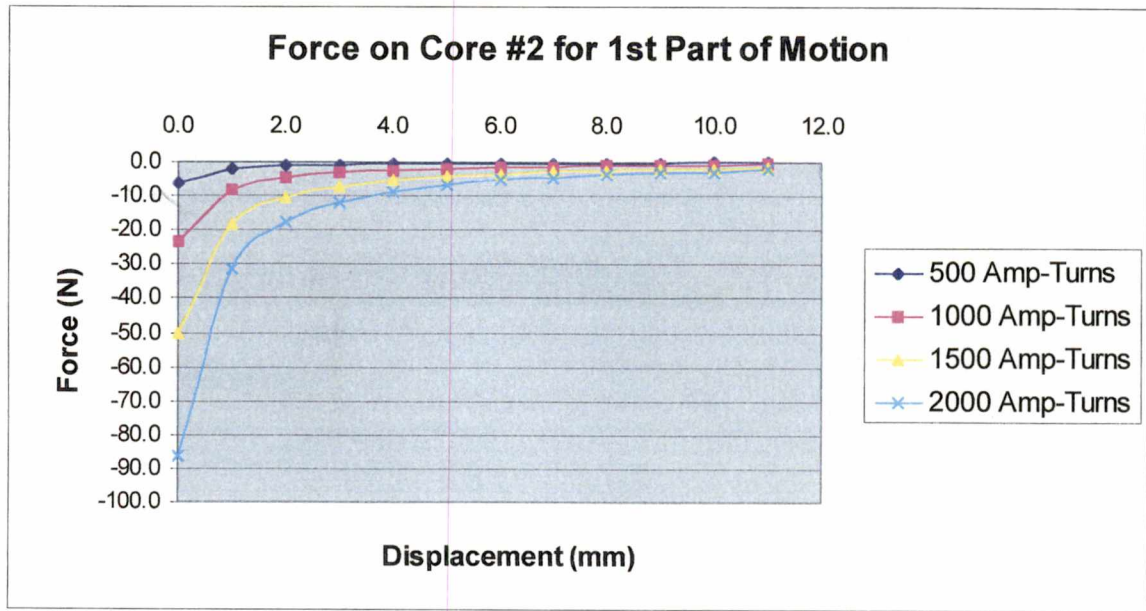


Figure 20: Force acting on core 2 during the first part of the solenoid's motion. Since it is negative at all locations, it is held against the stops, ensuring proper transition from the first part of the motion to the second part of the motion.

Now that the forces for the first part of the motion, figure 18, and the second part of the motion, figure 19, has been found, they can be combined into one plot showing the force through the whole motion. The results are plotted along with the MATLAB results in figure 21, for the 2000 amp-turn case. Note that the same types of plots will be viewed several times. To better understand these plots and terminology referred to in the text, refer to figure 22.

Similar results are obtained from the two models. However, the magnitude of the second hump is much larger in the finite element model and justifies further study of this model.

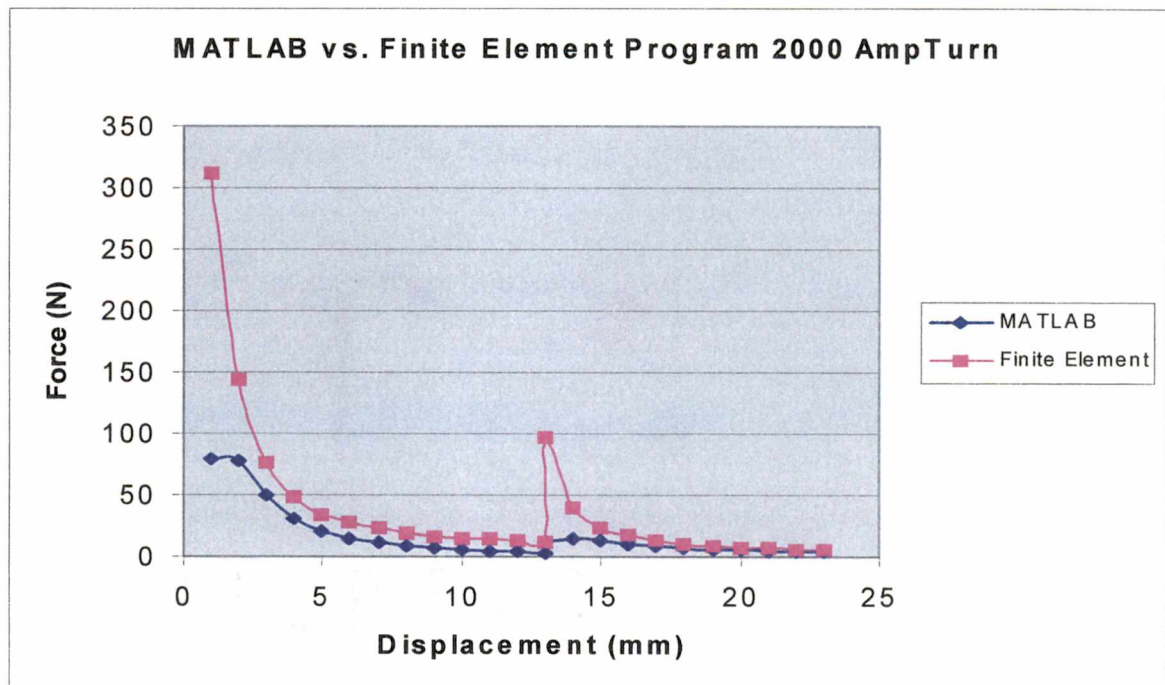


Figure 21: Relation between the Finite Element Code and the MATLAB code for the new solenoid design.

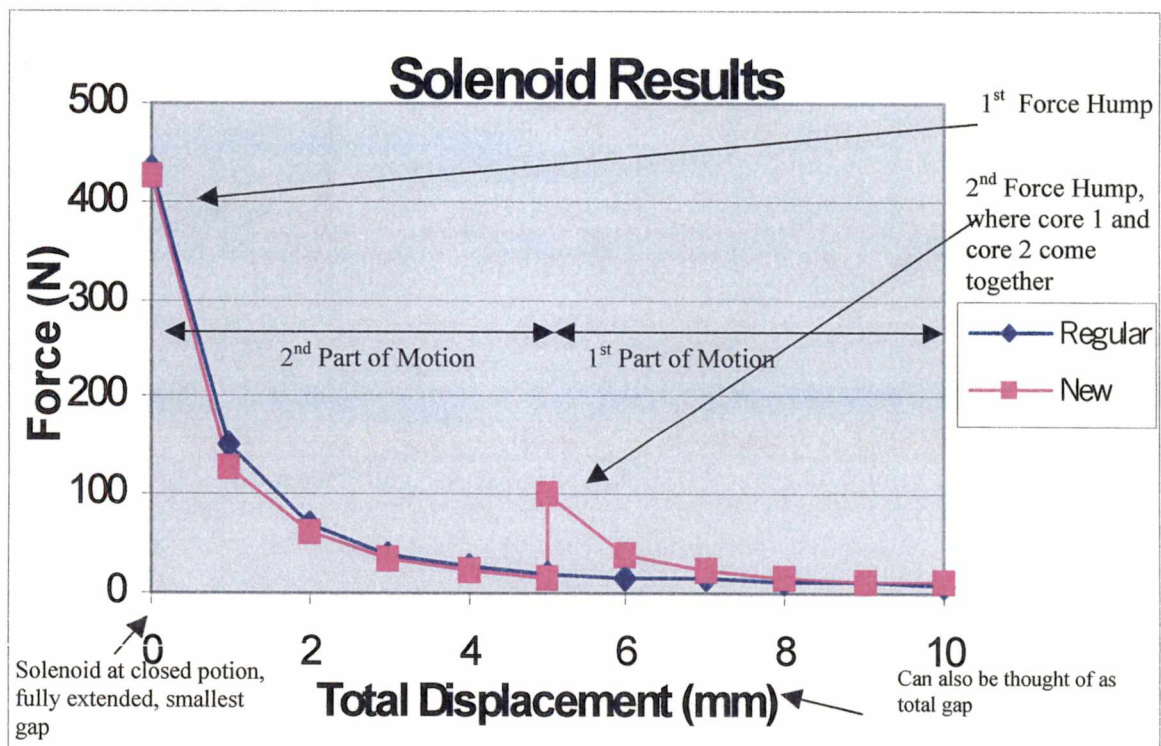


Figure 22: A typical graph and the names given to the different parts of the figure in the body of the text.

Chapter 9

In Depth Refinement of a Two-Stage Solenoid with Short Stroke

All solenoid models considered to this point have involved long strokes. However, most solenoids have a short stroke. Even with increased force in the middle of the motion, a long stroke is a bad design. Solenoids are normally limited by their smallest force. A new design should minimize the decrease of force with displacement. Similar conclusions to those already found are expected on a two stage solenoid design with a shorter stroke, 10mm. The following study will be for a solenoid size and geometry corresponding to dimensions of commercially available solenoids. The general dimensions of the solenoid are presented in figure 23.

For this geometry, the force for the two-stage solenoid and for an equivalent regular solenoid is presented in figure 24. (Note that from this point forward all models use 1500 amp-turns). The percent improvement is shown in figure 25. From this figure it is obvious that improvements are gained by the two-stage design. Yet, the force before the hump is reached is actually less than that of a single-stage solenoid. This is not desirable.

An endeavor to refine the geometry of the two-stage solenoid must now be undertaken. The goal is to maximize the force output of the two-stage solenoid. This is similar to the refinement performed in the MATLAB program. Just as with the MATLAB program, various dimensions are varied to determine the effect on the force. Results similar to those for the MATLAB code should be found.

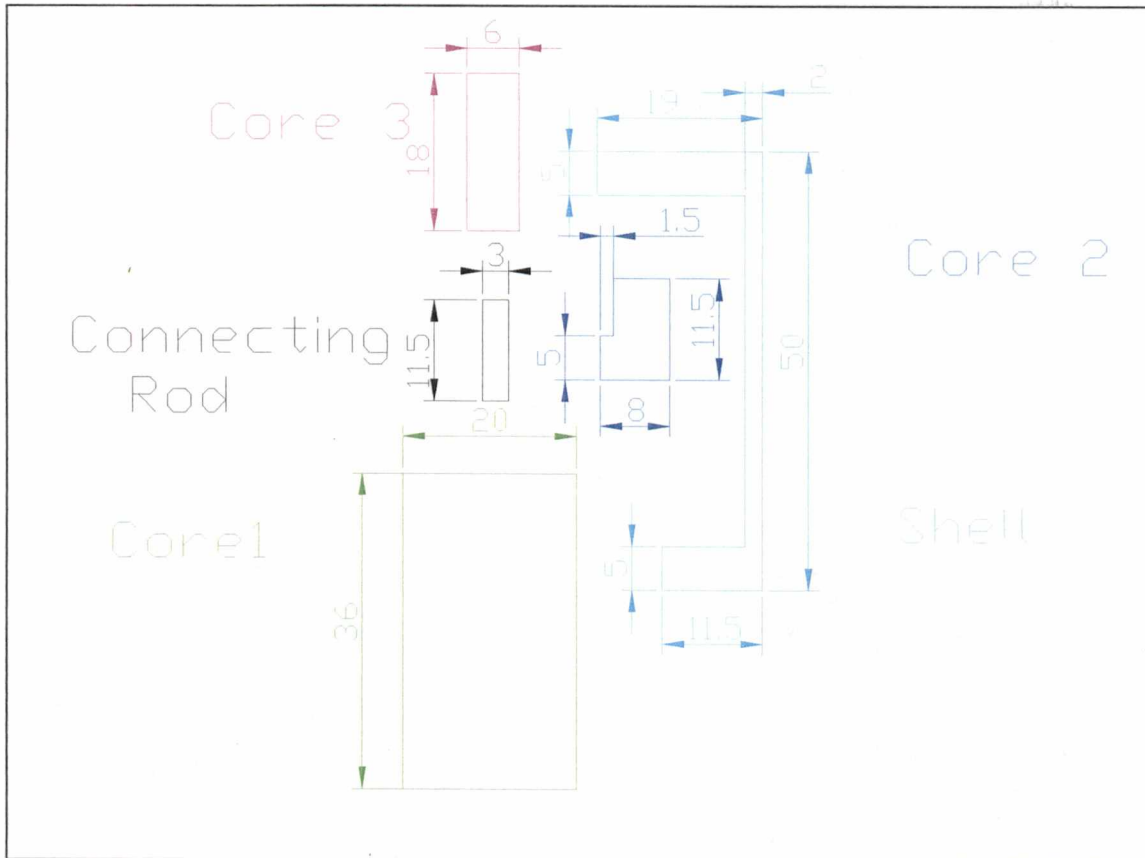


Figure 23: Dimensions for the solenoid to be refined. Core 1 and Core 3 are actually

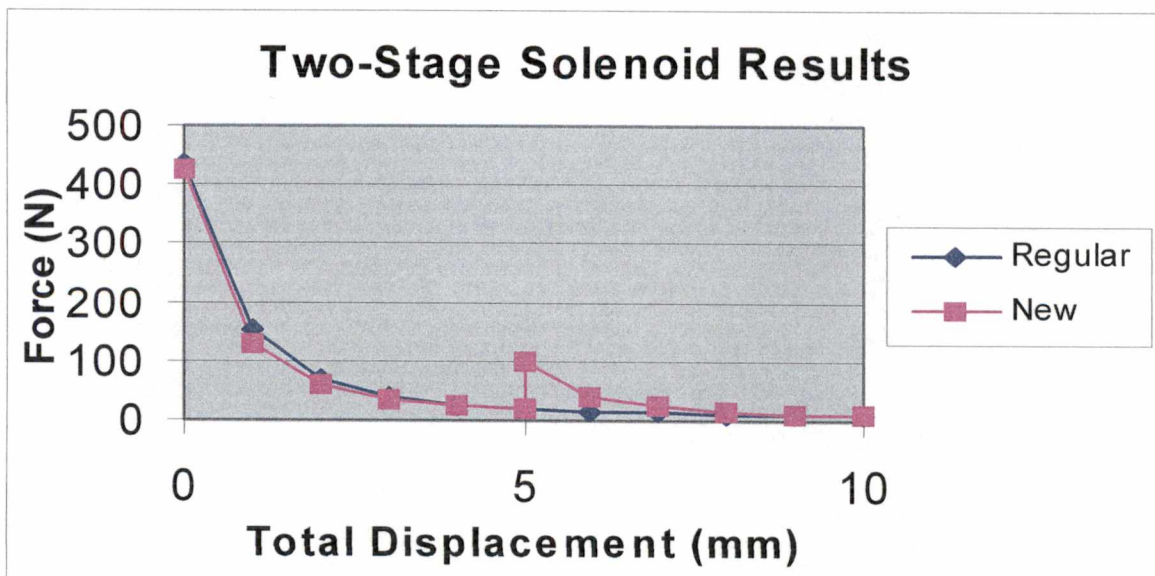


Figure 24: Force output for the two-stage solenoid presented in figure 23. The total displacement is 10 mm. Also plotted is the force of a regular solenoid.

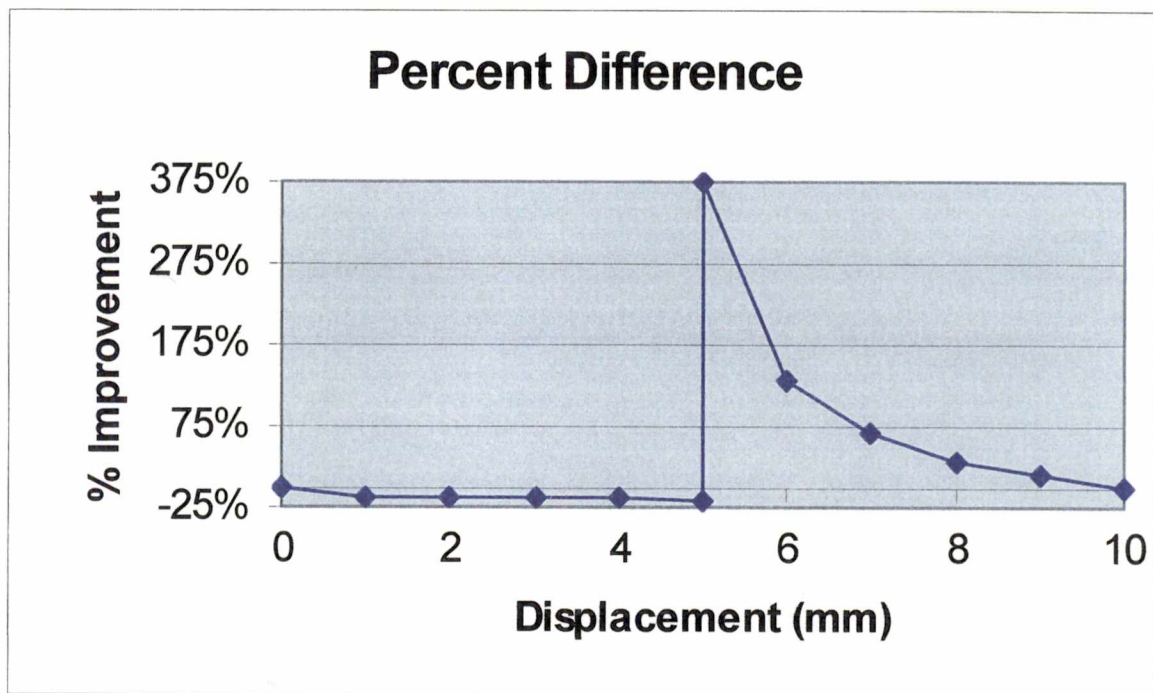


Figure 25: Difference between the two-stage solenoid and a regular solenoid for the data in figure 24.

Diameter of Core 3

First, the size of core 3 was varied. The radius was increased 2 mm. Figure 26 shows the percent change in force using this geometry as compared to the two-stage solenoid discussed and displayed in figure 23. As can be seen, an increase in the diameter of core 3 increases the force on the first part of the motion (5-10mm). However, it decreases the force in the last part of the motion (0-5 mm). Since one of our objectives is to increase the force where the difference is negative in figure 25, 0-5 mm, this design is not a good choice.

This result is expected, since a larger diameter third core allows more flux travel, and thus greater force between core 1 and core 2. Also as expected, the force for the

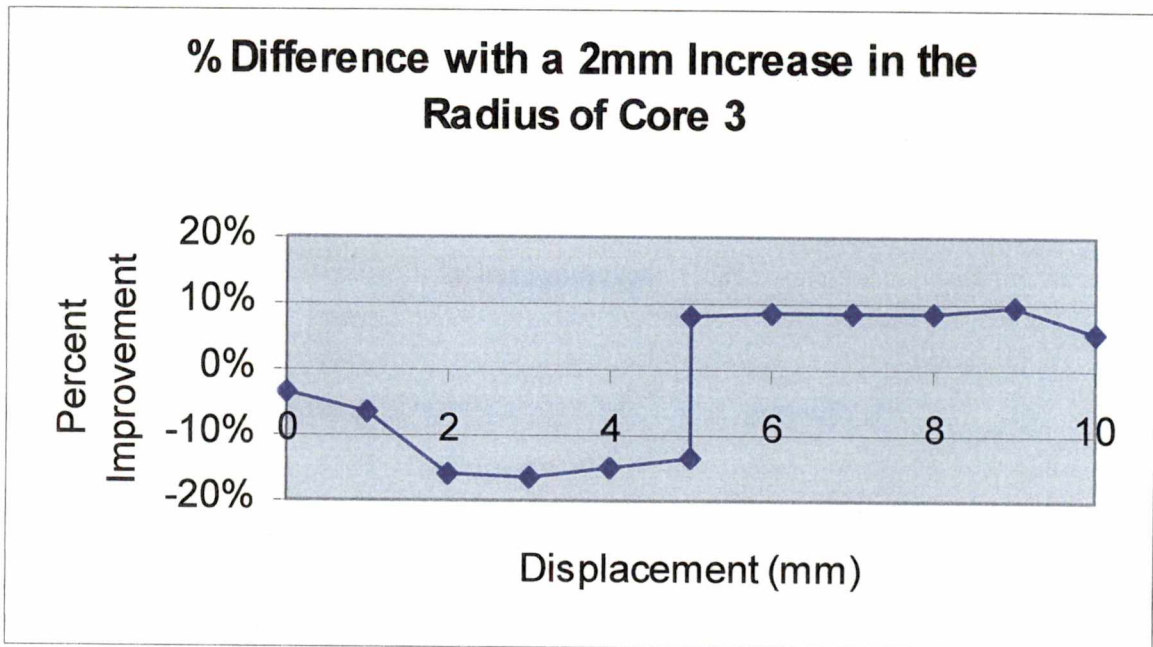


Figure 26: Change in the force output when the radius of core 3 is increased 2 mm.

second part of the motion is less since a smaller area is available for an attractive force between core 2 and the shell. Overall, the integral of the total force was decreased 3%. Similar results were found with the MATLAB code.

Length of Connector Rod

Next, the length of the rod separating core 1 and core 3 was increased 2 mm. This leaves core 3 in the hole for a shorter distance, but increases the gap between core 2 and core 3 when core 1 and core 2 are in contact. This increases the force during the second part of the motion. Figure 27 shows the percent increase in force for this geometry, as compared to the solenoid in figure 23. While increasing the length of this rod definitely changes the force, it does not seem to be very beneficial overall. For this change, the total force of the path increased 2%.

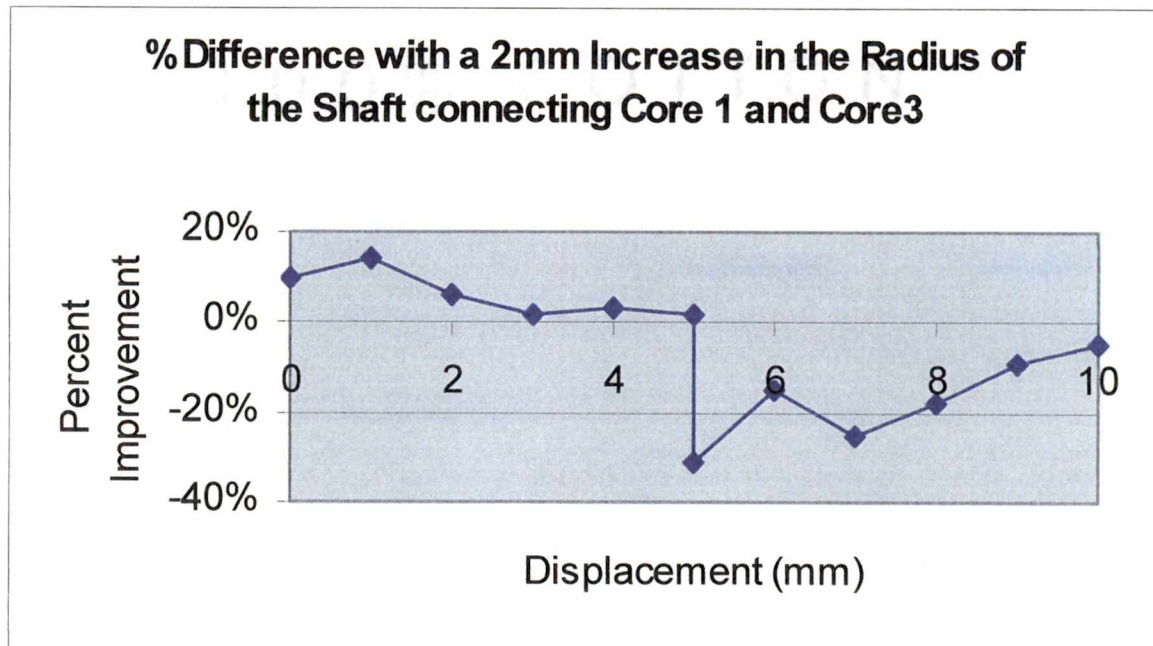


Figure 27: Change in the force output when the length of the connecting rod between core 1 and core 3 is increased 2 mm.

Shell Geometry

Next the effect of changing the geometry of the shell was studied. There was no change in wall thickness, which would obviously have an effect on the saturation level of the shell. Instead a lip was introduced as shown in figure 28. The lip dimension is increased from 0 to 2 mm and then from 0mm to 4mm. The effect on the force is seen in figure 29 and is obviously a bad choice. The only area improved is the very last part of the motion, where displacement is 0 to 2 mm. Since this is the last area we are hoping to increase, this change in geometry is not beneficial.

Diameter of Core 1

The next thing to be tested is the effect of increasing the diameter of core 1, in combination with various other changes. It is expected from previous findings that an

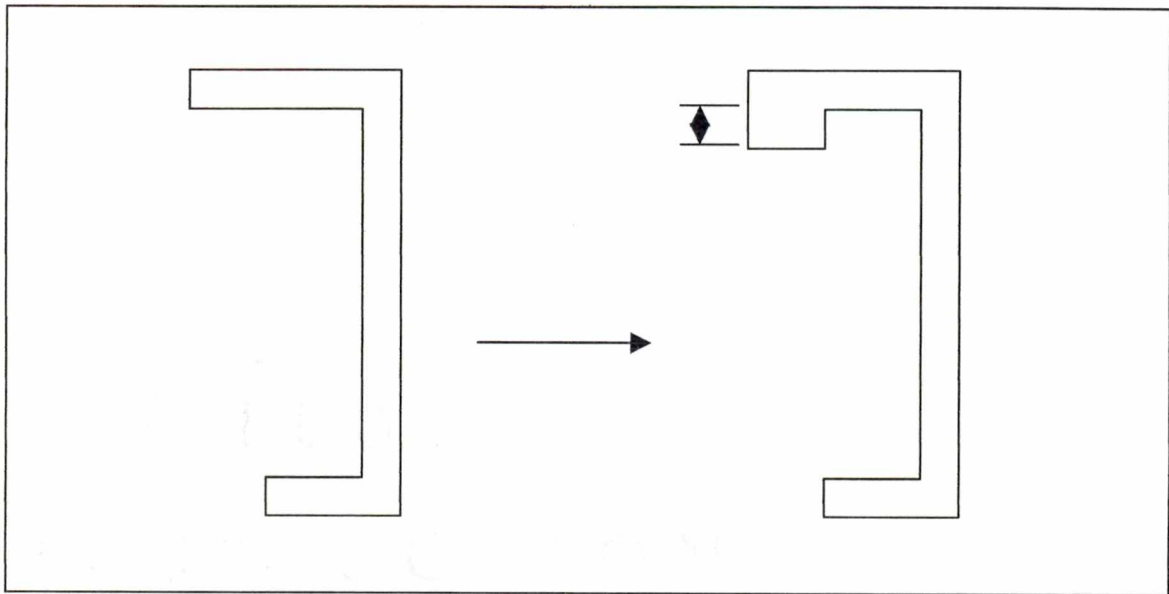


Figure 28: The variable being changed in figure 23. This is looking on half the cross section of the axial symmetric solenoid shell.

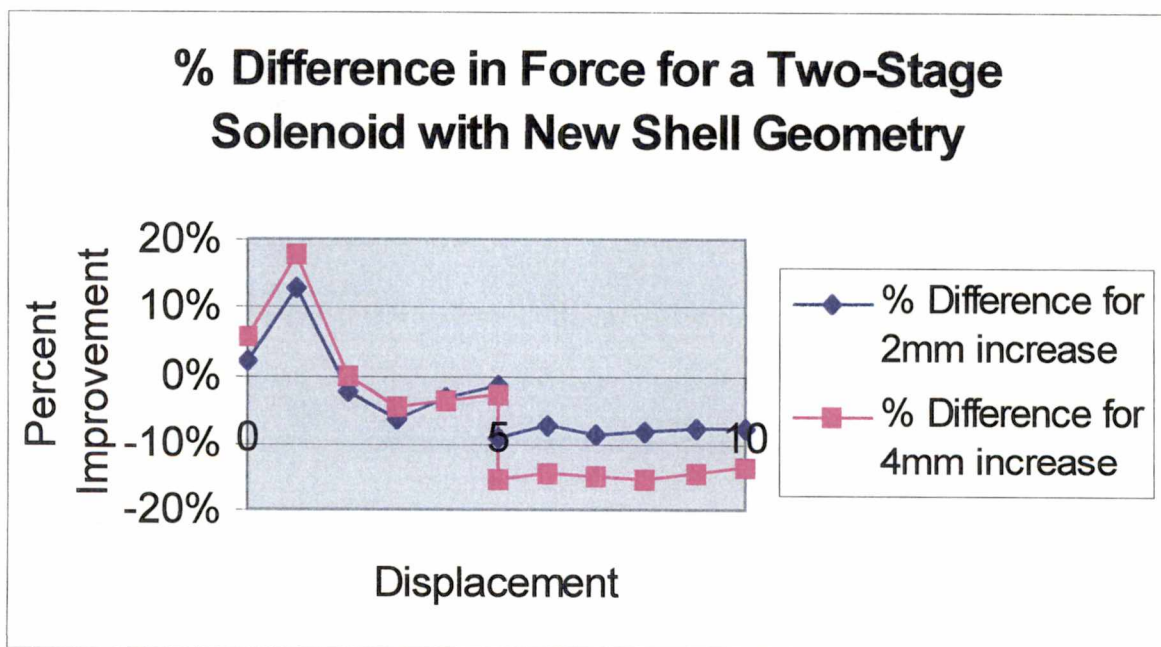


Figure 29: Change in the force output when the dimension presented in figure 22 is increased from 0 to 2mm and from 0 to 4mm. Both show that this is a bad change.

increase in diameter will create a larger force. Figure 30 shows plots of various geometries. Clearly, the diameter of the main core has a large impact on the forces. An increase in the diameter of core 1 and core 3 increases the force. When the diameter for core 3 is increased the force throughout the entire motion is decreased.

Altering the diameter also changes the equivalent model, see figure 3. Therefore to make comparison with a regular solenoid, a new model for the regular solenoid must be calculated. Further studies would prove useful in understanding how changes in the main core diameter changes the force output. This effort would require several thousand more data points, in which the diameter of the main cores, core 1 and core 2, are varied.

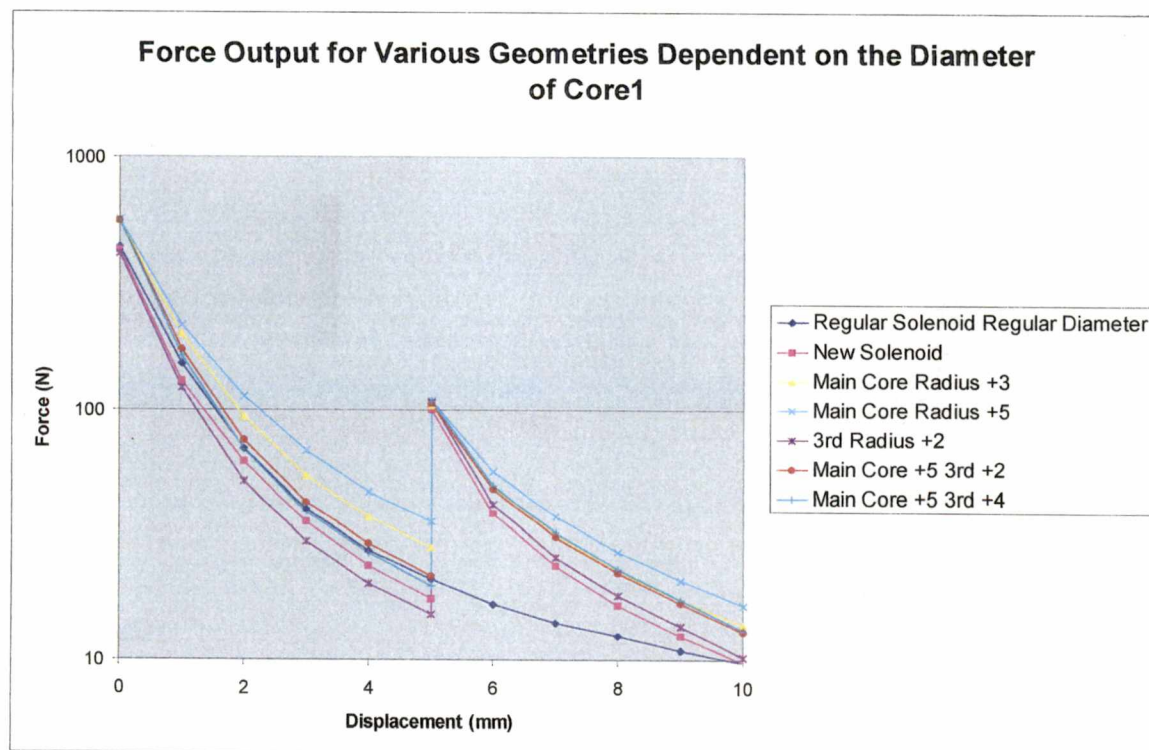


Figure 30: Various geometries with the diameter of core 1 (main core) changing. This is on a logarithmic plot so the variance at the lower numbers can be seen.

Smaller Initial Gap

One of the main goals of this study is to increase the force directly in front of the second hump. However, a variable that greatly improves this value has not been discovered. The effect of decreasing the total length of the stroke was also studied. This is accomplished by decreasing the distance traveled in the second part of the motion. In effect, this moves the second hump to the left in all plots seen with force versus displacement.

Figure 31 shows the force when the second part of the stroke is decreased from 5 mm to 3 mm, which decreases the initial gap between core 2 and the shell. The same basic curve is created, with the exception of the second hump. By decreasing the gap the

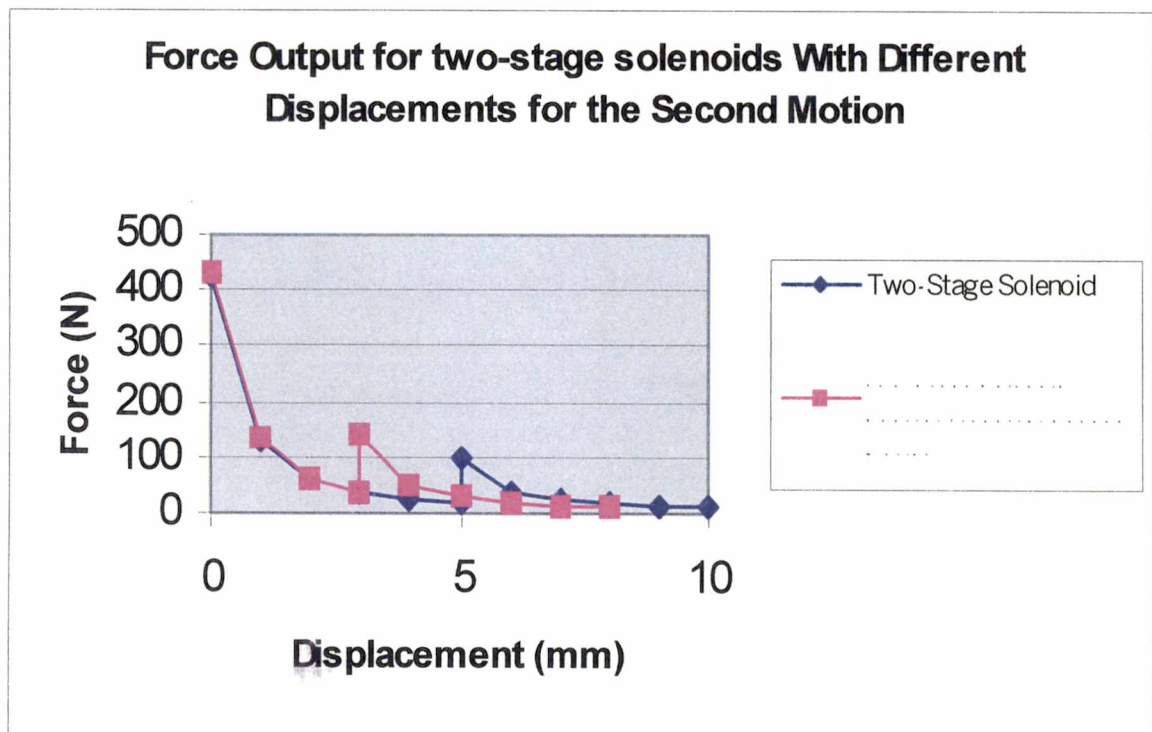


Figure 31: Initial two-stage solenoid design, and a two-stage solenoid that has smaller initial gap between core 2 and the shell. This value is decreased from 5 mm to 3 mm.

second hump is moved from the 5 mm location to the 3 mm location. Since the second hump starts when the force is at a greater value, the maximum value of the second hump is larger.

A comparison of the first 8 mm of travel can be made between the two designs. When this is done, it is found the new design has an average force value of 92.97 N, while the original has an average force value of 86.98 N. This is a 7% increase.

Data Collection

With the basic importance of different parts of the geometry better understood, data was obtained for various values of these parameters. The diameter of the third core was varied, along with the initial gap between core 2 and the shell, and the length of the connector between core 1 and core 3. The Maxwell software was used to solve the finite element problems for a range of values for each of these variables. Since a long amount of time is required to create a curve with a data point for each millimeter of displacement, only the most important variables can be studied. Also, the range of variation and step size must be minimized for these variables.

The Maxwell software allows the user to vary dimensions, and solve multiple finite element problems. Figure 32 shows the variables used and the range used for each. Several hundred data points are created with this setup. The problem now is to take this data and determine a relation between each variable and the force.

Index Choices

With all of the data found, best case scenarios can be obtained. Since so much data is compiled, a way of comparing it must be determined. This process is rather subjective, and for this reason the data is presented in the appendix for future reference.

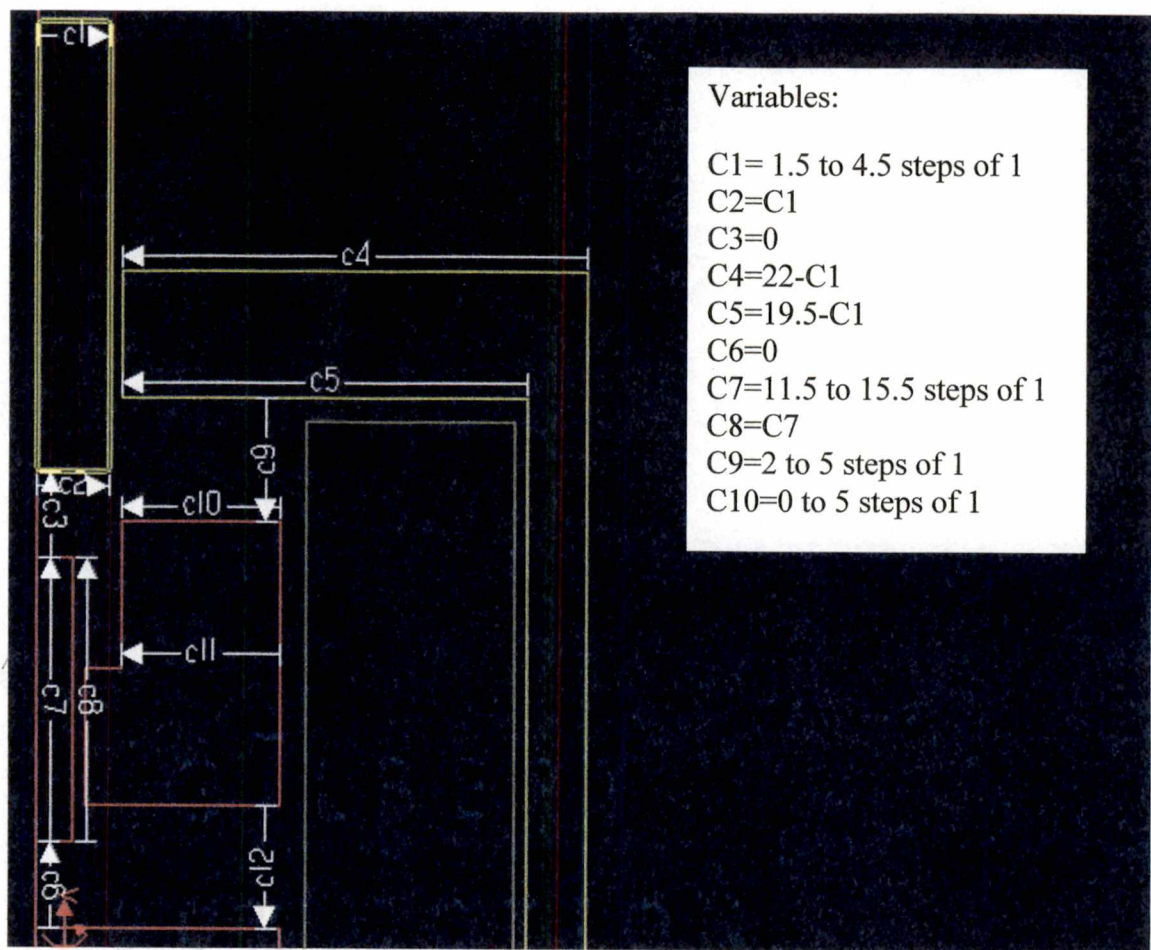


Figure 32: The upper portion of half of the cross section. All variables that were varied are defined as they were in the Ansoft Finite Element Software.

With the actual construction and testing of a two-stage solenoid, it will be possible to find those parts of the motion that need the force maximized for best operation. This will aid in determining what sort of index should be used.

For a two-stage solenoid there are two regions that have small force values, immediately before the second hump and the point where the gap is the largest. The other quantity of importance is the magnitude of the second hump. Theoretically the greater the force at this point, the greater the ability for the solenoid to get through the

location where force is small. This would apply only for a solenoid whose application allowed such motion.

Three regions have been emphasized that are critical. A relation will now be found between these three regions to find the best setup. The first attempt was to find a relation that mimics that used in the MATLAB code. The best index found in MATLAB was the average difference between the two-stage solenoid and a regular solenoid plus the average for the negative part of the graph. However, this cannot be used for the finite element program data, because the second force hump has a greater magnitude than in the MATLAB model. The average of the difference is dominated by the value at the second hump. Therefore a clear picture of the solenoid's force for these three areas, and the operation of the solenoid through its entire operation, can not be found.

After several attempts the following numerical index was chosen: The average force from a point right before the solenoid is completely closed to the second hump multiplied by the average value of the force of the second hump. This proved to be a desirable index system, and will be used to describe the data.

Results of Data with Index Applied

Figure 33 shows the results when the data is plotted using this index, with the diameter and length of the connecting rod as variables. From this figure, certain important conclusions can be drawn. First of all, a point is reached where the diameter of the third core proves to cause negative results. Also, it is seen when the diameter is small, the length of the rod connecting core 1 and core 3 should be longer. This has the effect of not allowing core 3 to remain in the hole quiet as long and being further from core 2 in its final position.

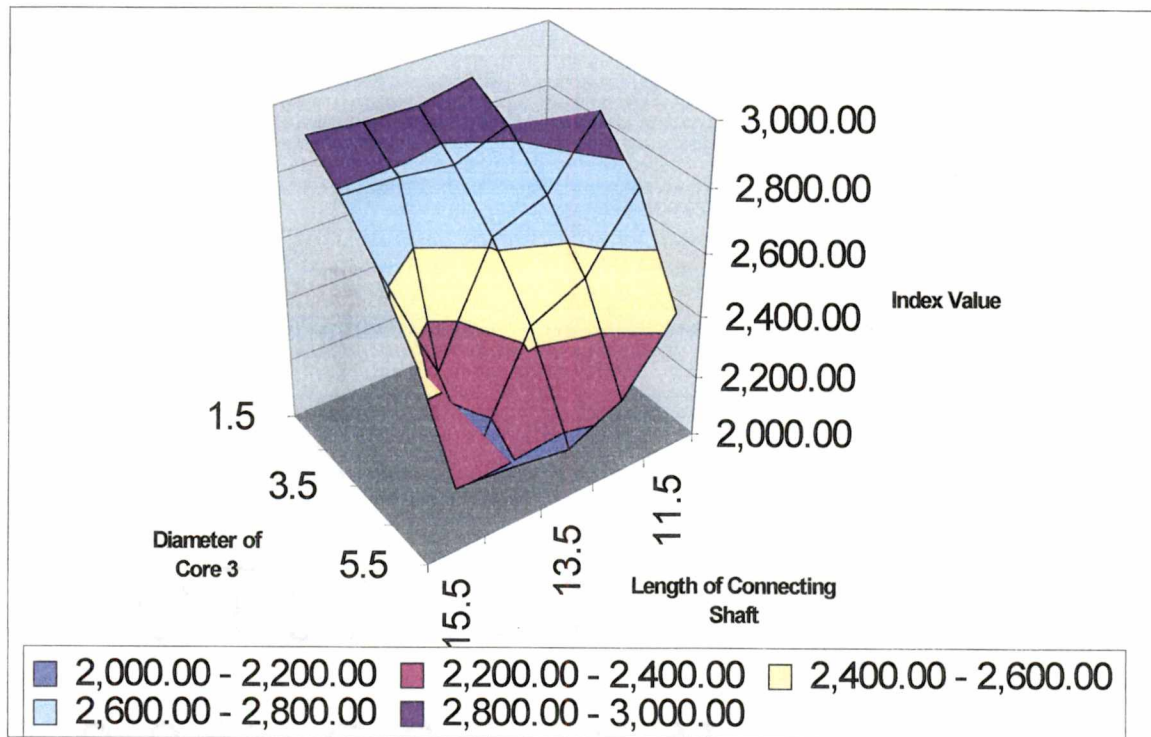


Figure 33: The results of applying the index to the data. This is for a stroke of 10mm. Different total strokes give basically the same results.

Since similar values are found for both of these situations, a judgement call must be made on which design is best. There are three good choices,

Diameter Core 3 = 3.5 Connector Rod Length = 11.5 Index Value =2,896.26

Diameter Core 3 = 2.5 Connector Rod Length = 12.5 Index Value =2,829.62

Diameter Core 3 = 1.5 Connector Rod Length = 12.5 Index Value =2,900.13

It appears that the latter two designs are best choices because they do not let as much flux travel through the system after the cores are moving together. This is because the gap between core 2 and core 3 is larger. Since the first choice closely resembles the best

results obtained from the MATLAB code, it was chosen. Possibly the effect created by the longer connector rod can be created by other means.

Other Things Found from Collected Data

Another thing that was varied in the data collected was the initial position of core 2. If the gap between it and the shell is reduced, the effective force through most the motion is increased. However, the important question is “Will the core be held against the stops until core 1 reaches it?”

Data was collected for the force on core 2 when core 1 has an initial gap of 5 mm between it and core 2. All results showed a negative force on core 2, meaning that it will be held in place. However, when the gap between core 3 and the shell is smallest and the gap between core 1 and core 2 is largest, the negative force is small, which could lead to problems. This data is also given in the appendix for future reference.

Chapter 10

Maximizing Control of Gap

A great deal has been learned by studying the effects of changing dimensions in the model. Yet the question now is, “Could the gap in the path from core2 to core 3 to the shell be increased, while reducing the gap during the time that core 1 is still moving toward core 2?” This will now be addressed.

I-Beam Design

Our objective is to produce the same motion, while yielding higher force. To accomplish this the attempt is to change the gap in the various paths. The first design change makes the cross section of the third core have the appearance of an I-beam.

Figure 34 shows the basic premise of this design. During the first part of the motion, the

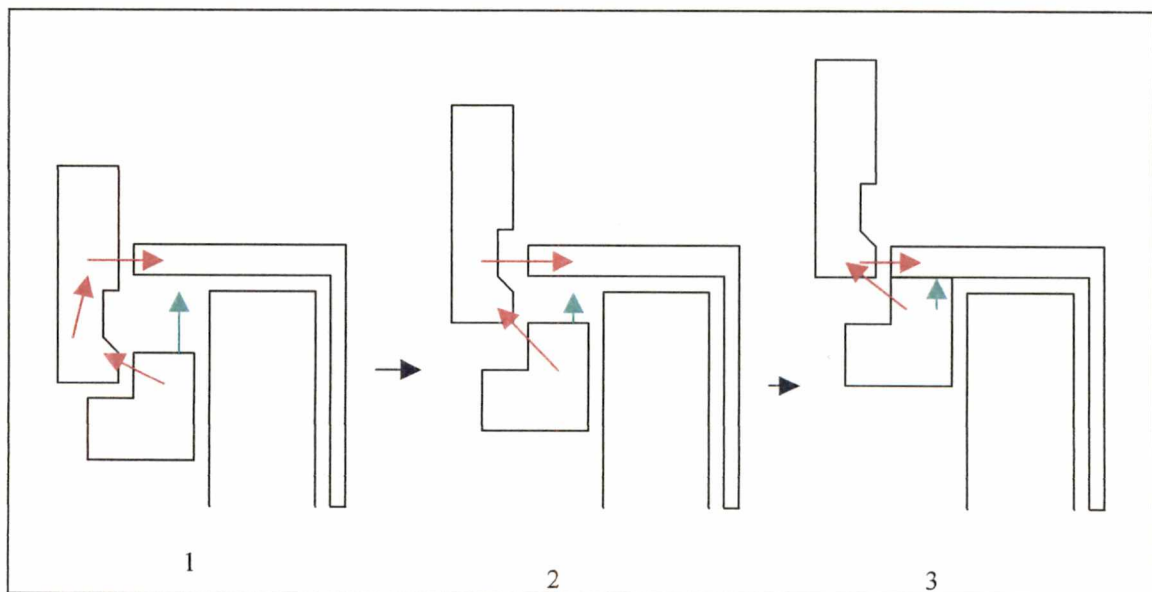


Figure 34: The motion of core 2 and core 3 for the I-beam design. Through the motion it is seen that the ratio of the gap following the red arrows vs. the gap following the green arrows increases as the cores move upward. This is exactly what is desired.

path through core 3 is the easiest way for the flux to travel. However, as core 1 reaches core 2, the cutout in core 3 makes it more difficult for flux to travel through this path. This is exactly what we desire.

Once again, the geometry can have a variety of dimensions. Using the variables shown in figure 35, it is possible to find the best results from the finite element software. Force data is obtained for the whole motion for each of these geometries. Once again an index is set up to compare this data. It is not as difficult to set up this index. By simply comparing the two-stage solenoid without the I-beam design, a difference for each data point can be found.

Next, the average value of the difference of all the data points for each geometry

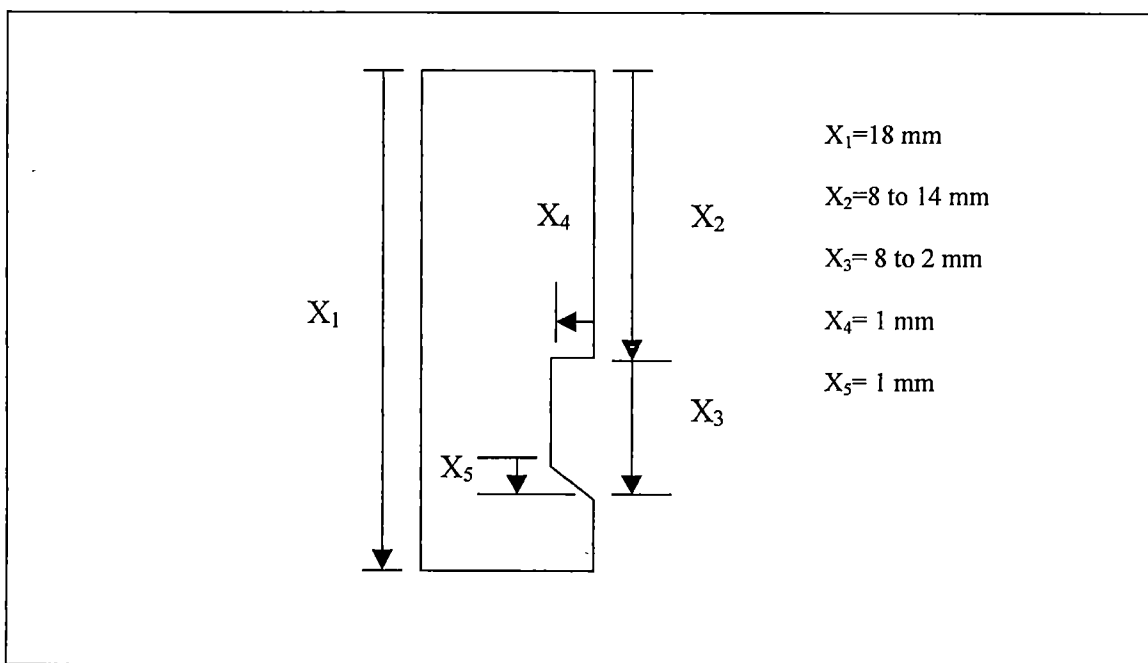


Figure 35: Core 3 in the I-beam model with the variables changed when the best geometry was found. It should be noted that the range of values used for x_3 depends on the value of x_4 , the sum of these two can not be larger than the total length of the core, 18 mm.

is obtained. Figure 36 shows the results by plotting the index value versus the two variables. The best geometry is with $X_3=6$ mm and $X_2=8$ mm. Figure 37, shows a plot of the difference between this design and the original two-stage design through the entire motion.

Finally we have found an improvement to the area before the second hump. An increase of 20% is found in this area. This in general is the only area improved, actually other areas are harmed. This value is helped only if the initial gap between core 2 and the shell is rather large (4 mm or greater).

The only other part of this geometry that could be questioned is the depth of the

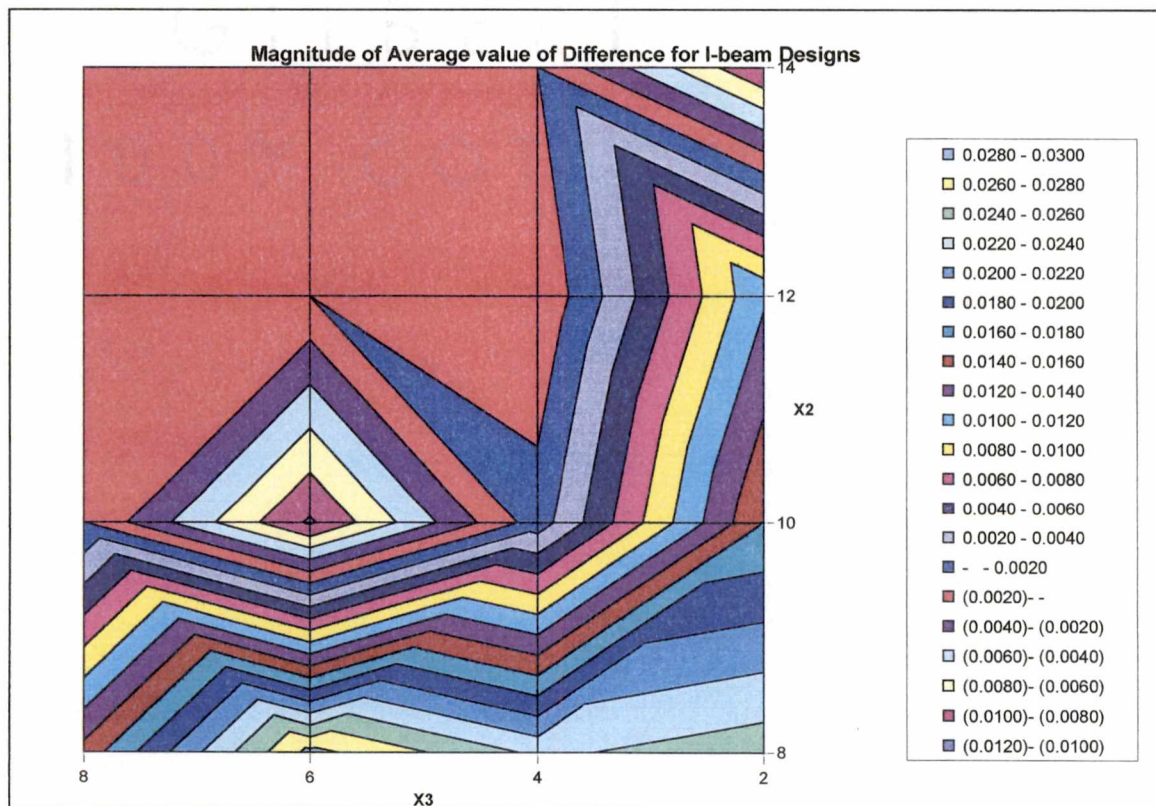


Figure 36: Results from applying the index for determining the best I-beam design. $X_3=6$ and $X_2=8$ is the best choice.

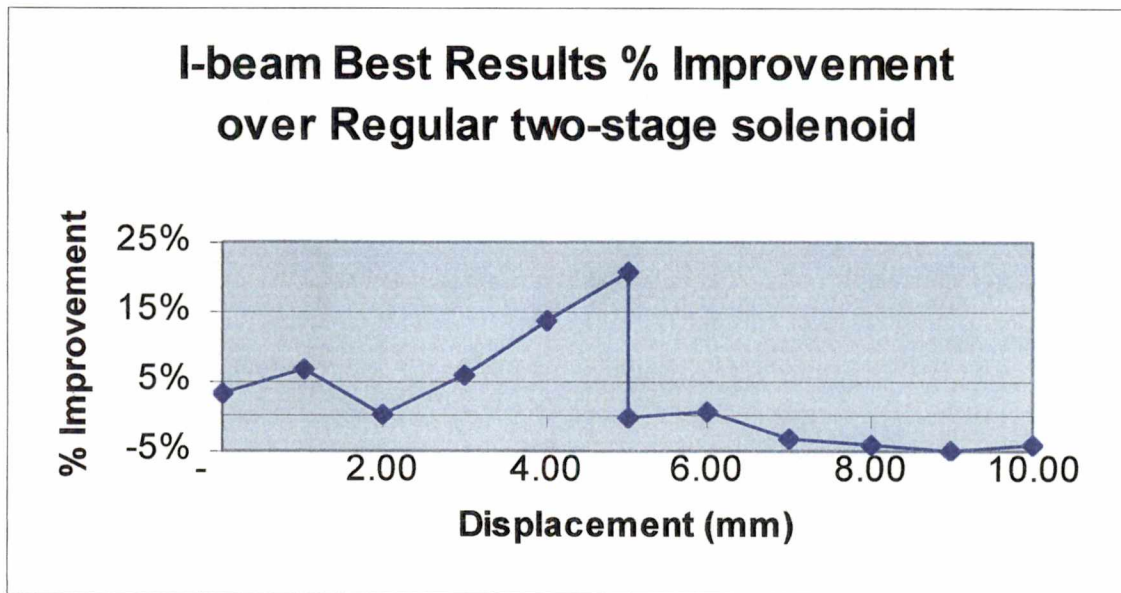


Figure 37: Improvement in the force through the motion of the two-stroke solenoid with the I-beam design as compared to a regular two-stage solenoid.

cutout in the I-beam. This can not be too large because this area is where oversaturation occurs to the greatest degree. For the best geometry found in the pervious section, the depth was varied from 1 mm to 1.5 mm. No change in force was found.

The best results were found for a diameter of 3 mm with the I-beam design. The values for force as a function of displacement are presented in chart 3, along with that of an equivalent regular solenoid. The average improvement over a regular solenoid is 48%, primarily due to the second hump.

Angled Design

Another design explored, to create the desired effect discussed in this section, was an angled design for core 3. Figure 38 shows the basic premise of this idea. From the figure it is apparent why this design should give good results. The gap is larger through the entire process. Yet there are difficulties. The gap increases when core 1 is moving

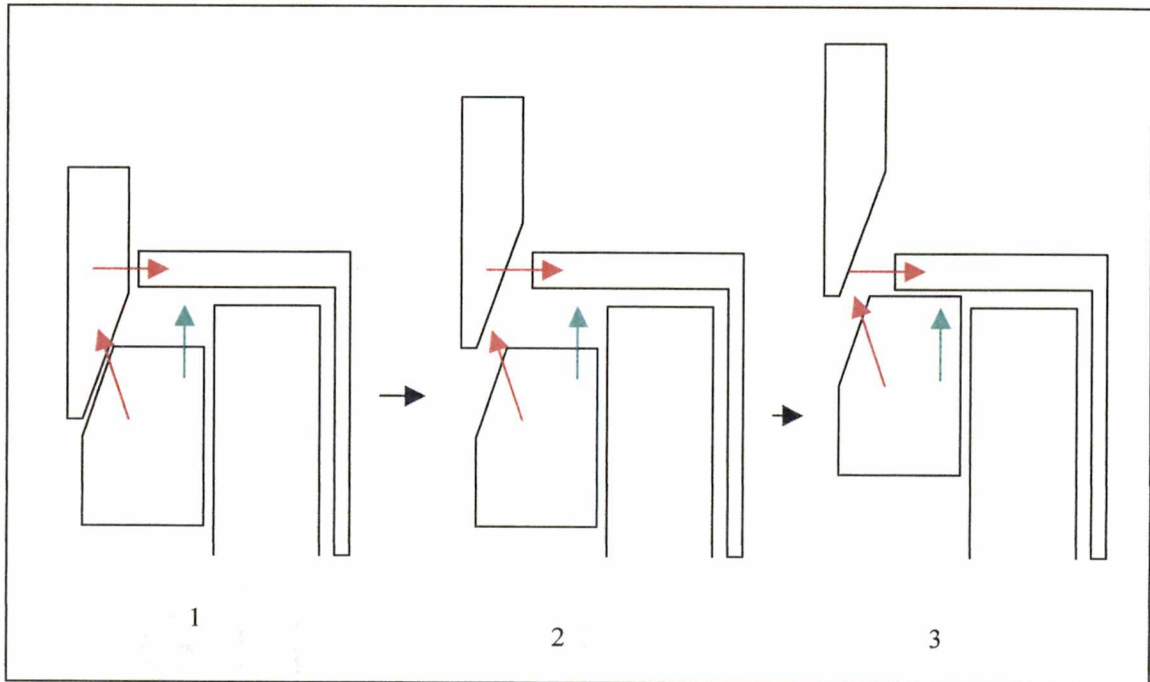


Figure 38: The motion of core 2 and core 3 for the Angled design. Through the motion it is seen that the ratio of the gap following the red arrows vs. the gap following the green arrows increases as the cores move upward. This is exactly what is desired.

toward core 2, thus decreasing the force output of the solenoid during this part of the motion. Also, since there is an angle on the surface between core 2 and core 3, there is a greater upward force on core 2. A few trials were made with small angles. The best results are shown in figure 39, for the design with the dimensions shown in figure 40. The results seem to be poorer than with the I-beam design. Therefore it is found that the angle design does not prove beneficial. The I-beam design is most effective in improving the force in the critical areas addressed.

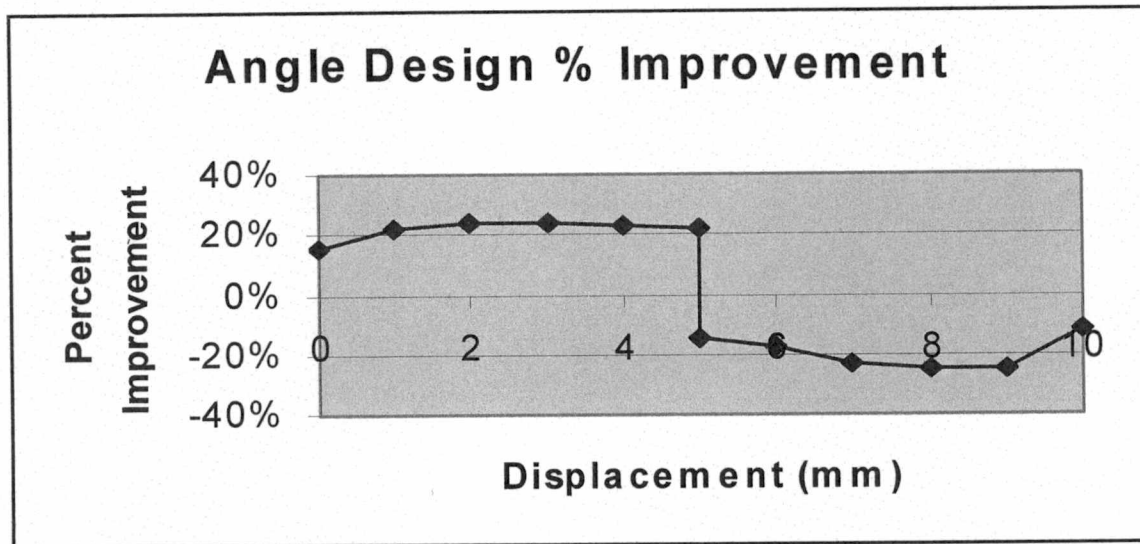


Figure 39: Percent improvement for the solenoid presented in figure 40, as compared to an equivalent two-stage solenoid.

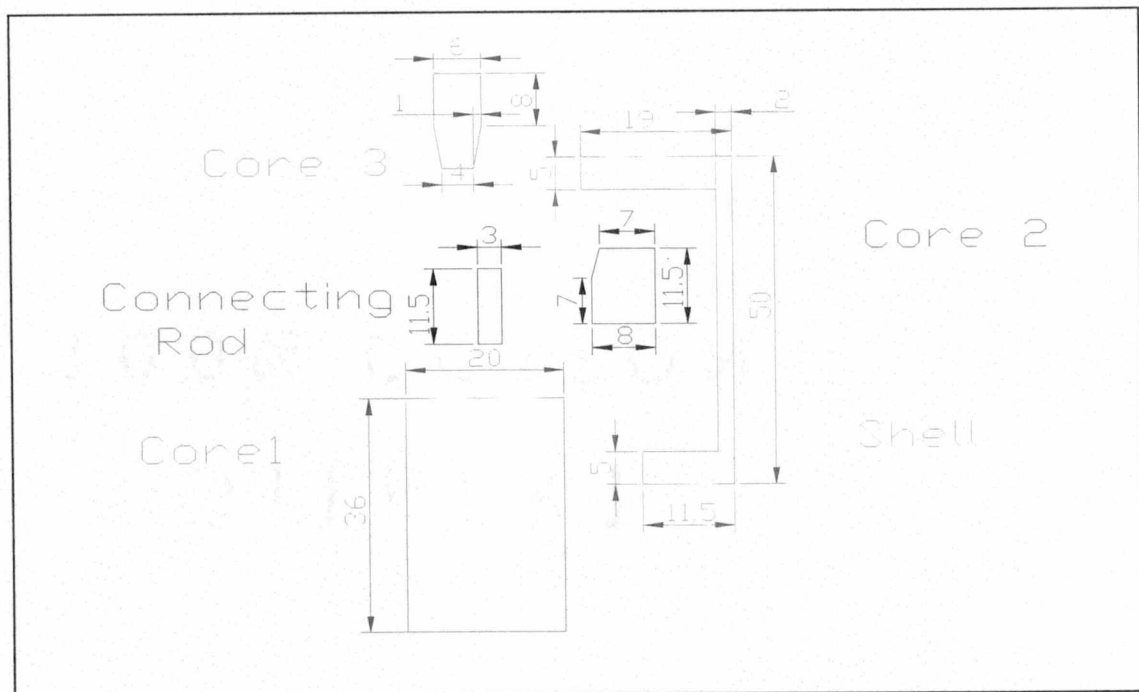


Figure 40: Best geometry found for the angle design.

Chapter 11

Design Tables for Two Stage Solenoids

With the data collected so far, it is possible to design solenoids for specific force outputs, and with a specific total stroke. The appendix contains 4 tables (Tables 4 - 8) which can be used in designing a desired force output. It has been demonstrated that the diameter of the third core is critical for best results. The tables contain data when the diameter of core 3 is 5 mm and 7 mm. To use these tables certain decisions must be made. The following procedure should be followed:

1) Determine if:

- a) you want to maximize the force output at the second hump and the force at the first minimum, while sacrificing the magnitude of the force at the second minimum. OR
- b) you want to maximize the force at the second minimum, but with a smaller max value for the second hump, while sacrificing the magnitude of the force at the first minimum.

2) Create your design so that:

- a) if you chose 1a, minimize the initial gap between core 2 and the shell, and then minimize the initial gap between core 1 and core 2.
- b) If you chose 1b, minimize the initial gap between core 1 and core 2, and then minimize the initial gap between core 2 and the shell.

3) After these choices have been made and you know which diameter of core 3 you will use, go to table 4. Based on your choice in 2, pick the largest value you want to use for

Gap1, the gap between core 2 and the shell. Record the value for that gap distance and all smaller gaps.

4) After the initial gap has been determined, go to table 5. Select the diameter you are using. Locate the initial value for Gap1 you chose, and now determine Gap2 to obtain the desired stroke. $\text{Gap1} + \text{Gap2} = \text{TotalStroke}$. Note this value and the value for all smaller gaps.

5) Note: Tables 6 and Tables 7 show the values of force for the I-beam design. This design is useful only for the (b) choices. It uses the dimensions for the I-beam shown to be best in the preceding section "I-beam design".

As a typical example, say that you need a total stroke of 7 mm. If you want the results for choice (a) in step 2, we could pick a value for gap1 of 2 mm in table 4. For a diameter of 2.5 mm the forces are (gap1=2, force=63.00); (gap1=1, force=141.33); (gap1=0 force=450.17). Now you go to table 5. Since you want a stroke of 7 mm, and gap1=2 mm, gap2 must be 5 mm. Therefore we take note of the values for the force for gap2=5 to 0 mm, when gap1=2. So (gap2=5, force=12.3); (gap2=4, force=15.87); (gap2=3, force=21.77); (gap2=2, force=32.96); (gap2=1, force=61.00); (gap2=0, force=192.23). Now we can combine these two groups of data to obtain: (totalgap=7, force=12.3); (totalgap=6, force=15.87); (totalgap=5, force=21.77); (totalgap=4, force=32.96); (totalgap=3, force=61.00); (totalgap=2, force=192.23); (totalgap=2, force=63.00); (totalgap=1, force=141.33); (totalgap=0, force=450.17).

Figure 41 shows the results, along with results for choice (b), and then with the I-beam model. Figure 42 shows the difference for each of these designs compared to a

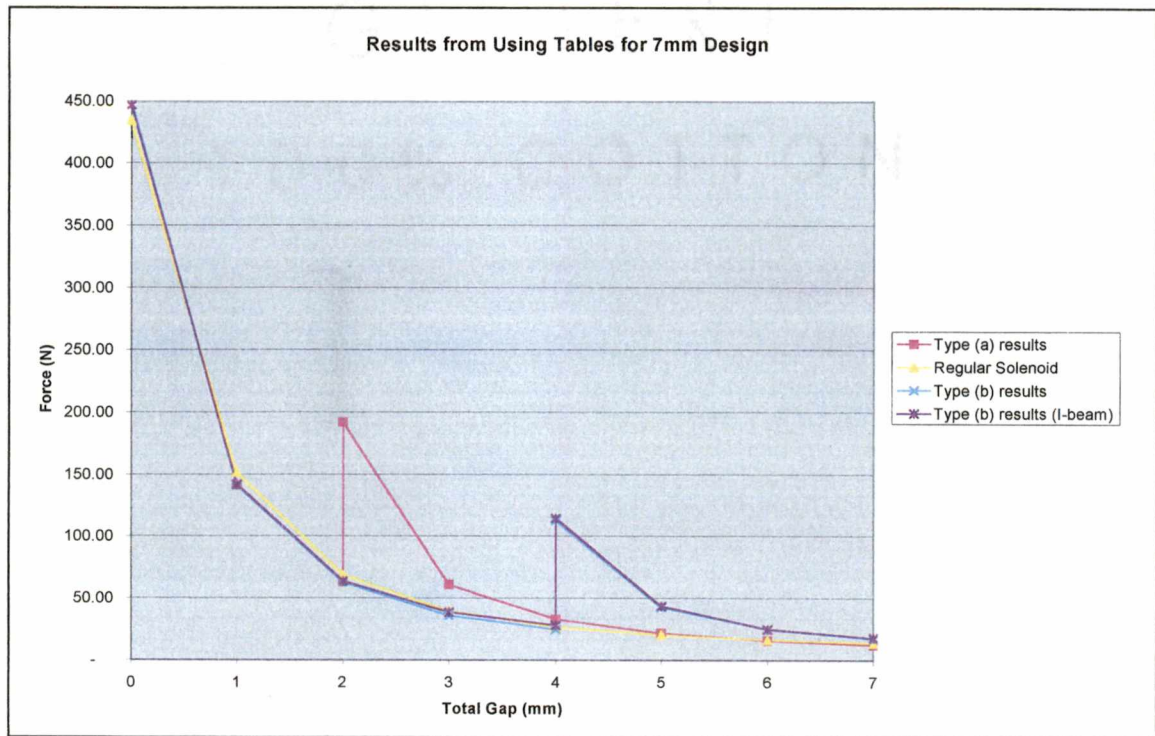


Figure 41: Results obtained by varying different initial gaps.

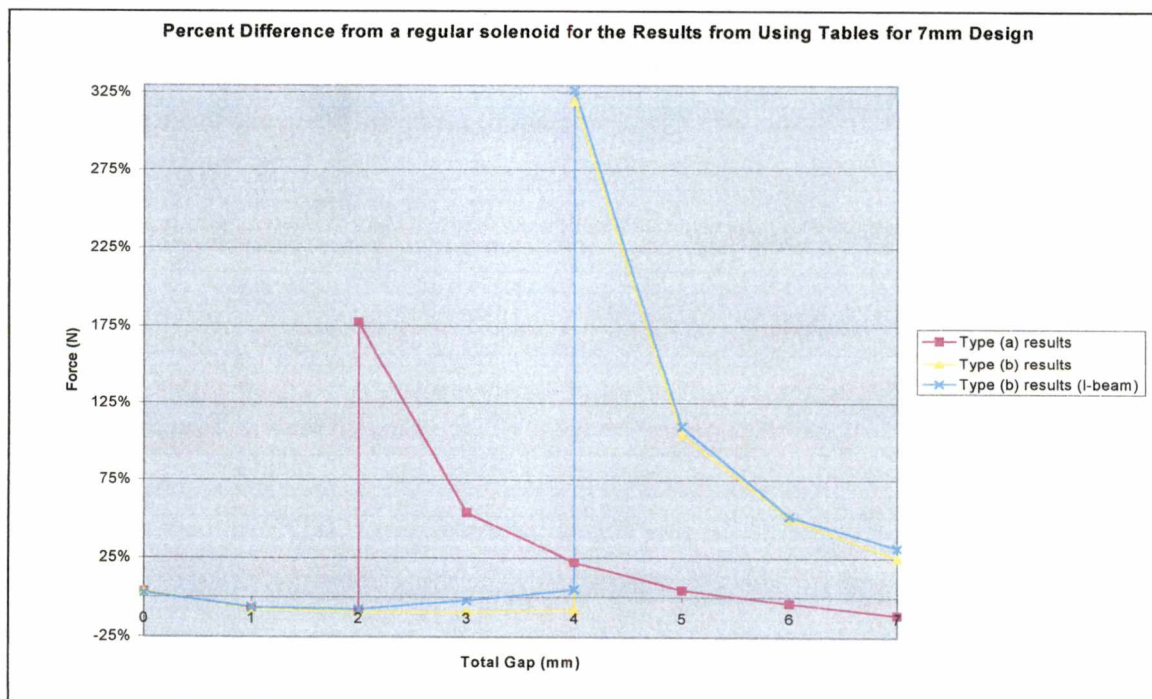


Figure 42: Percent difference from a regular solenoid for figure 41.

regular solenoid. It is difficult to decide which design is best as it depends on the application. The tables are given so that the design can be adapted to particular needs.

Chapter 12

Conclusions

The two-stage solenoid lives up to its theoretical promise after extensive analytical study. The MATLAB code and finite element software show basic similarities in the results found when certain geometries are varied. However, the finite element model proves to yield better results. The MATLAB code was useful in providing initial insight into the problem. However, its quantitative effectiveness in modeling the system is quite limited.

In these studies, the relative importance of different design parameters is demonstrated. The diameter of core 3 must be large enough to prevent oversaturation, but small enough so that the force between core 2 and the shell is not reduced excessively. The length of the connector rod should be such that core 3's bottom surface is flush with the top of core 2's top surface when core 1 is in contact with core 2. Both the MATLAB model and the finite element model confirm this result. However, if the diameter of core 3 is very small (< 3 mm), then this result is incorrect. Instead, one may want to make these two surfaces further apart.

The issue of saturating core 3 should be especially considered. In each design, core 3 is the first element to become saturated. This may prove to benefit the design. Saturation of core 3 is actually good for the second part of the motion. However, it is undesirable for this area to be saturated during the first part of the motion, and this is when it is most likely to be saturated. Therefore, as in many parts of the design benefits and consequences must be considered.

It was also shown that the location of the second hump can be moved by changing the length of the initial gap between core 2 and the shell. When this is varied, the starting value of force is higher, and a greater force is gained. Therefore, the shorter the stroke, the shorter the initial gap should be between core 2 and the shell, and the also the initial gap between core 1 and core 2. In particular the latter value should be minimized to 3mm or less. This is because after this value, much leveling off occurs.

The I-beam design proved beneficial. It was especially effective in improving the force in the area before the second hump. Since this is one of the trouble areas, the benefit of the I-beam design is obvious. However, this design is only beneficial if the initial gap between core 2 and the shell is large.

The true complexity in the design process is the difficulty in comparing results. This is because each geometry has many values to describe it, the force values through the entire motion. An index was setup by which one value could be used to compare different geometries. The index used related the diameter of core 3, the length of the connector rod and the force output, and provided a best geometry. This geometry was further improved by the I-beam design. Best results were found with core 3 having a diameter of 3 mm, and using the I-beam design. The results showed an average increase of force of 47.9%. Much of the benefit is gained at the second hump, where the maximum improvement is 376.4%. Areas with no improvement only occur in the middle of the second part of the motion, and at the very beginning of the first part of the motion. With a shorter stroke, these problem areas could be removed. In this design the only area that proves to be outside of the desirable range for the magnitude of flux density, is in the

reduced area in core 3. Everywhere else the magnitude of B is in the desired range less than 2.1 Tesla as can be seen in figure 43.

It is difficult to choose a specific “best” design. However, the tables provided can be used to optimize a design for a certain application. The procedure presented in Chapter 11 need only be followed to obtain the best results.

The results from this paper show the possibilities of this solenoid design. Future actions that should be taken include:

- 1) Construction of an actual device to verify results presented here

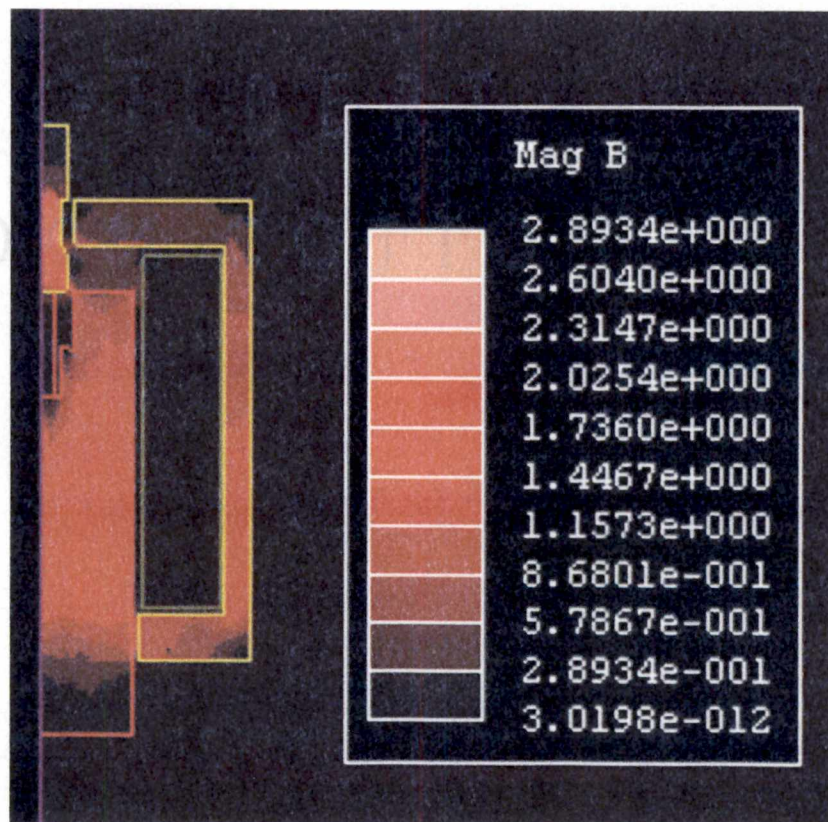


Figure 43: Magnitude of B (in Tesla) for the two-stage solenoid, when the values are largest.

- 2) Tests to determine which parts of the curve are most critical to ensure proper operation.
- 3) Refined choice in determining the best performance index to describe the system's entire force.
- 4) Conclusions on the best geometry for specific strokes, based on data presented in appendix
- 5) Experimentation with other geometrical parameters, such as thickness of shell, especially the upper portion of the shell.

With these further studies and the findings presented within, the effectiveness of the two-stage solenoid design will be established.

References

References

1. Slemon, G. R., Electric Machines, Addison-Wesley, London, 1980.
2. Ricker, R., Tri Core, Low Reluctance Tubular Solenoid (Patent # 5999073), United States Patent Office, Washington, 1996.
3. Getting Started: A 2D Parametric Problem, Ansoft Corporation, Pittsburgh, 1999.
4. Getting Started: A Magnetostatic Problem, Ansoft Corporation, Pittsburgh, 1999.

Appendix

Table 1: Constant values used when geometry is varied for the 3 core solenoid.

Location	Size
D1 (Diameter of core 1)	20mm
D2 (Diameter of core 2)	20mm
Rod (Diameter of the rod)	3 mm
t1 (Thickness of the shell)	3 mm
x1 (Gap between the case and first core)	.6 mm
x5 (Gap between core 2 and core 3)	.4 mm
x6 (Gap between core 3 and the case)	.4 mm
Xtotal	50 mm
I (Current)	5
N (Number of Turns)	400

Table 2: Results of Variance in Geometry, to obtain best results.

Average value of the difference	Sum of average value and negative average value	Special Average as described in text above	X _{3max} (mm)	X _{4max} (mm)	D ₃ (mm)	X _{hole} (mm)
2.659	0.449	2.192	35	15	14	35
2.077	1.577	1.915	24	26	6	24
2.985	-3.560	1.833	31	19	10	31

Table 3: Results for the best set up found with a total path of 10 mm.

Displacement (mm)	Regular Solenoid Force (N)	I-Beam Design Force (N)	% Difference
0	434.48	434.93	0.10%
1	151.98	138.25	-9.03%
2	69.21	61.35	-11.36%
3	39.62	37.23	-6.03%
4	26.94	26.63	-1.15%
5	20.8	20.98	0.87%
5	20.8	99.06	376.25%
6	16.49	38.18	131.53%
7	13.85	22.6	63.18%
8	12.35	15.63	26.56%
9	10.8	11.59	7.31%
10	9.68	9.37	-3.20%

Table 4
 No Cut Out
 2-Stage Solenoid Design Sheet Page 1

Diameter	Gap1	Force
2.5	5	19.38
2.5	4	24.82
2.5	3	35.96
2.5	2	63.00
2.5	1	141.33
2.5	0	450.17
3.5	5	17.14
3.5	4	22.12
3.5	3	32.51
3.5	2	57.62
3.5	1	132.93
3.5	0	432.36

Table 5
No Cut Out
2-Stage Solenoid Design Sheet Page 2

Diameter	Gap 1	Gap 2	Force
2.5	4	5	10.30
2.5	4	4	13.02
2.5	4	3	17.32
2.5	4	2	24.83
2.5	4	1	42.62
2.5	4	0	113.05
2.5	3	5	11.28
2.5	3	4	14.25
2.5	3	3	19.25
2.5	3	2	28.02
2.5	3	1	49.51
2.5	3	0	140.88
2.5	2	5	12.30
2.5	2	4	15.87
2.5	2	3	21.77
2.5	2	2	32.96
2.5	2	1	61.00
2.5	2	0	192.23
3.5	4	5	10.67
3.5	4	4	13.59
3.5	4	3	18.22
3.5	4	2	26.06
3.5	4	1	44.32
3.5	4	0	117.03
3.5	3	5	11.42
3.5	3	4	14.63
3.5	3	3	20.03
3.5	3	2	29.12
3.5	3	1	50.60
3.5	3	0	142.71
3.5	2	5	12.47
3.5	2	4	16.13
3.5	2	3	22.31
3.5	2	2	33.39
3.5	2	1	61.63
3.5	2	0	189.40

Table 6
I-Beam Design
2-Stage Solenoid Design Sheet Page 1

Diameter	Gap1	Force
2.5	5	22.11
2.5	4	28.29
2.5	3	38.76
2.5	2	64.01
2.5	1	142.24
2.5	0	446.78
3.5	5	20.98
3.5	4	26.63
3.5	3	37.23
3.5	2	61.35
3.5	1	138.25
3.5	0	434.93

Table 7
I-Beam Design
2-Stage Solenoid Design Sheet Page 2

Diameter	Gap 1	Gap 2	Force
2.5	4	5	9.8
2.5	4	4	12.5
2.5	4	3	18.2
2.5	4	2	24.99
2.5	4	1	43.68
2.5	4	0	114.99
2.5	3	5	10.89
2.5	3	4	13.94
2.5	3	3	19.11
2.5	3	2	28.75
2.5	3	1	51.16
2.5	3	0	141.88
2.5	2	5	12.12
2.5	2	4	15.74
2.5	2	3	22.23
2.5	2	2	33.94
2.5	2	1	62.07
2.5	2	0	193.73
3.5	4	5	10.25
3.5	4	4	13.06
3.5	4	3	17.53
3.5	4	2	25.47
3.5	4	1	44.35
3.5	4	0	117.86
3.5	3	5	11.18
3.5	3	4	14.02
3.5	3	3	19.24
3.5	3	2	28.69
3.5	3	1	51.33
3.5	3	0	143.79
3.5	2	5	12.19
3.5	2	4	15.71
3.5	2	3	21.89
3.5	2	2	33.89
3.5	2	1	62.28
3.5	2	0	189.83

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%       Two-Stage Solenoid Model (Force Output Producer)
%
%               Jeremy Myers
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This program finds the equivalent resistance model of a regular
% solenoid and a two-stage solenoid calculates the force on each core
% in the solenoid, and compares the two solenoids
% Data is presented in the form of several plots
% It also checks to make sure that the forces will allow appropriate
% results
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear all
% This program will analyze the force for a two part solenoid
% Metric Units Used Throughout

%inputs
' Input the diameter of the main core in millimeters';
d1=20;
' Input the diameter of the second core in millimeters';
d2=20;
' Input the diameter of the third core in millimeters';
d3=6;
' Input the diameter of the rod';
rod=3;
' Input the size of the shell thickness in millimeters';
t1=5;
' The gap between the case and first core(x1) (mm)';
x1=.5;
' The gap between core 2 and core 3 (mm)';
x5=.5;
' The gap between the case and the third core (x6) (mm)';
x6=.5;
' The largest value x3 can have based on the length of the rod
connecting core 1 & 3 (mm)';
x3max=5;
' The largest value x4 can have (mm)';
x4max=50;
' The depth of the hole in core #2';
xhole=5;
' Input the number of Amps(I)';
I=5;
' Input the number of Turns(N)';
N=400;
% Converts the above from millimeters to meters
d1=d1*.001;
d2=d2*.001;
d3=d3*.001;
rod=rod*.001;
t1=t1*.001;
x1=x1*.001;
x5=x5*.001;

```

```

x6=x6*.001;
x3max=x3max*.001;
x4max=x4max*.001;
xhole=xhole*.001;
% Permability mu
mu=4*pi*.0000001;
% The amp turns value(NI)
NI=N*I;
%
%
%This portion of the program will determine with the above equations,
what force will be created with single stage solenoid
%
%
%
%This portion of the program will determine with the above equations,
what force will be created with single stage solenoid
%
%This program will analyze the force for a normal solenoid
%
%a stepper which will analyze the force for different x positions
%
for stepsingle=1:((x3max+x4max)*1000);
    %x1 location of solenoid core (units m)
    xsingle(stepsingle)=stepsingle*.001;
    %Resistance from gap at R2
    R1(stepsingle)=x1/(d1*pi*t1*mu);
    %Resistance from gap at R1
    Rsingle(stepsingle)=xsingle(stepsingle)/(mu*pi*((d1^2)-
((rod+2*x6)^2))/4);
    Rtotal(stepsingle)=R1(stepsingle)+Rsingle(stepsingle);
    %Flux phe (units weber)
    phe(stepsingle)=NI/(Rtotal(stepsingle));
    %Check for over saturation (webers/m^2)
    Check=phe(stepsingle)/(d1*pi*t1);
    if Check > 1.25;
        phe(stepsingle)=1.25*(d1*pi*t1);
    end
    %Force (units newtons)
    F(stepsingle)=.5*phe(stepsingle)^2/((pi*((d1^2)-
((rod+2*x6)^2))/4)*mu);
end
%This creates a plot of the Flux
subplot (211);
plot(xsingle,phe);
title('Flux vs. Distance for a Regular Solenoid')
xlabel('Distance (m)')
ylabel('Flux (Webers)')
grid;
%This creates a plot of Force
subplot (212);
plot(xsingle,F);
title('Force vs. Distance for a Regular Solenoid');
xlabel('Distance (m)');

```

```

%ylabel('Force (Newtons)');
%grid;
%
%
%This part of the program will determine with the above equations, what
force will be created with a two step solenoid
%
%
% a stepper which will analyze the force for different x positions
% x begins with x at the furthest point
for step=1:(x4max*1000);
    x2=0;
    x3=x3max-x2;
    %converts location of solenoid core 2 to m
    x4(step)=step*.001;
    %This portion of the program will calculate the areas at each
resistance area
    a6=pi*d3*t1;
    if xhole > x3;
        a5=(xhole-x3)*pi*d3;
    else
        a5=0;
    end
    a4=(d2^2-(d3+2*x5)^2)*pi/4;
    a3=(pi*(d3^2)/4)-(pi*(rod^2)/4);
    if d2 <= d1;
        a2=(pi*(d2^2)/4)-pi*rod^2/4;
    else
        a2=(pi*(d1^2)/4)-pi*rod^2/4;
    end
    a1=pi*d1*t1;
    %This portion assigns values to each gap
    gap6=x6;
    gap5=x5;
    gap4=x4(step);
    gap3=x3;
    gap2=x2;
    gap1=x1;
    %This portion calculates the resistance at each point and then the
sum
    r6=gap6/(a6*mu);
    r5=gap5/(a5*mu);
    r4=gap4/(a4*mu);
    r3=gap3/(a3*mu);
    r2=gap2/(a2*mu);
    r1=gap1/(a1*mu);
    if a5 == 0
        rtotal=((((r3+r6)*r4)/(r3+r6+r4))+r2+r1;
    else

        rtotal((((r5*r3)/(r5+r3))+r6)*r4)/((((r5*r3)/(r5+r3))+r6)+r4))+r2+
r1;
    end
    %This portion checks the flux (weber) and makes sure it is not to
large

```

```

    fluxt(step)=NI/rtotal;
    check=fluxt(step)/a1;
    if check > 1.25;
        fluxt(step)=1.25*a1;
    end
    %This portion will calculate the flux at r3, r4, & r2
    if a5 == 0;
        flux3(step)=(fluxt(step)*r4)/(r6+r3+r4);
        flux4(step)=(fluxt(step)-flux3(step))    ;
    else
        flux3(step)=(fluxt(step)*r4)/(r3+r6+(r6*r3/r5)+r4+(r4*r3/r5));
        flux4(step)=(fluxt(step)-flux3(step)*(1+r3/r5));
    end
    %This portion calculates the force at 3 & 4 & Total
    force3(step)=(.5*flux3(step)^2)/(a3*mu);
    force4(step)=(.5*flux4(step)^2)/(a4*mu);
    forcet(step)=force4(step);
    distancet(step)=x4(step);
end
% x value continues with core 2 reaching its furthest point and x2
increasing
for step=(x4max*1000+1):(x4max*1000+x3max*1000);
    x2(step)=(step-x4max*1000)*.001;
    x3(step)=(x3max-x2(step));
    %converts location of solenoid core 2 to m
    x4(step)=x4max;
    %This portion of the program will calculate the areas at each
resistance area
    a6=pi*d3*t1;
    if xhole > x3(step);
        a5=(xhole-x3(step))*pi*d3;
    else
        a5=0;
    end
    a4=(d2^2-(d3+2*x5)^2)*pi/4;
    a3=pi*(d3^2)/4-(pi*(rod^2)/4);
    if d2 <= d1;
        a2=pi*(d2^2)/4-(pi*(rod^2)/4);
    else
        a2=pi*(d1^2)/4-(pi*(rod^2)/4);
    end
    a1=pi*d1*t1;
    %This portion assigns values to each gap
    gap6=x6;
    gap5=x5;
    gap4=x4(step);
    gap3=x3(step);
    gap2=x2(step);
    gap1=x1;
    %This portion calculates the resistance at each point and then the
sum
    r6=gap6/(a6*mu);
    r5=gap5/(a5*mu);
    r4=gap4/(a4*mu);
    r3=gap3/(a3*mu);

```

```

r2=gap2/(a2*mu);
r1=gap1/(a1*mu);
if a5 == 0
    rtotal=((r3+r6)*r4)/(r3+r6+r4))+r2+r1;
else
    rtotal=(((((r5*r3)/(r5+r3))+r6)*r4)/(((r5*r3)/(r5+r3))+r6)+r4))+r2+
r1;
end
%This portion checks the flux (weber) and makes sure it is not to
large
fluxt(step)=NI/rtotal;
check=fluxt(step)/a1;
if check > 1.25;
    fluxt(step)=1.25*a1;
end
%This portion will calculate the flux at r3, r4, & r2
if a5 == 0
    flux3(step)=(fluxt(step)*r4)/(r6+r3+r4);
    flux4(step)=(fluxt(step)-flux3(step)) ;
else
    flux3(step)=(fluxt(step)*r4)/(r3+r6+(r6*r3/r5)+r4+(r4*r3/r5));
    flux4(step)=(fluxt(step)-flux3(step)*(1+r3/r5));
end
flux2(step)=fluxt(step);
%This portion calculates the force at 2 & 3 & 4 & Total
force2(step)=(.5*flux2(step)^2)/(a2*mu);
force3(step)=(.5*flux3(step)^2)/(a3*mu);
force4(step)=(.5*flux4(step)^2)/(a4*mu);
forcet(step)=force2(step)-force3(step);
distancet(step)=(step)*.001;
%This portion makes sure that core 2 is held in place if it is not,
the force will show up as 0
if force3(step)+force4(step) < force2(step)
    error(step)=1;
    errorgraph(step)=0;
else
    error(step)=0;
    errorgraph(step)=1;
end
forcet(step)=forcet(step)*error(step);
end
figure(1);
clf;
%This portion will calculate the difference between a regular solenoid
and the two step
Difference=forcet-F;
difmin=min(Difference);
difmax=max(Difference);
difavg=mean(Difference);
l=length(Difference);
sumneg=0;
counter=0
for var=1:l
    if Difference(var)<0

```

```

        sumneg=sumneg+Difference(var)
        counter=counter+1
    end
end
clc
negdifavg=sumneg/counter
fmin=min(forcet);
fmax=max(forcet);
favg=mean(forcet);
fprintf('dif min value      dif max value      dif avg value      dif neg avg
force max      force min      force avg\n')
fprintf('%+10.6f      %+10.6f      %+10.6f      %+10.6f      %+10.6f
%+10.6f      %+10.6f\n',difmin, difmax, difavg, negdifavg,fmax,fmin,favg)

%This creates a plot of the force
subplot (231), plot(distancet,forcet)
    title('Force vs. Distance for a 3 stage solenoid')
    xlabel('Distance (m)')
    ylabel('Force (Newtons)')
    grid
subplot (232), plot(distancet,force2)
    title('Force2 vs. Distance')
    xlabel('Distance (m)')
    ylabel('Force (Newtons)')
    grid
subplot (233), plot(distancet,force3)
    title('Force3 vs. Distance')
    xlabel('Distance (m)')
    ylabel('Force (Newtons)')
    grid
subplot (234), plot(distancet,force4)
    title('Force4 vs. Distance')
    xlabel('Distance (m)')
    ylabel('Force (Newtons)')
    grid
subplot (235), plot(xsingle,F);
    title('Force vs. Distance (Reg)');
    xlabel('Distance (m)');
    ylabel('Force (Newtons)');
    grid;
subplot (236), plot(xsingle,Difference)
    title('Force3Stage-ForceRegular vs. Distance')
    xlabel('Distance (m)')
    ylabel('Force (Newtons)')
    grid
figure(2)
clf;
plot(distancet,errorgraph,'r*')
title('Error plot')
text(0,.5,'A value of 1 means that the arrangement wont work, core 2
is not held in place')
xlabel('Distance (m)')
ylabel('Error points')

```

```

    totallength=length(forcet)
    Difference=forcet-F;
    difmin=min(Difference(1:totallength-2));
    [value,position]=min(Difference(1:totallength-2));
    difmax=max(Difference(1:totallength-2));
    difavgspecial=mean(Difference(position:totallength-2));
    difavg=mean(Difference(1:totallength-2));
    l=length(Difference);

    sumneg=0;
    counter=0;
    for var=1:l-2
        if Difference(var)<0
            sumneg=sumneg+Difference(var);
            counter=counter+1;
        end
    end
    clc
    negdifavg=sumneg/counter;
    fmin=min(forcet(1:totallength-2));
    fmax=max(forcet(1:totallength-2));

    favg=mean(forcet(1:totallength-2));
    difcheck=(difavg+negdifavg);

    fprintf('The dif avg is%+10.6f The difavg+difneg is%+10.6f The
    difspecialavg is %+10.6f\n',difavg, difcheck, difavgspecial)
    mean(forcet)
    mean(F)

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%       Two-Stage Solenoid Model Refinement Code
%
%                               Jeremy Myers
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This program finds the best geometry for a given total length. This
% is done by changing different geometries and setting up an index to
% compare the results. The best results geometry is presented as the
% output.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear all
warning off;
n=0
difminold=0;
    difmaxold=0;
    difavgold=0;
    negdifavgold=0;
    fminold=0;
    fmaxold=0;
    favgold=0;
    difcheckold=-1000;
    errorsummed=0
% This program will analyze the force for a two part solenoid
% Metric Units Used Throughout
totallength=24
D1=20
D2=20
    for D3=1:1:19
        for X3MAX=1:totallength-1;
            for XHOLE=1:X3MAX+10;
                X4MAX=totallength-X3MAX;

%inputs
' Input the diameter of the main core in millimeters';
d1=D1;
' Input the diameter of the second core in millimeters';
d2=D2;
' Input the diameter of the third core in millimeters';
d3=D3;
' Input the diameter of the rod';
rod=3;
' Input the size of the shell thickness in millimeters';
t1=3;
' The gap between the case and first core(x1) (mm)';
x1=.6;
' The gap between core 2 and core 3 (mm)';
x5=.4;
' The gap between the case and the third core (x6) (mm)';
x6=.4;
' The largest value x3 can have based on the length of the rod
connecting core 1 & 3 (mm)';
x3max=X3MAX;
' The largest value x4 can have (mm)';

```

```

x4max=X4MAX;
' The depth of the hole in core #2';
xhole=XHOLE;
' Input the number of Amps(I)';
I=5;
' Input the number of Turns(N)';
N=400;

variables=[d1; d2; d3; rod; t1; x1; x5; x6; x3max; x4max; xhole; I; N];
% Converts the above from millimeters to meters
d1=d1*.001;
d2=d2*.001;
d3=d3*.001;
rod=rod*.001;
t1=t1*.001;
x1=x1*.001;
x5=x5*.001;
x6=x6*.001;
x3max=x3max*.001;
x4max=x4max*.001;
xhole=xhole*.001;
% Permability mu
mu=4*pi*.0000001;
% The amp turns value(NI)
NI=N*I;
%
%
%This portion of the program will determine with the above equations,
what force will be created with single stage solenoid
%
%
%
%
%This portion of the program will determine with the above equations,
what force will be created with single stage solenoid
%
%This program will analyze the force for a normal solenoid
%
%a stepper which will analyze the force for different x positions
%
for stepsingle=1:((x3max+x4max)*1000);
    %x1 location of solenoid core (units m)
    xsingle(stepsingle)=stepsingle*.001;
    %Resistance from gap at R2
    R1(stepsingle)=x1/(d1*pi*t1*mu);
    %Resistance from gap at R1
    Rsingle(stepsingle)=xsingle(stepsingle)/(mu*pi*((d1^2)-
((rod+2*x6)^2))/4);
    Rtotal(stepsingle)=R1(stepsingle)+Rsingle(stepsingle);
    %Flux phe (units weber)
    phe(stepsingle)=NI/(Rtotal(stepsingle));
    %Check for over saturation (webers/m^2)
    Check=phe(stepsingle)/(d1*pi*t1);
    if Check > 1.25;
        phe(stepsingle)=1.25*(d1*pi*t1);
    end
end

```

```

        end
        %Force (units newtons)
        F(stepsingle)=.5*phe(stepsingle)^2/((pi*((d1^2)-
        ((rod+2*x6)^2))/4)*mu);
    end
    %This creates a plot of the Flux
    %subplot (211);
    %plot(xsingle,phe);
    %title('Flux vs. Distance for a Regular Solenoid')
    %xlabel('Distance (m)')
    %ylabel('Flux (Webers)')
    %grid;
    %This creates a plot of Force
    %subplot (212);
    %plot(xsingle,F);
    %title('Force vs. Distance for a Regular Solenoid');
    %xlabel('Distance (m)');
    %ylabel('Force (Newtons)');
    %grid;
    %
    %
    %This part of the program will determine with the above equations, what
    force will be created with a two step solenoid
    %
    %
    % a stepper which will analyze the force for different x positions
    % x begins with x at the furthest point
    for step=1:(x4max*1000);
        x2=0;
        x3=x3max-x2;
        %converts location of solenoid core 2 to m
        x4(step)=step*.001;
        %This portion of the program will calculate the areas at each
        resistance area
        a6=pi*d3*t1;
        if xhole > x3;
            a5=(xhole-x3)*pi*d3;
        else
            a5=0;
        end
        a4=(d2^2-(d3+2*x5)^2)*pi/4;
        a3=(pi*(d3^2)/4)-(pi*(rod^2)/4);
        if d2 <= d1;
            a2=(pi*(d2^2)/4)-pi*rod^2/4;
        else
            a2=(pi*(d1^2)/4)-pi*rod^2/4;
        end
        a1=pi*d1*t1;
        %This portion assigns values to each gap
        gap6=x6;
        gap5=x5;
        gap4=x4(step);
        gap3=x3;
        gap2=x2;
        gap1=x1;
    end

```

```

    %This portion calculates the resistance at each point and then the
sum
    r6=gap6/(a6*mu);
    r5=gap5/(a5*mu);
    r4=gap4/(a4*mu);
    r3=gap3/(a3*mu);
    r2=gap2/(a2*mu);
    r1=gap1/(a1*mu);
    if a5 == 0
        rtotal=((r3+r6)*r4)/(r3+r6+r4))+r2+r1;
    else

        rtotal((((r5*r3)/(r5+r3))+r6)*r4)/((((r5*r3)/(r5+r3))+r6)+r4))+r2+
r1;
    end
    %This portion checks the flux (weber) and makes sure it is not to
large
    fluxt(step)=NI/rtotal;
    check=fluxt(step)/a1;
    if check > 1.25;
        fluxt(step)=1.25*a1;
    end
    %This portion will calculate the flux at r3, r4, & r2
    if a5 == 0;
        flux3(step)=(fluxt(step)*r4)/(r6+r3+r4);
        flux4(step)=(fluxt(step)-flux3(step)) ;
    else
        flux3(step)=(fluxt(step)*r4)/(r3+r6+(r6*r3/r5)+r4+(r4*r3/r5));
        flux4(step)=(fluxt(step)-flux3(step)*(1+r3/r5));
    end
    %This portion calculates the force at 3 & 4 & Total
    force3(step)=(.5*flux3(step)^2)/(a3*mu);
    force4(step)=(.5*flux4(step)^2)/(a4*mu);
    forcet(step)=force4(step);
    distancet(step)=x4(step);
end
% x value continues with core 2 reaching its furthest point and x2
increasing
for step=(x4max*1000+1):(x4max*1000+x3max*1000);
    x2(step)=(step-x4max*1000)*.001;
    x3(step)=(x3max-x2(step));
    %converts location of solenoid core 2 to m
    x4(step)=x4max;
    %This portion of the program will calculate the areas at each
resistance area
    a6=pi*d3*t1;
    if xhole > x3(step);
        a5=(xhole-x3(step))*pi*d3;
    else
        a5=0;
    end
    a4=(d2^2-(d3+2*x5)^2)*pi/4;
    a3=pi*(d3^2)/4-(pi*(rod^2)/4);
    if d2 <= d1;
        a2=pi*(d2^2)/4-(pi*(rod^2)/4);

```

```

else
    a2=pi*(d1^2)/4-(pi*(rod^2)/4);
end
a1=pi*d1*t1;
%This portion assigns values to each gap
gap6=x6;
gap5=x5;
gap4=x4(step);
gap3=x3(step);
gap2=x2(step);
gap1=x1;
%This portion calculates the resistance at each point and then the
sum
r6=gap6/(a6*mu);
r5=gap5/(a5*mu);
r4=gap4/(a4*mu);
r3=gap3/(a3*mu);
r2=gap2/(a2*mu);
r1=gap1/(a1*mu);
if a5 == 0
    rtotal=((r3+r6)*r4)/(r3+r6+r4)+r2+r1;
else
    rtotal((((r5*r3)/(r5+r3))+r6)*r4)/((((r5*r3)/(r5+r3))+r6)+r4))+r2+
r1;
end
%This portion checks the flux (weber) and makes sure it is not to
large
fluxt(step)=NI/rtotal;
check=fluxt(step)/a1;
if check > 1.25;
    fluxt(step)=1.25*a1;
end
%This portion will calculate the flux at r3, r4, & r2
if a5 == 0
    flux3(step)=(fluxt(step)*r4)/(r6+r3+r4);
    flux4(step)=(fluxt(step)-flux3(step)) ;
else
    flux3(step)=(fluxt(step)*r4)/(r3+r6+(r6*r3/r5)+r4+(r4*r3/r5));
    flux4(step)=(fluxt(step)-flux3(step)*(1+r3/r5));
end
flux2(step)=fluxt(step);
%This portion calculates the force at 2 & 3 & 4 & Total
force2(step)=(.5*flux2(step)^2)/(a2*mu);
force3(step)=(.5*flux3(step)^2)/(a3*mu);
force4(step)=(.5*flux4(step)^2)/(a4*mu);
forcet(step)=force2(step)-force3(step);
distancet(step)=(step)*.001;
%This portion makes sure that core 2 is held in place if it is not,
the force will show up as 0
if force3(step)+force4(step) < force2(step)
    error(step)=1;
    errorgraph(step)=0;
else
    error(step)=0;

```

```

        errorgraph(step)=1;
    end
    forcet(step)=forcet(step)*error(step);
end
%This portion will calculate the difference between a regular solenoid
and the two step
Difference=forcet-F;
difmin=min(Difference(1:totallength-2));
difmax=max(Difference(1:totallength-2));
difavg=mean(Difference(1:totallength-2));
l=length(Difference);
sumneg=0;
counter=0;
for var=1:l-2
    if Difference(var)<0
        sumneg=sumneg+Difference(var);
        counter=counter+1;
    end
end
clc
negdifavg=sumneg/counter;
fmin=min(forcet(1:totallength-2));
fmax=max(forcet(1:totallength-2));
favg=mean(forcet(1:totallength-2));
difcheck=(difavg+negdifavg);
%This portion saves the new data
if difcheck>difcheckold
    if sum(errorgraph)<=1
        difminold=difmin;
        difmaxold=difmax;
        difavgold=difavg;
        negdifavgold=negdifavg;
        fminold=fmin;
        fmaxold=fmax;
        favgold=favg;
        difcheckold=difcheck;
        variablesold=variables;
        errorsummed=sum(errorgraph);
    end
end
end
end
end
% This portion prints out the results
fprintf('%+10.6f      %+10.6f      %+10.6f      %+10.6f      %+10.6f\n',difminold, difmaxold, difavgold, negdifavgold, fmaxold, fminold, favgold, errorsummed)
variablesold
end

fprintf('dif min value      dif max value      dif avg value      dif neg avg\n')
fprintf('force max      force min      force avg      error\n')

```

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
1.50	11.50	10.00	1,038.00	0.09	0.66	8.98
1.50	11.50	9.00	988.00	0.10	0.75	11.16
1.50	11.50	8.00	994.00	0.11	0.66	14.86
1.50	11.50	7.00	1,090.00	0.13	0.73	21.03
1.50	11.50	6.00	1,013.00	0.15	0.83	35.27
1.50	11.50	5.00	934.00	0.21	0.85	70.42
1.50	11.50	5.00	934.00	0.21	0.86	20.32
1.50	11.50	4.00	1,145.00	0.23	0.70	26.89
1.50	11.50	3.00	1,043.00	0.27	0.63	39.78
1.50	11.50	2.00	1,004.00	0.31	1.08	67.86
1.50	11.50	1.00	1,170.00	0.38	0.65	148.85
1.50	11.50	0.00	1,055.00	0.47	0.70	447.21
1.50	12.50	10.00	995.00	0.09	0.67	8.97
1.50	12.50	9.00	1,015.00	0.10	0.79	11.15
1.50	12.50	8.00	1,017.00	0.11	0.62	14.50
1.50	12.50	7.00	1,096.00	0.13	0.75	20.34
1.50	12.50	6.00	1,233.00	0.15	0.64	33.42
1.50	12.50	5.00	977.00	0.21	0.82	89.44
1.50	12.50	5.00	975.00	0.21	0.66	19.76
1.50	12.50	4.00	1,042.00	0.23	0.86	25.95
1.50	12.50	3.00	1,169.00	0.26	0.67	38.23
1.50	12.50	2.00	1,218.00	0.31	0.55	67.55
1.50	12.50	1.00	1,204.00	0.38	0.55	152.31
1.50	12.50	-	1,231.00	0.47	0.48	446.48
1.50	13.50	10.00	1,040.00	0.09	0.70	8.88
1.50	13.50	9.00	996.00	0.10	0.81	10.86
1.50	13.50	8.00	1,057.00	0.11	0.63	14.17
1.50	13.50	7.00	1,087.00	0.13	0.76	19.15
1.50	13.50	6.00	923.00	0.15	0.99	33.04
1.50	13.50	5.00	1,024.00	0.21	0.83	88.31
1.50	13.50	5.00	798.00	0.21	0.95	19.27
1.50	13.50	4.00	1,018.00	0.23	0.83	25.51
1.50	13.50	3.00	1,216.00	0.26	0.62	38.73
1.50	13.50	2.00	1,132.00	0.31	0.62	68.71
1.50	13.50	1.00	1,256.00	0.38	0.52	153.75
1.50	13.50	-	1,213.00	0.47	0.56	422.31

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
1.50	14.50	10.00	989.00	0.09	0.71	8.57
1.50	14.50	9.00	1,033.00	0.10	0.77	10.61
1.50	14.50	8.00	1,022.00	0.11	0.75	12.82
1.50	14.50	7.00	1,015.00	0.13	0.88	19.03
1.50	14.50	6.00	977.00	0.15	0.81	33.09
1.50	14.50	5.00	1,008.00	0.20	0.77	87.23
1.50	14.50	5.00	1,006.00	0.20	0.81	19.42
1.50	14.50	4.00	832.00	0.23	0.95	26.31
1.50	14.50	3.00	875.00	0.26	0.84	39.76
1.50	14.50	2.00	1,174.00	0.31	0.54	69.74
1.50	14.50	1.00	1,239.00	0.38	0.55	153.58
1.50	14.50	-	1,198.00	0.47	0.58	446.59
1.50	15.50	10.00	1,047.00	0.09	0.65	8.35
1.50	15.50	9.00	991.00	0.10	0.86	9.48
1.50	15.50	8.00	945.00	0.11	0.74	12.90
1.50	15.50	7.00	1,066.00	0.12	0.70	19.31
1.50	15.50	6.00	977.00	0.15	0.82	33.17
1.50	15.50	5.00	1,040.00	0.20	0.64	87.12
1.50	15.50	5.00	803.00	0.20	0.85	20.00
1.50	15.50	4.00	985.00	0.23	0.67	26.96
1.50	15.50	3.00	908.00	0.26	0.90	40.09
1.50	15.50	2.00	888.00	0.31	0.88	69.54
1.50	15.50	1.00	1,211.00	0.38	0.55	153.55
1.50	15.50	-	1,168.00	0.48	0.49	450.36
2.50	11.50	10.00	1,049.00	0.09	0.77	9.53
2.50	11.50	9.00	999.00	0.10	0.85	11.87
2.50	11.50	8.00	1,269.00	0.12	0.53	15.94
2.50	11.50	7.00	1,080.00	0.14	0.89	22.51
2.50	11.50	6.00	1,297.00	0.16	0.72	37.81
2.50	11.50	5.00	956.00	0.22	0.83	73.01
2.50	11.50	5.00	955.00	0.22	0.86	19.38
2.50	11.50	4.00	1,182.00	0.25	0.86	24.82
2.50	11.50	3.00	1,050.00	0.27	1.44	35.96
2.50	11.50	2.00	1,041.00	0.32	1.07	63.00
2.50	11.50	1.00	1,156.00	0.38	0.83	141.33
2.50	11.50	-	1,082.00	0.47	0.68	450.17

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
2.50	12.50	10.00	1,022.00	0.09	0.85	9.36
2.50	12.50	9.00	1,021.00	0.10	0.85	11.71
2.50	12.50	8.00	1,014.00	0.12	0.94	14.94
2.50	12.50	7.00	1,095.00	0.13	0.87	20.99
2.50	12.50	6.00	1,259.00	0.16	0.65	32.73
2.50	12.50	5.00	1,258.00	0.22	0.61	91.99
2.50	12.50	5.00	1,251.00	0.22	0.65	18.38
2.50	12.50	4.00	1,014.00	0.24	1.00	24.27
2.50	12.50	3.00	1,133.00	0.27	0.71	36.29
2.50	12.50	2.00	1,173.00	0.31	0.71	64.19
2.50	12.50	1.00	1,198.00	0.38	0.57	148.17
2.50	12.50	-	1,217.00	0.46	0.46	429.83
2.50	13.50	10.00	1,034.00	0.09	0.78	9.19
2.50	13.50	9.00	996.00	0.10	0.97	10.83
2.50	13.50	8.00	1,352.00	0.12	0.52	13.80
2.50	13.50	7.00	1,089.00	0.13	0.88	17.82
2.50	13.50	6.00	1,166.00	0.16	0.87	32.79
2.50	13.50	5.00	1,000.00	0.21	0.85	89.00
2.50	13.50	5.00	1,000.00	0.21	0.72	18.31
2.50	13.50	4.00	998.00	0.23	0.81	24.44
2.50	13.50	3.00	1,170.00	0.26	0.61	37.04
2.50	13.50	2.00	1,129.00	0.31	0.64	66.33
2.50	13.50	1.00	1,264.00	0.38	0.53	150.66
2.50	13.50	-	1,221.00	0.46	0.57	446.05
2.50	14.50	10.00	990.00	0.09	0.89	8.47
2.50	14.50	9.00	1,022.00	0.10	0.93	9.96
2.50	14.50	8.00	1,026.00	0.11	0.82	11.76
2.50	14.50	7.00	1,008.00	0.13	0.97	18.45
2.50	14.50	6.00	1,225.00	0.15	0.74	32.93
2.50	14.50	5.00	1,263.00	0.21	0.56	87.45
2.50	14.50	5.00	995.00	0.21	0.82	18.64
2.50	14.50	4.00	1,043.00	0.23	0.74	25.12
2.50	14.50	3.00	1,117.00	0.26	0.57	38.41
2.50	14.50	2.00	891.00	0.31	0.88	67.63
2.50	14.50	1.00	1,264.00	0.38	0.53	151.06
2.50	14.50	-	1,203.00	0.47	0.53	448.62

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
2.50	15.50	10.00	1,034.00	0.09	0.83	7.70
2.50	15.50	9.00	1,292.00	0.10	0.72	8.53
2.50	15.50	8.00	987.00	0.11	0.73	12.47
2.50	15.50	7.00	1,042.00	0.12	0.81	18.93
2.50	15.50	6.00	948.00	0.15	0.78	32.47
2.50	15.50	5.00	1,019.00	0.20	0.67	86.25
2.50	15.50	5.00	783.00	0.20	0.91	19.20
2.50	15.50	4.00	986.00	0.23	0.73	26.16
2.50	15.50	3.00	1,159.00	0.26	0.55	39.22
2.50	15.50	2.00	1,155.00	0.31	0.56	68.21
2.50	15.50	1.00	1,224.00	0.38	0.58	151.11
2.50	15.50	-	1,207.00	0.46	0.57	445.87
3.50	11.50	10.00	1,023.00	0.10	0.90	9.99
3.50	11.50	9.00	1,287.00	0.11	0.74	12.63
3.50	11.50	8.00	1,269.00	0.13	0.71	16.88
3.50	11.50	7.00	1,397.00	0.15	0.89	24.13
3.50	11.50	6.00	1,289.00	0.18	0.92	39.78
3.50	11.50	5.00	1,203.00	0.24	0.72	101.70
3.50	11.50	5.00	1,205.00	0.24	0.68	17.14
3.50	11.50	4.00	1,109.00	0.26	0.91	22.12
3.50	11.50	3.00	972.00	0.28	1.67	32.51
3.50	11.50	2.00	1,043.00	0.32	1.12	57.62
3.50	11.50	1.00	1,136.00	0.38	0.87	132.93
3.50	11.50	-	1,066.00	0.46	0.67	432.36
3.50	12.50	10.00	999.00	0.10	0.86	9.75
3.50	12.50	9.00	1,292.00	0.11	0.82	12.16
3.50	12.50	8.00	1,307.00	0.12	0.72	15.62
3.50	12.50	7.00	1,414.00	0.14	0.76	20.94
3.50	12.50	6.00	1,209.00	0.17	0.90	32.48
3.50	12.50	5.00	1,144.00	0.22	0.78	94.20
3.50	12.50	5.00	1,150.00	0.22	0.75	16.69
3.50	12.50	4.00	1,196.00	0.24	0.85	22.42
3.50	12.50	3.00	1,096.00	0.27	0.73	33.41
3.50	12.50	2.00	1,126.00	0.31	0.76	59.83
3.50	12.50	1.00	1,146.00	0.38	0.78	141.94
3.50	12.50	-	1,140.00	0.47	0.66	431.64

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
3.50	13.50	10.00	1,024.00	0.10	0.99	9.21
3.50	13.50	9.00	1,290.00	0.11	0.88	11.20
3.50	13.50	8.00	1,341.00	0.12	0.68	13.47
3.50	13.50	7.00	1,351.00	0.14	0.79	17.02
3.50	13.50	6.00	1,060.00	0.16	0.89	32.31
3.50	13.50	5.00	1,184.00	0.21	0.76	89.69
3.50	13.50	5.00	911.00	0.21	0.91	16.94
3.50	13.50	4.00	1,282.00	0.23	0.83	22.82
3.50	13.50	3.00	1,123.00	0.26	0.57	34.76
3.50	13.50	2.00	1,054.00	0.30	0.77	63.24
3.50	13.50	1.00	1,169.00	0.37	0.59	145.77
3.50	13.50	-	1,132.00	0.47	0.60	435.37
3.50	14.50	10.00	1,271.00	0.10	0.82	8.46
3.50	14.50	9.00	1,292.00	0.11	0.79	9.68
3.50	14.50	8.00	1,291.00	0.12	0.59	10.92
3.50	14.50	7.00	1,224.00	0.13	0.69	17.93
3.50	14.50	6.00	1,151.00	0.15	0.82	32.38
3.50	14.50	5.00	981.00	0.21	0.78	66.83
3.50	14.50	5.00	986.00	0.21	0.63	17.45
3.50	14.50	4.00	1,043.00	0.23	0.85	23.83
3.50	14.50	3.00	1,109.00	0.26	0.53	36.77
3.50	14.50	2.00	1,139.00	0.30	0.53	64.97
3.50	14.50	1.00	1,220.00	0.37	0.65	146.54
3.50	14.50	-	1,188.00	0.47	0.54	442.87
3.50	15.50	10.00	1,336.00	0.09	0.64	7.37
3.50	15.50	9.00	975.00	0.10	0.93	7.90
3.50	15.50	8.00	932.00	0.11	0.93	11.83
3.50	15.50	7.00	1,268.00	0.13	0.63	18.46
3.50	15.50	6.00	1,221.00	0.15	0.59	32.21
3.50	15.50	5.00	1,297.00	0.20	0.54	85.62
3.50	15.50	5.00	1,002.00	0.20	0.75	18.21
3.50	15.50	4.00	999.00	0.22	0.64	25.03
3.50	15.50	3.00	1,135.00	0.25	0.50	37.84
3.50	15.50	2.00	1,151.00	0.30	0.51	65.49
3.50	15.50	1.00	1,212.00	0.37	0.60	146.71
3.50	15.50	-	1,197.00	0.47	0.50	434.96

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
4.50	11.50	10.00	1,018.00	0.10	0.97	10.25
4.50	11.50	9.00	972.00	0.12	0.96	13.25
4.50	11.50	8.00	981.00	0.13	1.00	17.69
4.50	11.50	7.00	1,362.00	0.15	0.83	25.25
4.50	11.50	6.00	1,273.00	0.18	0.93	41.60
4.50	11.50	5.00	1,203.00	0.25	0.80	106.22
4.50	11.50	5.00	1,207.00	0.25	0.75	15.1295
4.50	11.50	4.00	1,107.00	0.26	0.81	19.847
4.50	11.50	3.00	968.00	0.29	1.77	29.2564
4.50	11.50	2.00	1,072.00	0.32	1.19	52.016
4.50	11.50	1.00	1,128.00	0.37	0.87	121.8626
4.50	11.50	-	1,053.00	0.45	0.68	412.490159
4.50	12.50	10.00	1,268.00	0.10	0.75	10.03
4.50	12.50	9.00	1,025.00	0.11	0.96	12.52
4.50	12.50	8.00	978.00	0.13	0.99	15.82
4.50	12.50	7.00	1,430.00	0.15	0.73	21.39
4.50	12.50	6.00	1,196.00	0.17	0.88	32.27
4.50	12.50	5.00	1,137.00	0.23	0.80	95.78
4.50	12.50	5.00	1,136.00	0.23	0.69	15.17
4.50	12.50	4.00	1,179.00	0.25	0.87	20.24
4.50	12.50	3.00	1,093.00	0.27	0.84	30.48
4.50	12.50	2.00	1,103.00	0.31	0.85	55.09
4.50	12.50	1.00	1,104.00	0.37	0.84	132.87
4.50	12.50	-	1,127.00	0.45	0.52	420.26
4.50	13.50	10.00	1,025.00	0.10	0.81	9.51
4.50	13.50	9.00	979.00	0.11	1.00	11.22
4.50	13.50	8.00	1,049.00	0.12	1.00	13.33
4.50	13.50	7.00	1,334.00	0.14	0.76	16.52
4.50	13.50	6.00	1,076.00	0.16	1.04	31.84
4.50	13.50	5.00	1,169.00	0.22	0.78	89.80
4.50	13.50	5.00	1,155.00	0.22	0.82	15.68
4.50	13.50	4.00	1,268.00	0.23	0.64	20.80
4.50	13.50	3.00	1,079.00	0.26	0.69	32.06
4.50	13.50	2.00	1,053.00	0.30	0.74	59.37
4.50	13.50	1.00	1,138.00	0.37	0.73	137.90
4.50	13.50	-	821.00	0.47	0.83	424.56

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
4.50	14.50	10.00	965.00	0.10	0.93	8.51
4.50	14.50	9.00	1,303.00	0.11	0.71	9.54
4.50	14.50	8.00	1,298.00	0.12	0.61	10.39
4.50	14.50	7.00	1,214.00	0.13	0.81	17.33
4.50	14.50	6.00	1,128.00	0.15	0.83	31.90
4.50	14.50	5.00	946.00	0.21	0.86	65.97
4.50	14.50	5.00	947.00	0.21	0.76	16.12
4.50	14.50	4.00	983.00	0.23	0.89	22.02
4.50	14.50	3.00	1,049.00	0.25	0.52	34.30
4.50	14.50	2.00	1,091.00	0.30	0.78	61.29
4.50	14.50	1.00	1,084.00	0.37	0.88	138.77
4.50	14.50	-	1,135.00	0.45	0.51	420.61
4.50	15.50	10.00	1,024.00	0.10	0.89	7.16
4.50	15.50	9.00	976.00	0.10	0.90	7.36
4.50	15.50	8.00	1,196.00	0.11	0.58	11.43
4.50	15.50	7.00	945.00	0.13	0.99	17.92
4.50	15.50	6.00	925.00	0.15	0.94	31.70
4.50	15.50	5.00	962.00	0.20	0.88	83.95
4.50	15.50	5.00	742.00	0.20	0.97	16.85
4.50	15.50	4.00	955.00	0.22	0.99	23.75
4.50	15.50	3.00	1,094.00	0.25	0.52	35.77
4.50	15.50	2.00	1,052.00	0.30	1.03	61.93
4.50	15.50	1.00	1,179.00	0.37	0.73	139.29
4.50	15.50	-	1,140.00	0.45	0.52	423.77
5.50	11.50	10.00	946.00	0.11	0.94	10.37
5.50	11.50	9.00	1,182.00	0.12	0.93	13.69
5.50	11.50	8.00	1,152.00	0.13	0.85	18.63
5.50	11.50	7.00	1,274.00	0.16	0.95	26.34
5.50	11.50	6.00	1,503.00	0.19	0.70	43.33
5.50	11.50	5.00	1,093.00	0.26	1.11	109.69
5.50	11.50	5.00	1,092.00	0.26	0.93	13.76
5.50	11.50	4.00	1,078.00	0.27	1.12	17.56
5.50	11.50	3.00	945.00	0.29	1.83	25.12
5.50	11.50	2.00	981.00	0.32	1.41	45.03
5.50	11.50	1.00	1,073.00	0.37	1.17	103.34
5.50	11.50	-	1,001.00	0.42	0.71	369.61

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
5.50	12.50	10.00	922.00	0.10	0.99	10.37
5.50	12.50	9.00	1,201.00	0.12	0.88	13.00
5.50	12.50	8.00	1,212.00	0.13	0.73	16.46
5.50	12.50	7.00	1,274.00	0.15	0.79	21.87
5.50	12.50	6.00	1,091.00	0.18	0.98	31.70
5.50	12.50	5.00	1,098.00	0.23	1.02	96.40
5.50	12.50	5.00	1,093.00	0.23	0.82	13.66
5.50	12.50	4.00	1,149.00	0.25	0.98	17.94
5.50	12.50	3.00	980.00	0.27	1.56	26.57
5.50	12.50	2.00	1,008.00	0.30	1.06	48.68
5.50	12.50	1.00	1,058.00	0.36	1.24	117.31
5.50	12.50	-	1,076.00	0.42	0.59	369.24
5.50	13.50	10.00	1,206.00	0.10	0.78	9.74
5.50	13.50	9.00	1,203.00	0.11	0.84	11.51
5.50	13.50	8.00	1,223.00	0.13	0.68	13.61
5.50	13.50	7.00	1,226.00	0.14	0.80	16.00
5.50	13.50	6.00	1,013.00	0.16	1.15	30.95
5.50	13.50	5.00	1,136.00	0.22	0.79	89.17
5.50	13.50	5.00	1,148.00	0.22	0.83	13.96
5.50	13.50	4.00	1,152.00	0.23	0.75	18.78
5.50	13.50	3.00	981.00	0.26	1.21	28.32
5.50	13.50	2.00	980.00	0.29	1.05	53.58
5.50	13.50	1.00	1,111.00	0.35	0.74	123.58
5.50	13.50	-	1,075.00	0.41	0.62	374.62
5.50	14.50	10.00	1,186.00	0.10	0.79	8.65
5.50	14.50	9.00	928.00	0.11	0.99	9.56
5.50	14.50	8.00	1,157.00	0.12	0.64	9.85
5.50	14.50	7.00	1,173.00	0.13	0.81	16.70
5.50	14.50	6.00	1,075.00	0.16	0.88	31.21
5.50	14.50	5.00	887.00	0.21	0.92	84.32
5.50	14.50	5.00	888.00	0.21	0.91	14.84
5.50	14.50	4.00	1,149.00	0.22	0.79	20.11
5.50	14.50	3.00	965.00	0.25	0.81	31.60
5.50	14.50	2.00	1,013.00	0.29	1.31	56.60
5.50	14.50	1.00	1,125.00	0.35	0.94	125.15
5.50	14.50	-	1,079.00	0.41	0.59	372.18

Raw Data for Total Motion of 10 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
5.50	15.50	10.00	936.00	0.10	0.92	7.19
5.50	15.50	9.00	1,138.00	0.10	0.82	6.81
5.50	15.50	8.00	1,151.00	0.11	0.68	11.00
5.50	15.50	7.00	1,195.00	0.13	0.69	17.45
5.50	15.50	6.00	1,102.00	0.15	0.72	31.00
5.50	15.50	5.00	888.00	0.20	0.88	81.86
5.50	15.50	5.00	886.00	0.20	0.94	15.68
5.50	15.50	4.00	1,138.00	0.22	0.74	22.01
5.50	15.50	3.00	1,005.00	0.25	1.00	32.98
5.50	15.50	2.00	1,008.00	0.29	0.99	57.00
5.50	15.50	1.00	1,129.00	0.35	0.74	125.92
5.50	15.50	-	1,086.00	0.41	0.58	373.56

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
1.50	11.50	9.00	1,006.00	0.09	9.73
1.50	11.50	8.00	1,084.00	0.10	12.27
1.50	11.50	7.00	1,050.00	0.12	16.25
1.50	11.50	6.00	1,005.00	0.14	23.44
1.50	11.50	5.00	1,422.00	0.17	40.88
1.50	11.50	4.00	1,161.00	0.23	109.10
1.50	11.50	4.00	1,145.00	0.23	26.89
1.50	11.50	3.00	1,043.00	0.27	39.78
1.50	11.50	2.00	1,004.00	0.31	67.86
1.50	11.50	1.00	1,170.00	0.38	148.85
1.50	11.50	-	1,055.00	0.47	447.21
1.50	12.50	9.00	1,067.00	0.09	9.71
1.50	12.50	8.00	1,027.00	0.10	12.23
1.50	12.50	7.00	1,095.00	0.12	15.92
1.50	12.50	6.00	1,021.00	0.14	22.98
1.50	12.50	5.00	1,265.00	0.17	38.63
1.50	12.50	4.00	1,045.00	0.23	106.68
1.50	12.50	4.00	1,042.00	0.23	25.95
1.50	12.50	3.00	1,169.00	0.26	38.23
1.50	12.50	2.00	1,218.00	0.31	67.55
1.50	12.50	1.00	1,204.00	0.38	152.31
1.50	12.50	-	1,231.00	0.47	446.48
1.50	13.50	9.00	1,039.00	0.09	9.58
1.50	13.50	8.00	1,042.00	0.10	12.00
1.50	13.50	7.00	1,132.00	0.12	15.54
1.50	13.50	6.00	935.00	0.14	21.47
1.50	13.50	5.00	1,056.00	0.17	37.41
1.50	13.50	4.00	1,022.00	0.23	104.94
1.50	13.50	4.00	1,018.00	0.23	25.51
1.50	13.50	3.00	1,216.00	0.26	38.73
1.50	13.50	2.00	1,132.00	0.31	68.71
1.50	13.50	1.00	1,256.00	0.38	153.75
1.50	13.50	-	1,213.00	0.47	422.31
1.50	14.50	9.00	1,041.00	0.09	9.40
1.50	14.50	8.00	1,058.00	0.10	11.69
1.50	14.50	7.00	1,046.00	0.12	14.34
1.50	14.50	6.00	987.00	0.14	21.39
1.50	14.50	5.00	1,056.00	0.16	38.02
1.50	14.50	4.00	1,077.00	0.23	104.56
1.50	14.50	4.00	832.00	0.23	26.31
1.50	14.50	3.00	875.00	0.26	39.76
1.50	14.50	2.00	1,174.00	0.31	69.74
1.50	14.50	1.00	1,239.00	0.38	153.58
1.50	14.50	-	1,198.00	0.47	446.59

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
1.50	15.50	9.00	1,071.00	0.09	8.99
1.50	15.50	8.00	973.00	0.10	10.49
1.50	15.50	7.00	1,066.00	0.12	14.47
1.50	15.50	6.00	977.00	0.13	21.71
1.50	15.50	5.00	1,098.00	0.16	38.42
1.50	15.50	4.00	978.00	0.23	104.75
1.50	15.50	4.00	985.00	0.23	26.96
1.50	15.50	3.00	908.00	0.26	40.09
1.50	15.50	2.00	888.00	0.31	69.54
1.50	15.50	1.00	1,211.00	0.38	153.55
1.50	15.50	-	1,168.00	0.48	450.36
2.50	11.50	9.00	1,037.00	0.10	10.30
2.50	11.50	8.00	1,094.00	0.11	13.02
2.50	11.50	7.00	1,361.00	0.13	17.32
2.50	11.50	6.00	1,021.00	0.15	24.83
2.50	11.50	5.00	1,135.00	0.18	42.62
2.50	11.50	4.00	1,194.00	0.24	113.05
2.50	11.50	4.00	1,182.00	0.25	24.82
2.50	11.50	3.00	1,050.00	0.27	35.96
2.50	11.50	2.00	1,041.00	0.32	63.00
2.50	11.50	1.00	1,156.00	0.38	141.33
2.50	11.50	-	1,082.00	0.47	450.17
2.50	12.50	9.00	1,090.00	0.10	10.13
2.50	12.50	8.00	1,041.00	0.11	12.70
2.50	12.50	7.00	1,095.00	0.12	16.34
2.50	12.50	6.00	1,049.00	0.14	23.14
2.50	12.50	5.00	1,299.00	0.17	37.82
2.50	12.50	4.00	1,021.00	0.24	108.01
2.50	12.50	4.00	1,014.00	0.24	24.27
2.50	12.50	3.00	1,133.00	0.27	36.29
2.50	12.50	2.00	1,173.00	0.31	64.19
2.50	12.50	1.00	1,198.00	0.38	148.17
2.50	12.50	-	1,217.00	0.46	429.83
2.50	13.50	9.00	1,043.00	0.10	9.80
2.50	13.50	8.00	1,051.00	0.11	12.06
2.50	13.50	7.00	1,148.00	0.12	15.04
2.50	13.50	6.00	1,217.00	0.14	20.32
2.50	13.50	5.00	1,036.00	0.17	37.50
2.50	13.50	4.00	997.00	0.23	104.98
2.50	13.50	4.00	998.00	0.23	24.44
2.50	13.50	3.00	1,170.00	0.26	37.04
2.50	13.50	2.00	1,129.00	0.31	66.33
2.50	13.50	1.00	1,264.00	0.38	150.66
2.50	13.50	-	1,221.00	0.46	446.05

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
2.50	14.50	9.00	1,047.00	0.10	9.41
2.50	14.50	8.00	1,090.00	0.11	11.11
2.50	14.50	7.00	1,359.00	0.12	13.24
2.50	14.50	6.00	972.00	0.14	20.93
2.50	14.50	5.00	1,040.00	0.16	37.64
2.50	14.50	4.00	1,039.00	0.23	103.47
2.50	14.50	4.00	1,043.00	0.23	25.12
2.50	14.50	3.00	1,117.00	0.26	38.41
2.50	14.50	2.00	891.00	0.31	67.63
2.50	14.50	1.00	1,264.00	0.38	151.06
2.50	14.50	-	1,203.00	0.47	448.62
2.50	15.50	9.00	1,090.00	0.10	8.57
2.50	15.50	8.00	1,263.00	0.11	9.81
2.50	15.50	7.00	1,091.00	0.12	14.05
2.50	15.50	6.00	951.00	0.13	21.35
2.50	15.50	5.00	1,066.00	0.16	37.86
2.50	15.50	4.00	986.00	0.23	103.61
2.50	15.50	4.00	986.00	0.23	26.16
2.50	15.50	3.00	1,159.00	0.26	39.22
2.50	15.50	2.00	1,155.00	0.31	68.21
2.50	15.50	1.00	1,224.00	0.38	151.11
2.50	15.50	-	1,207.00	0.46	445.87
3.50	11.50	9.00	1,018.00	0.10	10.67
3.50	11.50	8.00	1,078.00	0.12	13.59
3.50	11.50	7.00	1,360.00	0.13	18.22
3.50	11.50	6.00	1,312.00	0.15	26.06
3.50	11.50	5.00	1,418.00	0.19	44.32
3.50	11.50	4.00	1,113.00	0.26	117.03
3.50	11.50	4.00	1,109.00	0.26	22.12
3.50	11.50	3.00	972.00	0.28	32.51
3.50	11.50	2.00	1,043.00	0.32	57.62
3.50	11.50	1.00	1,136.00	0.38	132.93
3.50	11.50	-	1,066.00	0.46	432.36
3.50	12.50	9.00	1,075.00	0.10	10.44
3.50	12.50	8.00	1,353.00	0.12	13.16
3.50	12.50	7.00	1,416.00	0.13	16.80
3.50	12.50	6.00	1,326.00	0.15	23.18
3.50	12.50	5.00	1,213.00	0.18	36.99
3.50	12.50	4.00	1,207.00	0.24	109.26
3.50	12.50	4.00	1,196.00	0.24	22.42
3.50	12.50	3.00	1,096.00	0.27	33.41
3.50	12.50	2.00	1,126.00	0.31	59.83
3.50	12.50	1.00	1,146.00	0.38	141.94
3.50	12.50	-	1,140.00	0.47	431.64

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
3.50	13.50	9.00	1,352.00	0.10	10.07
3.50	13.50	8.00	1,350.00	0.11	12.23
3.50	13.50	7.00	1,133.00	0.13	14.81
3.50	13.50	6.00	1,142.00	0.14	19.41
3.50	13.50	5.00	1,222.00	0.17	36.96
3.50	13.50	4.00	1,288.00	0.23	104.72
3.50	13.50	4.00	1,282.00	0.23	22.82
3.50	13.50	3.00	1,123.00	0.26	34.76
3.50	13.50	2.00	1,054.00	0.30	63.24
3.50	13.50	1.00	1,169.00	0.37	145.77
3.50	13.50	-	1,132.00	0.47	435.37
3.50	14.50	9.00	1,026.00	0.10	9.28
3.50	14.50	8.00	1,355.00	0.11	10.85
3.50	14.50	7.00	1,300.00	0.12	12.59
3.50	14.50	6.00	1,174.00	0.14	20.34
3.50	14.50	5.00	1,371.00	0.17	37.08
3.50	14.50	4.00	1,043.00	0.23	102.22
3.50	14.50	4.00	1,043.00	0.23	23.83
3.50	14.50	3.00	1,109.00	0.26	36.77
3.50	14.50	2.00	1,139.00	0.30	64.97
3.50	14.50	1.00	1,220.00	0.37	146.54
3.50	14.50	-	1,188.00	0.47	442.87
3.50	15.50	9.00	1,074.00	0.10	8.26
3.50	15.50	8.00	1,202.00	0.11	9.15
3.50	15.50	7.00	1,032.00	0.12	13.52
3.50	15.50	6.00	973.00	0.13	20.83
3.50	15.50	5.00	1,068.00	0.16	37.17
3.50	15.50	4.00	776.00	0.22	101.27
3.50	15.50	4.00	999.00	0.22	25.03
3.50	15.50	3.00	1,135.00	0.25	37.84
3.50	15.50	2.00	1,151.00	0.30	65.49
3.50	15.50	1.00	1,212.00	0.37	146.71
3.50	15.50	-	1,197.00	0.47	434.96
4.50	11.50	9.00	979.00	0.11	10.87
4.50	11.50	8.00	1,046.00	0.12	14.09
4.50	11.50	7.00	982.00	0.14	18.79
4.50	11.50	6.00	1,326.00	0.16	27.21
4.50	11.50	5.00	1,406.00	0.19	45.68
4.50	11.50	4.00	1,112.00	0.26	119.78
4.50	11.50	4.00	1,107.00	0.26	19.847
4.50	11.50	3.00	968.00	0.29	29.2564
4.50	11.50	2.00	1,072.00	0.32	52.016
4.50	11.50	1.00	1,128.00	0.37	121.8626
4.50	11.50	-	1,053.00	0.45	412.4902

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
4.50	12.50	9.00	1,052.00	0.11	10.72
4.50	12.50	8.00	1,270.00	0.12	13.48
4.50	12.50	7.00	1,096.00	0.13	17.12
4.50	12.50	6.00	1,327.00	0.15	23.44
4.50	12.50	5.00	1,209.00	0.18	36.79
4.50	12.50	4.00	1,192.00	0.25	109.03
4.50	12.50	4.00	1,179.00	0.25	20.24
4.50	12.50	3.00	1,093.00	0.27	30.48
4.50	12.50	2.00	1,103.00	0.31	55.09
4.50	12.50	1.00	1,104.00	0.37	132.87
4.50	12.50	-	1,127.00	0.45	420.26
4.50	13.50	9.00	977.00	0.10	10.16
4.50	13.50	8.00	1,371.00	0.12	12.33
4.50	13.50	7.00	1,431.00	0.13	14.86
4.50	13.50	6.00	1,136.00	0.15	18.86
4.50	13.50	5.00	1,214.00	0.17	36.25
4.50	13.50	4.00	1,269.00	0.23	103.31
4.50	13.50	4.00	1,268.00	0.23	20.80
4.50	13.50	3.00	1,079.00	0.26	32.06
4.50	13.50	2.00	1,053.00	0.30	59.37
4.50	13.50	1.00	1,138.00	0.37	137.90
4.50	13.50	-	821.00	0.47	424.56
4.50	14.50	9.00	1,047.00	0.10	9.29
4.50	14.50	8.00	1,342.00	0.11	10.70
4.50	14.50	7.00	1,004.00	0.12	11.97
4.50	14.50	6.00	1,156.00	0.14	19.70
4.50	14.50	5.00	1,328.00	0.17	36.22
4.50	14.50	4.00	982.00	0.23	100.21
4.50	14.50	4.00	983.00	0.23	22.02
4.50	14.50	3.00	1,049.00	0.25	34.30
4.50	14.50	2.00	1,091.00	0.30	61.29
4.50	14.50	1.00	1,084.00	0.37	138.77
4.50	14.50	-	1,135.00	0.45	420.61
4.50	15.50	9.00	1,038.00	0.10	8.05
4.50	15.50	8.00	1,205.00	0.11	8.58
4.50	15.50	7.00	1,007.00	0.12	12.96
4.50	15.50	6.00	944.00	0.13	20.29
4.50	15.50	5.00	1,021.00	0.16	36.21
4.50	15.50	4.00	959.00	0.22	99.22
4.50	15.50	4.00	955.00	0.22	23.75
4.50	15.50	3.00	1,094.00	0.25	35.77
4.50	15.50	2.00	1,052.00	0.30	61.93
4.50	15.50	1.00	1,179.00	0.37	139.29
4.50	15.50	-	1,140.00	0.45	423.77

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
5.50	11.50	9.00	911.00	0.11	10.94
5.50	11.50	8.00	1,226.00	0.12	14.44
5.50	11.50	7.00	1,231.00	0.14	19.57
5.50	11.50	6.00	1,161.00	0.16	28.11
5.50	11.50	5.00	1,272.00	0.20	46.38
5.50	11.50	4.00	1,080.00	0.27	122.57
5.50	11.50	4.00	0.27	1.12	17.56
5.50	11.50	3.00	0.29	1.83	25.12
5.50	11.50	2.00	0.32	1.41	45.03
5.50	11.50	1.00	0.37	1.17	103.34
5.50	11.50	-	0.42	0.71	369.61
5.50	12.50	9.00	933.00	0.11	10.93
5.50	12.50	8.00	1,204.00	0.12	13.79
5.50	12.50	7.00	1,272.00	0.14	17.62
5.50	12.50	6.00	1,158.00	0.16	23.67
5.50	12.50	5.00	1,172.00	0.18	35.39
5.50	12.50	4.00	1,149.00	0.25	108.78
5.50	12.50	4.00	0.25	0.98	17.94
5.50	12.50	3.00	0.27	1.56	26.57
5.50	12.50	2.00	0.30	1.06	48.68
5.50	12.50	1.00	0.36	1.24	117.31
5.50	12.50	-	0.42	0.59	369.24
5.50	13.50	9.00	944.00	0.11	10.27
5.50	13.50	8.00	1,208.00	0.12	12.48
5.50	13.50	7.00	1,275.00	0.13	14.86
5.50	13.50	6.00	1,097.00	0.15	18.16
5.50	13.50	5.00	1,173.00	0.17	35.20
5.50	13.50	4.00	1,152.00	0.23	101.67
5.50	13.50	4.00	0.23	0.75	18.78
5.50	13.50	3.00	0.26	1.21	28.32
5.50	13.50	2.00	0.29	1.05	53.58
5.50	13.50	1.00	0.35	0.74	123.58
5.50	13.50	-	0.41	0.62	374.62
5.50	14.50	9.00	1,206.00	0.10	9.47
5.50	14.50	8.00	1,217.00	0.11	10.58
5.50	14.50	7.00	1,242.00	0.13	11.42
5.50	14.50	6.00	1,147.00	0.14	18.95
5.50	14.50	5.00	1,212.00	0.17	35.18
5.50	14.50	4.00	1,164.00	0.22	97.93
5.50	14.50	4.00	0.22	0.79	20.11
5.50	14.50	3.00	0.25	0.81	31.60
5.50	14.50	2.00	0.29	1.31	56.60
5.50	14.50	1.00	0.35	0.94	125.15
5.50	14.50	-	0.41	0.59	372.18

Raw Data for Total Motion of 9 mm for solenoid in Figure 17 current =1500 A

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Force(N)
5.50	15.50	9.00	943.00	0.10	7.98
5.50	15.50	8.00	1,136.00	0.11	8.09
5.50	15.50	7.00	985.00	0.12	12.32
5.50	15.50	6.00	1,102.00	0.14	19.61
5.50	15.50	5.00	1,216.00	0.16	35.22
5.50	15.50	4.00	1,137.00	0.22	96.95
5.50	15.50	4.00	0.22	0.74	22.01
5.50	15.50	3.00	0.25	1.00	32.98
5.50	15.50	2.00	0.29	0.99	57.00
5.50	15.50	1.00	0.35	0.74	125.92
5.50	15.50	-	0.41	0.58	373.56

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
1.50	11.50	8.00	1,086.00	0.10	0.59	10.83
1.50	11.50	7.00	1,108.00	0.11	0.74	13.61
1.50	11.50	6.00	975.00	0.13	0.84	18.20
1.50	11.50	5.00	1,092.00	0.15	0.87	26.93
1.50	11.50	4.00	1,325.00	0.19	0.64	47.65
1.50	11.50	3.00	1,212.00	0.27	0.78	138.46
1.50	11.50	3.00	1,043.00	0.27	0.63	39.78
1.50	11.50	2.00	1,004.00	0.31	1.08	67.86
1.50	11.50	1.00	1,170.00	0.38	0.65	148.85
1.50	11.50	-	1,055.00	0.47	0.70	447.21
1.50	12.50	8.00	1,075.00	0.10	0.61	10.79
1.50	12.50	7.00	853.00	0.11	1.00	13.47
1.50	12.50	6.00	1,029.00	0.13	0.79	18.07
1.50	12.50	5.00	1,041.00	0.15	0.88	26.30
1.50	12.50	4.00	1,348.00	0.19	0.77	46.15
1.50	12.50	3.00	1,031.00	0.26	0.97	134.84
1.50	12.50	3.00	1,169.00	0.26	0.67	38.23
1.50	12.50	2.00	1,218.00	0.31	0.55	67.55
1.50	12.50	1.00	1,204.00	0.38	0.55	152.31
1.50	12.50	-	1,231.00	0.47	0.48	446.48
1.50	13.50	8.00	1,090.00	0.10	0.62	10.62
1.50	13.50	7.00	1,099.00	0.11	0.79	13.26
1.50	13.50	6.00	964.00	0.13	0.94	17.56
1.50	13.50	5.00	1,079.00	0.15	0.98	24.85
1.50	13.50	4.00	1,048.00	0.18	0.88	45.11
1.50	13.50	3.00	831.00	0.26	0.98	133.21
1.50	13.50	3.00	1,216.00	0.26	0.62	38.73
1.50	13.50	2.00	1,132.00	0.31	0.62	68.71
1.50	13.50	1.00	1,256.00	0.38	0.52	153.75
1.50	13.50	-	1,213.00	0.47	0.56	422.31
1.50	14.50	8.00	1,074.00	0.10	0.71	10.48
1.50	14.50	7.00	1,043.00	0.11	0.90	12.96
1.50	14.50	6.00	1,016.00	0.13	0.94	16.39
1.50	14.50	5.00	1,047.00	0.15	0.88	24.85
1.50	14.50	4.00	1,125.00	0.18	0.77	45.57
1.50	14.50	3.00	1,019.00	0.26	0.84	134.31
1.50	14.50	3.00	875.00	0.26	0.84	39.76
1.50	14.50	2.00	1,174.00	0.31	0.54	69.74
1.50	14.50	1.00	1,239.00	0.38	0.55	153.58
1.50	14.50	-	1,198.00	0.47	0.58	446.59

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
1.50	15.50	8.00	988.00	0.10	0.95	10.09
1.50	15.50	7.00	1,077.00	0.11	0.84	12.16
1.50	15.50	6.00	951.00	0.13	0.91	16.57
1.50	15.50	5.00	1,094.00	0.15	0.81	25.40
1.50	15.50	4.00	1,074.00	0.18	0.82	45.97
1.50	15.50	3.00	812.00	0.26	0.94	133.84
1.50	15.50	3.00	908.00	0.26	0.90	40.09
1.50	15.50	2.00	888.00	0.31	0.88	69.54
1.50	15.50	1.00	1,211.00	0.38	0.55	153.55
1.50	15.50	-	1,168.00	0.48	0.49	450.36
2.50	11.50	8.00	1,092.00	0.11	0.62	11.28
2.50	11.50	7.00	1,137.00	0.12	0.84	14.25
2.50	11.50	6.00	1,250.00	0.13	0.57	19.25
2.50	11.50	5.00	1,103.00	0.16	0.95	28.02
2.50	11.50	4.00	1,351.00	0.19	0.72	49.51
2.50	11.50	3.00	1,252.00	0.27	0.82	140.88
2.50	11.50	3.00	1,050.00	0.27	1.44	35.96
2.50	11.50	2.00	1,041.00	0.32	1.07	63.00
2.50	11.50	1.00	1,156.00	0.38	0.83	141.33
2.50	11.50	-	1,082.00	0.47	0.68	450.17
2.50	12.50	8.00	1,080.00	0.11	0.68	11.04
2.50	12.50	7.00	1,426.00	0.12	0.50	14.03
2.50	12.50	6.00	1,042.00	0.13	0.88	18.15
2.50	12.50	5.00	1,368.00	0.16	0.69	26.53
2.50	12.50	4.00	1,360.00	0.19	0.69	44.66
2.50	12.50	3.00	1,019.00	0.27	0.84	134.99
2.50	12.50	3.00	1,133.00	0.27	0.71	36.29
2.50	12.50	2.00	1,173.00	0.31	0.71	64.19
2.50	12.50	1.00	1,198.00	0.38	0.57	148.17
2.50	12.50	-	1,217.00	0.46	0.46	429.83
2.50	13.50	8.00	1,077.00	0.10	0.69	10.87
2.50	13.50	7.00	1,128.00	0.12	0.79	13.26
2.50	13.50	6.00	1,268.00	0.13	0.60	17.06
2.50	13.50	5.00	1,064.00	0.15	0.87	23.75
2.50	13.50	4.00	1,340.00	0.18	0.68	44.54
2.50	13.50	3.00	1,041.00	0.26	0.67	132.26
2.50	13.50	3.00	1,170.00	0.26	0.61	37.04
2.50	13.50	2.00	1,129.00	0.31	0.64	66.33
2.50	13.50	1.00	1,264.00	0.38	0.53	150.66
2.50	13.50	-	1,221.00	0.46	0.57	446.05

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
2.50	14.50	8.00	1,076.00	0.10	0.74	10.25
2.50	14.50	7.00	1,369.00	0.12	0.54	12.44
2.50	14.50	6.00	1,008.00	0.13	0.87	15.55
2.50	14.50	5.00	1,040.00	0.15	0.87	24.40
2.50	14.50	4.00	1,076.00	0.18	0.80	44.84
2.50	14.50	3.00	1,003.00	0.26	0.71	131.96
2.50	14.50	3.00	1,117.00	0.26	0.57	38.41
2.50	14.50	2.00	891.00	0.31	0.88	67.63
2.50	14.50	1.00	1,264.00	0.38	0.53	151.06
2.50	14.50	-	1,203.00	0.47	0.53	448.62
2.50	15.50	8.00	1,316.00	0.10	0.57	9.63
2.50	15.50	7.00	1,075.00	0.11	0.78	11.47
2.50	15.50	6.00	988.00	0.13	0.88	16.16
2.50	15.50	5.00	1,064.00	0.15	0.76	24.96
2.50	15.50	4.00	1,029.00	0.18	0.88	45.14
2.50	15.50	3.00	1,049.00	0.26	0.83	132.30
2.50	15.50	3.00	1,159.00	0.26	0.55	39.22
2.50	15.50	2.00	1,155.00	0.31	0.56	68.21
2.50	15.50	1.00	1,224.00	0.38	0.58	151.11
2.50	15.50	-	1,207.00	0.46	0.57	445.87
3.50	11.50	8.00	1,067.00	0.11	0.76	11.42
3.50	11.50	7.00	1,135.00	0.12	0.99	14.63
3.50	11.50	6.00	1,217.00	0.14	0.74	20.03
3.50	11.50	5.00	1,420.00	0.16	0.80	29.12
3.50	11.50	4.00	1,266.00	0.20	0.82	50.60
3.50	11.50	3.00	1,147.00	0.28	0.75	142.71
3.50	11.50	3.00	972.00	0.28	1.67	32.51
3.50	11.50	2.00	1,043.00	0.32	1.12	57.62
3.50	11.50	1.00	1,136.00	0.38	0.87	132.93
3.50	11.50	-	1,066.00	0.46	0.67	432.36
3.50	12.50	8.00	1,076.00	0.11	0.87	11.29
3.50	12.50	7.00	1,414.00	0.12	0.57	14.23
3.50	12.50	6.00	1,019.00	0.14	0.96	18.50
3.50	12.50	5.00	1,276.00	0.16	0.74	26.38
3.50	12.50	4.00	1,264.00	0.19	1.03	43.32
3.50	12.50	3.00	1,268.00	0.27	0.77	134.34
3.50	12.50	3.00	1,096.00	0.27	0.73	33.41
3.50	12.50	2.00	1,126.00	0.31	0.76	59.83
3.50	12.50	1.00	1,146.00	0.38	0.78	141.94
3.50	12.50	-	1,140.00	0.47	0.66	431.64

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
3.50	13.50	8.00	1,066.00	0.11	0.85	10.94
3.50	13.50	7.00	1,416.00	0.12	0.59	13.27
3.50	13.50	6.00	1,199.00	0.13	0.73	16.84
3.50	13.50	5.00	1,271.00	0.15	0.92	23.05
3.50	13.50	4.00	1,014.00	0.18	0.95	43.57
3.50	13.50	3.00	1,018.00	0.26	0.74	129.80
3.50	13.50	3.00	1,123.00	0.26	0.57	34.76
3.50	13.50	2.00	1,054.00	0.30	0.77	63.24
3.50	13.50	1.00	1,169.00	0.37	0.59	145.77
3.50	13.50	-	1,132.00	0.47	0.60	435.37
3.50	14.50	8.00	1,041.00	0.11	0.91	10.25
3.50	14.50	7.00	1,271.00	0.12	0.66	12.17
3.50	14.50	6.00	1,208.00	0.13	0.71	14.89
3.50	14.50	5.00	1,040.00	0.15	0.81	23.66
3.50	14.50	4.00	1,073.00	0.18	0.82	43.82
3.50	14.50	3.00	989.00	0.26	0.69	100.49
3.50	14.50	3.00	1,109.00	0.26	0.53	36.77
3.50	14.50	2.00	1,139.00	0.30	0.53	64.97
3.50	14.50	1.00	1,220.00	0.37	0.65	146.54
3.50	14.50	-	1,188.00	0.47	0.54	442.87
3.50	15.50	8.00	946.00	0.10	0.82	9.40
3.50	15.50	7.00	1,271.00	0.11	0.63	10.85
3.50	15.50	6.00	981.00	0.13	0.79	15.68
3.50	15.50	5.00	1,056.00	0.15	0.77	24.33
3.50	15.50	4.00	1,022.00	0.18	0.75	44.49
3.50	15.50	3.00	1,021.00	0.25	0.69	129.40
3.50	15.50	3.00	1,135.00	0.25	0.50	37.84
3.50	15.50	2.00	1,151.00	0.30	0.51	65.49
3.50	15.50	1.00	1,212.00	0.37	0.60	146.71
3.50	15.50	-	1,197.00	0.47	0.50	434.96
4.50	11.50	8.00	1,069.00	0.11	0.83	11.57
4.50	11.50	7.00	1,055.00	0.12	0.94	14.88
4.50	11.50	6.00	970.00	0.14	1.00	20.26
4.50	11.50	5.00	1,103.00	0.17	1.00	29.64
4.50	11.50	4.00	1,260.00	0.21	0.95	51.62
4.50	11.50	3.00	1,177.00	0.29	0.89	143.12
4.50	11.50	3.00	968.00	0.29	1.77	29.2564
4.50	11.50	2.00	1,072.00	0.32	1.19	52.016
4.50	11.50	1.00	1,128.00	0.37	0.87	121.8626
4.50	11.50	-	1,053.00	0.45	0.68	412.490159

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
4.50	12.50	8.00	1,327.00	0.11	0.55	11.42
4.50	12.50	7.00	1,446.00	0.12	0.54	14.45
4.50	12.50	6.00	1,024.00	0.14	0.98	18.79
4.50	12.50	5.00	1,276.00	0.16	0.78	26.42
4.50	12.50	4.00	1,268.00	0.19	1.01	42.67
4.50	12.50	3.00	1,302.00	0.27	0.77	131.86
4.50	12.50	3.00	1,093.00	0.27	0.84	30.48
4.50	12.50	2.00	1,103.00	0.31	0.85	55.09
4.50	12.50	1.00	1,104.00	0.37	0.84	132.87
4.50	12.50	-	1,127.00	0.45	0.52	420.26
4.50	13.50	8.00	1,069.00	0.11	0.86	10.95
4.50	13.50	7.00	1,103.00	0.12	0.90	13.34
4.50	13.50	6.00	1,182.00	0.14	0.73	16.77
4.50	13.50	5.00	1,272.00	0.15	0.89	22.33
4.50	13.50	4.00	1,329.00	0.19	0.78	42.17
4.50	13.50	3.00	1,301.00	0.26	0.70	126.69
4.50	13.50	3.00	1,079.00	0.26	0.69	32.06
4.50	13.50	2.00	1,053.00	0.30	0.74	59.37
4.50	13.50	1.00	1,138.00	0.37	0.73	137.90
4.50	13.50	-	821.00	0.47	0.83	424.56
4.50	14.50	8.00	1,072.00	0.11	0.77	10.24
4.50	14.50	7.00	1,275.00	0.12	0.64	12.07
4.50	14.50	6.00	1,224.00	0.13	0.71	14.21
4.50	14.50	5.00	1,045.00	0.15	0.85	22.76
4.50	14.50	4.00	1,358.00	0.18	0.61	42.67
4.50	14.50	3.00	960.00	0.25	0.62	125.04
4.50	14.50	3.00	1,049.00	0.25	0.52	34.30
4.50	14.50	2.00	1,091.00	0.30	0.78	61.29
4.50	14.50	1.00	1,084.00	0.37	0.88	138.77
4.50	14.50	-	1,135.00	0.45	0.51	420.61
4.50	15.50	8.00	934.00	0.10	0.96	9.16
4.50	15.50	7.00	1,302.00	0.11	0.68	10.32
4.50	15.50	6.00	991.00	0.13	0.97	15.06
4.50	15.50	5.00	1,028.00	0.15	0.82	23.60
4.50	15.50	4.00	980.00	0.18	0.83	43.21
4.50	15.50	3.00	1,003.00	0.25	0.67	125.20
4.50	15.50	3.00	1,094.00	0.25	0.52	35.77
4.50	15.50	2.00	1,052.00	0.30	1.03	61.93
4.50	15.50	1.00	1,179.00	0.37	0.73	139.29
4.50	15.50	-	1,140.00	0.45	0.52	423.77

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
5.50	11.50	8.00	975.00	0.11	0.88	11.69
5.50	11.50	7.00	1,313.00	0.13	0.62	15.27
5.50	11.50	6.00	1,138.00	0.14	0.77	20.88
5.50	11.50	5.00	1,274.00	0.17	0.79	30.50
5.50	11.50	4.00	1,257.00	0.21	1.08	52.23
5.50	11.50	3.00	1,137.00	0.29	0.93	141.46
5.50	11.50	3.00	945.00	0.29	1.83	25.12
5.50	11.50	2.00	981.00	0.32	1.41	45.03
5.50	11.50	1.00	1,073.00	0.37	1.17	103.34
5.50	11.50	-	1,001.00	0.42	0.71	369.61
5.50	12.50	8.00	977.00	0.11	0.88	11.54
5.50	12.50	7.00	1,004.00	0.12	0.82	14.63
5.50	12.50	6.00	1,195.00	0.14	0.75	18.98
5.50	12.50	5.00	1,250.00	0.16	0.80	26.36
5.50	12.50	4.00	1,222.00	0.20	0.90	41.39
5.50	12.50	3.00	1,181.00	0.27	0.80	127.74
5.50	12.50	3.00	980.00	0.27	1.56	26.57
5.50	12.50	2.00	1,008.00	0.30	1.06	48.68
5.50	12.50	1.00	1,058.00	0.36	1.24	117.31
5.50	12.50	-	1,076.00	0.42	0.59	369.24
5.50	13.50	8.00	975.00	0.11	0.93	11.06
5.50	13.50	7.00	1,004.00	0.12	0.87	13.46
5.50	13.50	6.00	1,152.00	0.14	0.74	16.56
5.50	13.50	5.00	1,252.00	0.16	0.83	21.23
5.50	13.50	4.00	1,205.00	0.19	0.78	40.48
5.50	13.50	3.00	1,180.00	0.26	0.78	121.82
5.50	13.50	3.00	981.00	0.26	1.21	28.32
5.50	13.50	2.00	980.00	0.29	1.05	53.58
5.50	13.50	1.00	1,111.00	0.35	0.74	123.58
5.50	13.50	-	1,075.00	0.41	0.62	374.62
5.50	14.50	8.00	945.00	0.11	0.90	10.25
5.50	14.50	7.00	1,265.00	0.12	0.60	11.91
5.50	14.50	6.00	1,162.00	0.13	0.74	13.37
5.50	14.50	5.00	1,231.00	0.15	0.68	21.99
5.50	14.50	4.00	1,213.00	0.18	0.76	41.01
5.50	14.50	3.00	1,146.00	0.25	0.71	119.77
5.50	14.50	3.00	965.00	0.25	0.81	31.60
5.50	14.50	2.00	1,013.00	0.29	1.31	56.60
5.50	14.50	1.00	1,125.00	0.35	0.94	125.15
5.50	14.50	-	1,079.00	0.41	0.59	372.18

Raw Data for Total Motion of 8 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
5.50	15.50	8.00	922.00	0.11	0.94	9.00
5.50	15.50	7.00	1,268.00	0.11	0.64	9.67
5.50	15.50	6.00	1,170.00	0.13	0.63	14.48
5.50	15.50	5.00	1,212.00	0.15	0.64	22.85
5.50	15.50	4.00	1,176.00	0.18	0.70	41.82
5.50	15.50	3.00	1,194.00	0.25	0.76	119.94
5.50	15.50	3.00	1,005.00	0.25	1.00	32.98
5.50	15.50	2.00	1,008.00	0.29	0.99	57.00
5.50	15.50	1.00	1,129.00	0.35	0.74	125.92
5.50	15.50	-	1,086.00	0.41	0.58	373.56

Raw Data for Total Motion of 7 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
1.50	11.50	7.00	1,091.00	0.11	0.64	12.08
1.50	11.50	6.00	1,009.00	0.12	0.77	15.51
1.50	11.50	5.00	1,032.00	0.14	0.84	21.12
1.50	11.50	4.00	1,006.00	0.17	0.85	32.14
1.50	11.50	3.00	1,066.00	0.21	0.94	60.25
1.50	11.50	2.00	843.00	0.31	0.99	148.78
1.50	11.50	2.00	1,004.00	0.31	1.08	67.86
1.50	11.50	1.00	1,170.00	0.38	0.65	148.85
1.50	11.50	-	1,055.00	0.47	0.70	447.21
1.50	12.50	7.00	1,110.00	0.11	0.65	12.11
1.50	12.50	6.00	1,259.00	0.12	0.62	15.36
1.50	12.50	5.00	999.00	0.14	0.94	20.85
1.50	12.50	4.00	1,059.00	0.17	0.86	31.54
1.50	12.50	3.00	1,294.00	0.21	0.86	57.33
1.50	12.50	2.00	785.00	0.31	0.97	146.58
1.50	12.50	2.00	1,218.00	0.31	0.55	67.55
1.50	12.50	1.00	1,204.00	0.38	0.55	152.31
1.50	12.50	-	1,231.00	0.47	0.48	446.48
1.50	13.50	7.00	1,089.00	0.11	0.67	11.88
1.50	13.50	6.00	1,199.00	0.12	0.62	15.14
1.50	13.50	5.00	1,394.00	0.14	0.60	20.55
1.50	13.50	4.00	1,033.00	0.17	0.82	29.85
1.50	13.50	3.00	1,077.00	0.21	0.77	57.48
1.50	13.50	2.00	929.00	0.31	0.72	189.54
1.50	13.50	2.00	1,132.00	0.31	0.62	68.71
1.50	13.50	1.00	1,256.00	0.38	0.52	153.75
1.50	13.50	-	1,213.00	0.47	0.56	422.31
1.50	14.50	7.00	1,014.00	0.11	0.75	11.80
1.50	14.50	6.00	983.00	0.12	0.84	14.86
1.50	14.50	5.00	1,030.00	0.14	0.82	19.32
1.50	14.50	4.00	1,081.00	0.16	0.82	30.45
1.50	14.50	3.00	1,031.00	0.21	0.76	58.33
1.50	14.50	2.00	754.00	0.31	0.95	147.70
1.50	14.50	2.00	1,174.00	0.31	0.54	69.74
1.50	14.50	1.00	1,239.00	0.38	0.55	153.58
1.50	14.50	-	1,198.00	0.47	0.58	446.59
1.50	15.50	7.00	1,080.00	0.11	0.69	11.48
1.50	15.50	6.00	951.00	0.12	0.94	14.10
1.50	15.50	5.00	1,049.00	0.14	0.72	19.94
1.50	15.50	4.00	1,021.00	0.16	0.75	30.97
1.50	15.50	3.00	1,091.00	0.21	0.79	58.61
1.50	15.50	2.00	973.00	0.31	0.69	190.03
1.50	15.50	2.00	888.00	0.31	0.88	69.54
1.50	15.50	1.00	1,211.00	0.38	0.55	153.55
1.50	15.50	-	1,168.00	0.48	0.49	450.36

Raw Data for Total Motion of 7 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
2.50	11.50	7.00	1,096.00	0.11	0.67	12.30
2.50	11.50	6.00	1,320.00	0.13	0.49	15.87
2.50	11.50	5.00	1,043.00	0.14	0.82	21.77
2.50	11.50	4.00	1,327.00	0.17	0.63	32.96
2.50	11.50	3.00	1,388.00	0.22	0.86	61.00
2.50	11.50	2.00	1,123.00	0.32	0.79	192.23
2.50	11.50	2.00	1,041.00	0.32	1.07	63.00
2.50	11.50	1.00	1,156.00	0.38	0.83	141.33
2.50	11.50	-	1,082.00	0.47	0.68	450.17
2.50	12.50	7.00	1,136.00	0.11	0.66	12.29
2.50	12.50	6.00	1,295.00	0.13	0.76	15.67
2.50	12.50	5.00	1,306.00	0.14	0.74	21.24
2.50	12.50	4.00	1,065.00	0.17	0.99	31.32
2.50	12.50	3.00	1,325.00	0.21	0.79	56.69
2.50	12.50	2.00	974.00	0.31	0.82	186.75
2.50	12.50	2.00	1,173.00	0.31	0.71	64.19
2.50	12.50	1.00	1,198.00	0.38	0.57	148.17
2.50	12.50	-	1,217.00	0.46	0.46	429.83
2.50	13.50	7.00	1,133.00	0.11	0.70	11.94
2.50	13.50	6.00	1,221.00	0.13	0.78	15.14
2.50	13.50	5.00	1,082.00	0.14	0.93	19.91
2.50	13.50	4.00	1,330.00	0.17	0.62	29.22
2.50	13.50	3.00	1,043.00	0.21	0.92	56.72
2.50	13.50	2.00	929.00	0.31	0.74	185.97
2.50	13.50	2.00	1,129.00	0.31	0.64	66.33
2.50	13.50	1.00	1,264.00	0.38	0.53	150.66
2.50	13.50	-	1,221.00	0.46	0.57	446.05
2.50	14.50	7.00	1,347.00	0.11	0.53	11.68
2.50	14.50	6.00	1,292.00	0.12	0.83	14.52
2.50	14.50	5.00	1,035.00	0.14	0.84	18.88
2.50	14.50	4.00	1,087.00	0.16	0.72	29.89
2.50	14.50	3.00	1,018.00	0.20	0.86	57.39
2.50	14.50	2.00	977.00	0.31	0.71	186.43
2.50	14.50	2.00	891.00	0.31	0.88	67.63
2.50	14.50	1.00	1,264.00	0.38	0.53	151.06
2.50	14.50	-	1,203.00	0.47	0.53	448.62
2.50	15.50	7.00	1,091.00	0.11	0.98	10.95
2.50	15.50	6.00	1,224.00	0.12	0.80	13.75
2.50	15.50	5.00	1,059.00	0.14	0.69	19.49
2.50	15.50	4.00	1,003.00	0.16	0.75	30.56
2.50	15.50	3.00	1,043.00	0.20	0.87	57.76
2.50	15.50	2.00	977.00	0.31	0.69	186.55
2.50	15.50	2.00	1,155.00	0.31	0.56	68.21
2.50	15.50	1.00	1,224.00	0.38	0.58	151.11
2.50	15.50	-	1,207.00	0.46	0.57	445.87

Raw Data for Total Motion of 7 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
3.50	11.50	7.00	1,097.00	0.11	0.80	12.47
3.50	11.50	6.00	1,017.00	0.13	0.93	16.13
3.50	11.50	5.00	1,326.00	0.15	0.75	22.31
3.50	11.50	4.00	1,273.00	0.17	0.77	33.39
3.50	11.50	3.00	1,326.00	0.22	0.94	61.63
3.50	11.50	2.00	1,136.00	0.32	0.87	189.40
3.50	11.50	2.00	1,043.00	0.32	1.12	57.62
3.50	11.50	1.00	1,136.00	0.38	0.87	132.93
3.50	11.50	-	1,066.00	0.46	0.67	432.36
3.50	12.50	7.00	1,126.00	0.11	0.79	12.32
3.50	12.50	6.00	988.00	0.13	0.93	15.77
3.50	12.50	5.00	1,271.00	0.15	0.79	21.19
3.50	12.50	4.00	1,326.00	0.17	0.74	31.02
3.50	12.50	3.00	1,341.00	0.21	0.84	55.10
3.50	12.50	2.00	956.00	0.31	0.86	182.00
3.50	12.50	2.00	1,126.00	0.31	0.76	59.83
3.50	12.50	1.00	1,146.00	0.38	0.78	141.94
3.50	12.50	-	1,140.00	0.47	0.66	431.64
3.50	13.50	7.00	1,098.00	0.11	0.77	12.01
3.50	13.50	6.00	1,152.00	0.13	0.78	15.11
3.50	13.50	5.00	1,336.00	0.14	0.71	19.81
3.50	13.50	4.00	1,352.00	0.17	0.65	28.31
3.50	13.50	3.00	1,322.00	0.21	0.84	55.26
3.50	13.50	2.00	905.00	0.30	0.92	180.70
3.50	13.50	2.00	1,054.00	0.30	0.77	63.24
3.50	13.50	1.00	1,169.00	0.37	0.59	145.77
3.50	13.50	-	1,132.00	0.47	0.60	435.37
3.50	14.50	7.00	981.00	0.11	0.85	11.51
3.50	14.50	6.00	1,222.00	0.12	0.89	14.23
3.50	14.50	5.00	1,055.00	0.14	0.84	18.11
3.50	14.50	4.00	1,093.00	0.16	0.74	29.04
3.50	14.50	3.00	1,032.00	0.20	0.81	56.06
3.50	14.50	2.00	954.00	0.30	0.71	141.24
3.50	14.50	2.00	1,139.00	0.30	0.53	64.97
3.50	14.50	1.00	1,220.00	0.37	0.65	146.54
3.50	14.50	-	1,188.00	0.47	0.54	442.87
3.50	15.50	7.00	1,351.00	0.11	0.58	10.89
3.50	15.50	6.00	1,264.00	0.12	0.84	13.10
3.50	15.50	5.00	1,064.00	0.14	0.79	18.89
3.50	15.50	4.00	1,303.00	0.16	0.51	29.90
3.50	15.50	3.00	1,034.00	0.20	0.88	56.33
3.50	15.50	2.00	953.00	0.30	0.79	180.91
3.50	15.50	2.00	1,151.00	0.30	0.51	65.49
3.50	15.50	1.00	1,212.00	0.37	0.60	146.71
3.50	15.50	-	1,197.00	0.47	0.50	434.96

Raw Data for Total Motion of 7 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
4.50	11.50	7.00	1,368.00	0.12	0.59	12.45
4.50	11.50	6.00	1,000.00	0.13	0.98	16.34
4.50	11.50	5.00	1,334.00	0.15	0.70	22.51
4.50	11.50	4.00	1,271.00	0.18	0.82	33.61
4.50	11.50	3.00	1,269.00	0.22	1.12	61.55
4.50	11.50	2.00	1,149.00	0.32	0.74	184.69
4.50	11.50	2.00	1,072.00	0.32	1.19	52.016
4.50	11.50	1.00	1,128.00	0.37	0.87	121.8626
4.50	11.50	-	1,053.00	0.45	0.68	412.49016
4.50	12.50	7.00	1,114.00	0.11	0.76	12.40
4.50	12.50	6.00	1,292.00	0.13	0.81	15.90
4.50	12.50	5.00	1,232.00	0.15	0.80	21.20
4.50	12.50	4.00	1,300.00	0.17	0.85	30.83
4.50	12.50	3.00	1,327.00	0.21	0.77	53.09
4.50	12.50	2.00	1,197.00	0.31	0.62	175.29
4.50	12.50	2.00	1,103.00	0.31	0.85	55.09
4.50	12.50	1.00	1,104.00	0.37	0.84	132.87
4.50	12.50	-	1,127.00	0.45	0.52	420.26
4.50	13.50	7.00	1,095.00	0.11	0.96	11.88
4.50	13.50	6.00	1,153.00	0.13	0.88	15.00
4.50	13.50	5.00	1,307.00	0.14	0.88	19.53
4.50	13.50	4.00	1,347.00	0.17	0.72	27.15
4.50	13.50	3.00	1,318.00	0.20	0.81	53.02
4.50	13.50	2.00	1,130.00	0.30	0.61	173.75
4.50	13.50	2.00	1,053.00	0.30	0.74	59.37
4.50	13.50	1.00	1,138.00	0.37	0.73	137.90
4.50	13.50	-	821.00	0.47	0.83	424.56
4.50	14.50	7.00	982.00	0.11	0.83	11.45
4.50	14.50	6.00	1,198.00	0.13	0.81	13.96
4.50	14.50	5.00	1,053.00	0.14	0.86	17.31
4.50	14.50	4.00	1,048.00	0.16	0.93	27.99
4.50	14.50	3.00	1,271.00	0.20	0.76	54.38
4.50	14.50	2.00	1,174.00	0.30	0.69	173.54
4.50	14.50	2.00	1,091.00	0.30	0.78	61.29
4.50	14.50	1.00	1,084.00	0.37	0.88	138.77
4.50	14.50	-	1,135.00	0.45	0.51	420.61
4.50	15.50	7.00	1,002.00	0.11	0.98	10.69
4.50	15.50	6.00	1,271.00	0.12	0.84	12.55
4.50	15.50	5.00	1,039.00	0.14	0.92	18.16
4.50	15.50	4.00	1,265.00	0.16	0.64	29.08
4.50	15.50	3.00	1,268.00	0.20	0.76	55.01
4.50	15.50	2.00	886.00	0.30	0.97	172.79
4.50	15.50	2.00	1,052.00	0.30	1.03	61.93
4.50	15.50	1.00	1,179.00	0.37	0.73	139.29
4.50	15.50	-	1,140.00	0.45	0.52	423.77

Raw Data for Total Motion of 7 mm for solenoid in Figure 17

Core 3 Dia (mm)	Shaft Length (mm)	Total Gap	# Triangles	Energy(J)	Error(%)	Force(N)
5.50	11.50	7.00	1,005.00	0.12	0.89	12.50
5.50	11.50	6.00	920.00	0.13	0.97	16.45
5.50	11.50	5.00	1,223.00	0.15	0.80	22.71
5.50	11.50	4.00	1,258.00	0.18	0.82	33.67
5.50	11.50	3.00	1,266.00	0.22	0.91	60.74
5.50	11.50	2.00	1,057.00	0.32	1.02	175.45
5.50	11.50	2.00	981.00	0.32	1.41	45.03
5.50	11.50	1.00	1,073.00	0.37	1.17	103.34
5.50	11.50	-	1,001.00	0.42	0.71	369.61
5.50	12.50	7.00	1,005.00	0.12	0.79	12.42
5.50	12.50	6.00	1,152.00	0.13	0.84	15.96
5.50	12.50	5.00	1,221.00	0.15	0.87	21.21
5.50	12.50	4.00	1,252.00	0.17	0.79	30.25
5.50	12.50	3.00	1,229.00	0.21	0.99	50.33
5.50	12.50	2.00	1,104.00	0.30	0.87	165.13
5.50	12.50	2.00	1,008.00	0.30	1.06	48.68
5.50	12.50	1.00	1,058.00	0.36	1.24	117.31
5.50	12.50	-	1,076.00	0.42	0.59	369.24
5.50	13.50	7.00	1,007.00	0.11	0.87	11.98
5.50	13.50	6.00	1,137.00	0.13	1.03	14.98
5.50	13.50	5.00	1,273.00	0.15	0.84	19.17
5.50	13.50	4.00	1,254.00	0.17	0.74	25.82
5.50	13.50	3.00	1,205.00	0.20	0.78	50.64
5.50	13.50	2.00	1,054.00	0.29	1.10	162.76
5.50	13.50	2.00	980.00	0.29	1.05	53.58
5.50	13.50	1.00	1,111.00	0.35	0.74	123.58
5.50	13.50	-	1,075.00	0.41	0.62	374.62
5.50	14.50	7.00	979.00	0.11	0.89	11.32
5.50	14.50	6.00	1,160.00	0.13	0.81	13.61
5.50	14.50	5.00	1,255.00	0.14	0.79	16.51
5.50	14.50	4.00	1,269.00	0.16	0.65	26.70
5.50	14.50	3.00	1,181.00	0.20	0.90	51.99
5.50	14.50	2.00	1,108.00	0.29	0.79	162.85
5.50	14.50	2.00	1,013.00	0.29	1.31	56.60
5.50	14.50	1.00	1,125.00	0.35	0.94	125.15
5.50	14.50	-	1,079.00	0.41	0.59	372.18
5.50	15.50	7.00	979.00	0.11	0.93	10.35
5.50	15.50	6.00	1,154.00	0.12	0.92	11.80
5.50	15.50	5.00	1,251.00	0.14	0.73	17.45
5.50	15.50	4.00	1,152.00	0.16	0.69	28.02
5.50	15.50	3.00	1,208.00	0.20	0.83	52.40
5.50	15.50	2.00	1,110.00	0.29	0.93	162.49
5.50	15.50	2.00	1,008.00	0.29	0.99	57.00
5.50	15.50	1.00	1,129.00	0.35	0.74	125.92
5.50	15.50	-	1,086.00	0.41	0.58	373.56

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter Core 3	Length of Connecting Shaft	Distance Between core 2 and shell	Distance Between Core 1 and Core 2	Triangles	Error(%)	Force(N)
1.50	11.50	5.00	5.00	1,038.00	0.66	(3.12)
1.50	11.50	5.00	4.00	988.00	0.75	(4.45)
1.50	11.50	5.00	3.00	994.00	0.66	(6.83)
1.50	11.50	5.00	2.00	1,090.00	0.73	(11.53)
1.50	11.50	4.00	5.00	1,002.00	0.73	(3.16)
1.50	11.50	4.00	4.00	1,084.00	0.68	(4.59)
1.50	11.50	4.00	3.00	1,050.00	0.74	(7.22)
1.50	11.50	4.00	2.00	1,005.00	0.82	(12.23)
1.50	11.50	3.00	5.00	1,084.00	0.61	(3.03)
1.50	11.50	3.00	4.00	1,108.00	0.74	(4.58)
1.50	11.50	3.00	3.00	975.00	0.84	(7.20)
1.50	11.50	3.00	2.00	1,092.00	0.87	(12.79)
1.50	11.50	2.00	5.00	1,089.00	0.68	(2.58)
1.50	11.50	2.00	4.00	1,009.00	0.77	(4.04)
1.50	11.50	2.00	3.00	1,032.00	0.84	(6.80)
1.50	11.50	2.00	2.00	1,006.00	0.85	(13.03)
1.50	12.50	5.00	5.00	995.00	0.67	(3.06)
1.50	12.50	5.00	4.00	1,015.00	0.79	(4.40)
1.50	12.50	5.00	3.00	1,017.00	0.62	(6.69)
1.50	12.50	5.00	2.00	1,096.00	0.75	(11.02)
1.50	12.50	4.00	5.00	1,067.00	0.72	(3.12)
1.50	12.50	4.00	4.00	1,027.00	0.75	(4.52)
1.50	12.50	4.00	3.00	1,095.00	0.75	(6.97)
1.50	12.50	4.00	2.00	1,021.00	0.87	(11.74)
1.50	12.50	3.00	5.00	1,072.00	0.66	(2.98)
1.50	12.50	3.00	4.00	853.00	1.00	(4.39)
1.50	12.50	3.00	3.00	1,029.00	0.79	(7.10)
1.50	12.50	3.00	2.00	1,041.00	0.88	(12.29)
1.50	12.50	2.00	5.00	1,109.00	0.68	(2.61)
1.50	12.50	2.00	4.00	1,259.00	0.62	(4.00)
1.50	12.50	2.00	3.00	999.00	0.94	(6.67)
1.50	12.50	2.00	2.00	1,059.00	0.86	(12.44)
1.50	13.50	5.00	5.00	1,040.00	0.70	(2.98)
1.50	13.50	5.00	4.00	996.00	0.81	(4.23)
1.50	13.50	5.00	3.00	1,057.00	0.63	(6.35)
1.50	13.50	5.00	2.00	1,087.00	0.76	(9.82)
1.50	13.50	4.00	5.00	1,038.00	0.71	(3.04)
1.50	13.50	4.00	4.00	1,042.00	0.76	(4.34)
1.50	13.50	4.00	3.00	1,132.00	0.71	(6.65)
1.50	13.50	4.00	2.00	935.00	0.99	(10.45)
1.50	13.50	3.00	5.00	1,087.00	0.62	(2.96)
1.50	13.50	3.00	4.00	1,099.00	0.79	(4.23)
1.50	13.50	3.00	3.00	964.00	0.94	(6.71)
1.50	13.50	3.00	2.00	1,079.00	0.98	(10.93)
1.50	13.50	2.00	5.00	1,090.00	0.69	(2.39)
1.50	13.50	2.00	4.00	1,199.00	0.62	(3.91)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter	Length of	Distance Between	Distance Between	Triangles	Error(%)	Force(N)
Core 3	Connecting Shaft	core 2 and shell	Core 1 and Core 2			
1.50	13.50	2.00	3.00	1,394.00	0.60	(6.46)
1.50	13.50	2.00	2.00	1,033.00	0.82	(10.77)
1.50	14.50	5.00	5.00	989.00	0.71	(2.82)
1.50	14.50	5.00	4.00	1,033.00	0.77	(3.95)
1.50	14.50	5.00	3.00	1,022.00	0.75	(5.32)
1.50	14.50	5.00	2.00	1,015.00	0.88	(9.82)
1.50	14.50	4.00	5.00	1,041.00	0.78	(2.90)
1.50	14.50	4.00	4.00	1,058.00	0.77	(4.08)
1.50	14.50	4.00	3.00	1,046.00	0.86	(5.59)
1.50	14.50	4.00	2.00	987.00	0.85	(10.53)
1.50	14.50	3.00	5.00	1,068.00	0.69	(2.71)
1.50	14.50	3.00	4.00	1,043.00	0.90	(3.99)
1.50	14.50	3.00	3.00	1,016.00	0.94	(5.66)
1.50	14.50	3.00	2.00	1,047.00	0.88	(11.08)
1.50	14.50	2.00	5.00	1,014.00	0.75	(2.33)
1.50	14.50	2.00	4.00	983.00	0.84	(3.46)
1.50	14.50	2.00	3.00	1,030.00	0.82	(5.21)
1.50	14.50	2.00	2.00	1,081.00	0.82	(10.92)
1.50	15.50	5.00	5.00	1,047.00	0.65	(2.57)
1.50	15.50	5.00	4.00	991.00	0.86	(3.06)
1.50	15.50	5.00	3.00	945.00	0.74	(5.50)
1.50	15.50	5.00	2.00	1,066.00	0.70	(10.08)
1.50	15.50	4.00	5.00	1,067.00	0.75	(2.64)
1.50	15.50	4.00	4.00	973.00	0.85	(3.20)
1.50	15.50	4.00	3.00	1,066.00	0.77	(5.83)
1.50	15.50	4.00	2.00	977.00	0.84	(10.63)
1.50	15.50	3.00	5.00	986.00	0.96	(2.49)
1.50	15.50	3.00	4.00	1,077.00	0.84	(3.16)
1.50	15.50	3.00	3.00	951.00	0.91	(5.89)
1.50	15.50	3.00	2.00	1,094.00	0.81	(11.25)
1.50	15.50	2.00	5.00	1,079.00	0.69	(2.00)
1.50	15.50	2.00	4.00	951.00	0.94	(2.69)
1.50	15.50	2.00	3.00	1,049.00	0.72	(5.32)
1.50	15.50	2.00	2.00	1,021.00	0.75	(11.17)
2.50	11.50	5.00	5.00	1,049.00	0.77	(4.57)
2.50	11.50	5.00	4.00	999.00	0.85	(6.16)
2.50	11.50	5.00	3.00	1,269.00	0.53	(9.06)
2.50	11.50	5.00	2.00	1,080.00	0.89	(14.03)
2.50	11.50	4.00	5.00	1,037.00	0.78	(4.82)
2.50	11.50	4.00	4.00	1,094.00	0.72	(6.44)
2.50	11.50	4.00	3.00	1,361.00	0.56	(9.43)
2.50	11.50	4.00	2.00	1,021.00	0.98	(14.64)
2.50	11.50	3.00	5.00	1,090.00	0.62	(4.84)
2.50	11.50	3.00	4.00	1,137.00	0.84	(6.65)
2.50	11.50	3.00	3.00	1,250.00	0.57	(9.82)
2.50	11.50	3.00	2.00	1,103.00	0.95	(15.80)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter	Length of	Distance Between	Distance Between	Triangles	Error(%)	Force(N)
Core 3	Connecting Shaft	core 2 and shell	Core 1 and Core 2			
2.50	11.50	2.00	5.00	1,095.00	0.70	(4.40)
2.50	11.50	2.00	4.00	1,320.00	0.49	(6.45)
2.50	11.50	2.00	3.00	1,043.00	0.82	(9.66)
2.50	11.50	2.00	2.00	1,327.00	0.63	(16.42)
2.50	12.50	5.00	5.00	1,022.00	0.85	(4.43)
2.50	12.50	5.00	4.00	1,021.00	0.85	(5.92)
2.50	12.50	5.00	3.00	1,014.00	0.94	(8.23)
2.50	12.50	5.00	2.00	1,095.00	0.87	(12.42)
2.50	12.50	4.00	5.00	1,090.00	0.72	(4.59)
2.50	12.50	4.00	4.00	1,041.00	0.91	(6.13)
2.50	12.50	4.00	3.00	1,095.00	0.83	(8.63)
2.50	12.50	4.00	2.00	1,049.00	0.91	(13.20)
2.50	12.50	3.00	5.00	1,077.00	0.68	(4.66)
2.50	12.50	3.00	4.00	1,426.00	0.50	(6.41)
2.50	12.50	3.00	3.00	1,042.00	0.88	(8.87)
2.50	12.50	3.00	2.00	1,368.00	0.69	(14.16)
2.50	12.50	2.00	5.00	1,135.00	0.67	(4.25)
2.50	12.50	2.00	4.00	1,295.00	0.76	(6.07)
2.50	12.50	2.00	3.00	1,306.00	0.74	(8.86)
2.50	12.50	2.00	2.00	1,065.00	0.99	(13.98)
2.50	13.50	5.00	5.00	1,034.00	0.78	(4.23)
2.50	13.50	5.00	4.00	996.00	0.97	(5.21)
2.50	13.50	5.00	3.00	1,352.00	0.52	(7.03)
2.50	13.50	5.00	2.00	1,089.00	0.88	(9.36)
2.50	13.50	4.00	5.00	1,048.00	0.92	(4.33)
2.50	13.50	4.00	4.00	1,051.00	0.92	(5.50)
2.50	13.50	4.00	3.00	1,148.00	0.90	(7.39)
2.50	13.50	4.00	2.00	1,217.00	0.62	(10.18)
2.50	13.50	3.00	5.00	1,075.00	0.71	(4.29)
2.50	13.50	3.00	4.00	1,128.00	0.79	(5.63)
2.50	13.50	3.00	3.00	1,268.00	0.59	(7.68)
2.50	13.50	3.00	2.00	1,064.00	0.87	(10.98)
2.50	13.50	2.00	5.00	1,130.00	0.69	(4.02)
2.50	13.50	2.00	4.00	1,221.00	0.78	(5.32)
2.50	13.50	2.00	3.00	1,082.00	0.93	(7.28)
2.50	13.50	2.00	2.00	1,330.00	0.62	(11.44)
2.50	14.50	5.00	5.00	990.00	0.89	(3.61)
2.50	14.50	5.00	4.00	1,022.00	0.93	(4.19)
2.50	14.50	5.00	3.00	1,026.00	0.82	(4.79)
2.50	14.50	5.00	2.00	1,008.00	0.97	(9.84)
2.50	14.50	4.00	5.00	1,048.00	0.82	(3.85)
2.50	14.50	4.00	4.00	1,090.00	0.79	(4.52)
2.50	14.50	4.00	3.00	1,359.00	0.58	(5.27)
2.50	14.50	4.00	2.00	972.00	0.87	(10.53)
2.50	14.50	3.00	5.00	1,073.00	0.74	(3.77)
2.50	14.50	3.00	4.00	1,369.00	0.54	(4.60)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter	Length of	Distance Between	Distance Between			
Core 3	Connecting Shaft	core 2 and shell	Core 1 and Core 2	Triangles	Error(%)	Force(N)
2.50	14.50	3.00	3.00	1,008.00	0.87	(5.71)
2.50	14.50	3.00	2.00	1,040.00	0.87	(11.18)
2.50	14.50	2.00	5.00	1,350.00	0.56	(3.37)
2.50	14.50	2.00	4.00	1,292.00	0.83	(4.27)
2.50	14.50	2.00	3.00	1,035.00	0.84	(5.46)
2.50	14.50	2.00	2.00	1,087.00	0.72	(11.14)
2.50	15.50	5.00	5.00	1,034.00	0.83	(2.70)
2.50	15.50	5.00	4.00	1,292.00	0.72	(2.65)
2.50	15.50	5.00	3.00	987.00	0.73	(5.41)
2.50	15.50	5.00	2.00	1,042.00	0.81	(10.08)
2.50	15.50	4.00	5.00	1,090.00	0.78	(2.92)
2.50	15.50	4.00	4.00	1,263.00	0.67	(2.93)
2.50	15.50	4.00	3.00	1,091.00	0.75	(5.77)
2.50	15.50	4.00	2.00	951.00	0.86	(10.69)
2.50	15.50	3.00	5.00	1,318.00	0.57	(2.97)
2.50	15.50	3.00	4.00	1,075.00	0.78	(3.18)
2.50	15.50	3.00	3.00	988.00	0.88	(5.92)
2.50	15.50	3.00	2.00	1,064.00	0.76	(11.28)
2.50	15.50	2.00	5.00	1,090.00	0.98	(2.52)
2.50	15.50	2.00	4.00	1,224.00	0.80	(2.88)
2.50	15.50	2.00	3.00	1,059.00	0.69	(5.46)
2.50	15.50	2.00	2.00	1,003.00	0.75	(11.00)
3.50	11.50	5.00	5.00	1,023.00	0.90	(6.16)
3.50	11.50	5.00	4.00	1,287.00	0.74	(8.25)
3.50	11.50	5.00	3.00	1,269.00	0.71	(11.32)
3.50	11.50	5.00	2.00	1,397.00	0.89	(17.05)
3.50	11.50	4.00	5.00	1,018.00	0.89	(6.35)
3.50	11.50	4.00	4.00	1,078.00	0.87	(8.48)
3.50	11.50	4.00	3.00	1,360.00	0.85	(11.75)
3.50	11.50	4.00	2.00	1,312.00	0.82	(17.89)
3.50	11.50	3.00	5.00	1,067.00	0.76	(6.27)
3.50	11.50	3.00	4.00	1,135.00	0.99	(8.49)
3.50	11.50	3.00	3.00	1,217.00	0.74	(12.15)
3.50	11.50	3.00	2.00	1,420.00	0.80	(18.79)
3.50	11.50	2.00	5.00	1,097.00	0.80	(5.88)
3.50	11.50	2.00	4.00	1,017.00	0.93	(8.05)
3.50	11.50	2.00	3.00	1,326.00	0.75	(11.86)
3.50	11.50	2.00	2.00	1,273.00	0.77	(19.05)
3.50	12.50	5.00	5.00	999.00	0.86	(5.81)
3.50	12.50	5.00	4.00	1,292.00	0.82	(7.57)
3.50	12.50	5.00	3.00	1,307.00	0.72	(10.01)
3.50	12.50	5.00	2.00	1,414.00	0.76	(13.79)
3.50	12.50	4.00	5.00	1,075.00	0.83	(6.09)
3.50	12.50	4.00	4.00	1,353.00	0.81	(7.83)
3.50	12.50	4.00	3.00	1,416.00	0.69	(10.37)
3.50	12.50	4.00	2.00	1,326.00	0.71	(14.73)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter Core 3	Length of Connecting Shaft	Distance Between core 2 and shell	Distance Between Core 1 and Core 2	Triangles	Error(%)	Force(N)
3.50	12.50	3.00	5.00	1,076.00	0.87	(5.94)
3.50	12.50	3.00	4.00	1,414.00	0.57	(7.87)
3.50	12.50	3.00	3.00	1,019.00	0.96	(10.39)
3.50	12.50	3.00	2.00	1,276.00	0.74	(15.53)
3.50	12.50	2.00	5.00	1,126.00	0.79	(5.55)
3.50	12.50	2.00	4.00	988.00	0.93	(7.31)
3.50	12.50	2.00	3.00	1,271.00	0.79	(10.39)
3.50	12.50	2.00	2.00	1,326.00	0.74	(15.77)
3.50	13.50	5.00	5.00	1,024.00	0.99	(5.24)
3.50	13.50	5.00	4.00	1,290.00	0.88	(6.46)
3.50	13.50	5.00	3.00	1,341.00	0.68	(7.66)
3.50	13.50	5.00	2.00	1,351.00	0.79	(9.48)
3.50	13.50	4.00	5.00	1,352.00	0.73	(5.52)
3.50	13.50	4.00	4.00	1,350.00	0.73	(6.70)
3.50	13.50	4.00	3.00	1,133.00	0.94	(8.08)
3.50	13.50	4.00	2.00	1,142.00	0.99	(10.31)
3.50	13.50	3.00	5.00	1,066.00	0.85	(5.47)
3.50	13.50	3.00	4.00	1,416.00	0.59	(6.67)
3.50	13.50	3.00	3.00	1,199.00	0.73	(8.54)
3.50	13.50	3.00	2.00	1,271.00	0.92	(11.44)
3.50	13.50	2.00	5.00	1,098.00	0.77	(4.99)
3.50	13.50	2.00	4.00	1,152.00	0.78	(6.32)
3.50	13.50	2.00	3.00	1,336.00	0.71	(8.31)
3.50	13.50	2.00	2.00	1,352.00	0.65	(11.76)
3.50	14.50	5.00	5.00	1,271.00	0.82	(4.44)
3.50	14.50	5.00	4.00	1,292.00	0.79	(4.71)
3.50	14.50	5.00	3.00	1,291.00	0.59	(4.75)
3.50	14.50	5.00	2.00	1,224.00	0.69	(9.98)
3.50	14.50	4.00	5.00	1,026.00	0.81	(4.53)
3.50	14.50	4.00	4.00	1,355.00	0.59	(5.02)
3.50	14.50	4.00	3.00	1,300.00	0.66	(5.31)
3.50	14.50	4.00	2.00	1,174.00	0.70	(10.72)
3.50	14.50	3.00	5.00	1,041.00	0.91	(4.58)
3.50	14.50	3.00	4.00	1,271.00	0.66	(5.17)
3.50	14.50	3.00	3.00	1,208.00	0.71	(5.86)
3.50	14.50	3.00	2.00	1,040.00	0.81	(11.28)
3.50	14.50	2.00	5.00	981.00	0.85	(4.16)
3.50	14.50	2.00	4.00	1,222.00	0.89	(4.89)
3.50	14.50	2.00	3.00	1,055.00	0.84	(5.69)
3.50	14.50	2.00	2.00	1,093.00	0.74	(11.30)
3.50	15.50	5.00	5.00	1,336.00	0.64	(3.03)
3.50	15.50	5.00	4.00	975.00	0.93	(2.48)
3.50	15.50	5.00	3.00	932.00	0.93	(5.38)
3.50	15.50	5.00	2.00	1,268.00	0.63	(10.27)
3.50	15.50	4.00	5.00	1,074.00	0.80	(3.23)
3.50	15.50	4.00	4.00	1,202.00	0.76	(2.94)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter Core 3	Length of Connecting Shaft	Distance Between core 2 and shell	Distance Between Core 1 and Core 2	Triangles	Error(%)	Force(N)
3.50	15.50	4.00	3.00	1,032.00	0.90	(5.75)
3.50	15.50	4.00	2.00	973.00	0.93	(10.83)
3.50	15.50	3.00	5.00	946.00	0.82	(3.34)
3.50	15.50	3.00	4.00	1,271.00	0.63	(3.24)
3.50	15.50	3.00	3.00	981.00	0.79	(6.00)
3.50	15.50	3.00	2.00	1,056.00	0.77	(11.35)
3.50	15.50	2.00	5.00	1,351.00	0.58	(3.05)
3.50	15.50	2.00	4.00	1,264.00	0.84	(3.04)
3.50	15.50	2.00	3.00	1,064.00	0.79	(5.55)
3.50	15.50	2.00	2.00	1,303.00	0.51	(11.11)
4.50	11.50	5.00	5.00	1,018.00	0.97	(7.02)
4.50	11.50	5.00	4.00	972.00	0.96	(9.41)
4.50	11.50	5.00	3.00	981.00	1.00	(13.08)
4.50	11.50	5.00	2.00	1,362.00	0.83	(19.40)
4.50	11.50	4.00	5.00	979.00	0.97	(7.15)
4.50	11.50	4.00	4.00	1,046.00	0.90	(9.65)
4.50	11.50	4.00	3.00	982.00	0.97	(13.33)
4.50	11.50	4.00	2.00	1,326.00	0.75	(20.14)
4.50	11.50	3.00	5.00	1,069.00	0.83	(7.08)
4.50	11.50	3.00	4.00	1,055.00	0.94	(9.66)
4.50	11.50	3.00	3.00	970.00	1.00	(13.37)
4.50	11.50	3.00	2.00	1,103.00	1.00	(20.71)
4.50	11.50	2.00	5.00	1,368.00	0.59	(6.80)
4.50	11.50	2.00	4.00	1,000.00	0.98	(9.19)
4.50	11.50	2.00	3.00	1,334.00	0.70	(13.35)
4.50	11.50	2.00	2.00	1,271.00	0.82	(20.97)
4.50	12.50	5.00	5.00	1,268.00	0.75	(6.88)
4.50	12.50	5.00	4.00	1,025.00	0.96	(8.57)
4.50	12.50	5.00	3.00	978.00	0.99	(11.13)
4.50	12.50	5.00	2.00	1,430.00	0.73	(15.08)
4.50	12.50	4.00	5.00	1,052.00	0.83	(6.93)
4.50	12.50	4.00	4.00	1,270.00	0.71	(8.81)
4.50	12.50	4.00	3.00	1,096.00	0.92	(11.50)
4.50	12.50	4.00	2.00	1,327.00	0.65	(15.93)
4.50	12.50	3.00	5.00	1,327.00	0.55	(6.87)
4.50	12.50	3.00	4.00	1,446.00	0.54	(8.87)
4.50	12.50	3.00	3.00	1,024.00	0.98	(11.65)
4.50	12.50	3.00	2.00	1,276.00	0.78	(16.78)
4.50	12.50	2.00	5.00	1,114.00	0.76	(6.44)
4.50	12.50	2.00	4.00	1,292.00	0.81	(8.49)
4.50	12.50	2.00	3.00	1,232.00	0.80	(11.53)
4.50	12.50	2.00	2.00	1,300.00	0.85	(16.99)
4.50	13.50	5.00	5.00	1,025.00	0.81	(6.12)
4.50	13.50	5.00	4.00	979.00	1.00	(7.13)
4.50	13.50	5.00	3.00	1,049.00	1.00	(8.34)
4.50	13.50	5.00	2.00	1,334.00	0.76	(9.59)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter Core 3	Length of Connecting Shaft	Distance Between core 2 and shell	Distance Between Core 1 and Core 2	Triangles	Error(%)	Force(N)
4.50	13.50	4.00	5.00	977.00	0.85	(6.18)
4.50	13.50	4.00	4.00	1,371.00	0.67	(7.47)
4.50	13.50	4.00	3.00	1,431.00	0.65	(8.84)
4.50	13.50	4.00	2.00	1,136.00	0.85	(10.61)
4.50	13.50	3.00	5.00	1,069.00	0.86	(6.16)
4.50	13.50	3.00	4.00	1,103.00	0.90	(7.49)
4.50	13.50	3.00	3.00	1,182.00	0.73	(9.19)
4.50	13.50	3.00	2.00	1,272.00	0.89	(11.55)
4.50	13.50	2.00	5.00	1,095.00	0.96	(5.79)
4.50	13.50	2.00	4.00	1,153.00	0.88	(7.15)
4.50	13.50	2.00	3.00	1,307.00	0.88	(9.05)
4.50	13.50	2.00	2.00	1,347.00	0.72	(12.01)
4.50	14.50	5.00	5.00	965.00	0.93	(4.96)
4.50	14.50	5.00	4.00	1,303.00	0.71	(5.13)
4.50	14.50	5.00	3.00	1,298.00	0.61	(4.77)
4.50	14.50	5.00	2.00	1,214.00	0.81	(10.01)
4.50	14.50	4.00	5.00	1,047.00	0.80	(5.13)
4.50	14.50	4.00	4.00	1,342.00	0.66	(5.48)
4.50	14.50	4.00	3.00	1,004.00	1.00	(5.37)
4.50	14.50	4.00	2.00	1,156.00	0.71	(10.80)
4.50	14.50	3.00	5.00	1,072.00	0.77	(5.16)
4.50	14.50	3.00	4.00	1,275.00	0.64	(5.67)
4.50	14.50	3.00	3.00	1,224.00	0.71	(5.91)
4.50	14.50	3.00	2.00	1,045.00	0.85	(11.33)
4.50	14.50	2.00	5.00	982.00	0.83	(4.82)
4.50	14.50	2.00	4.00	1,198.00	0.81	(5.43)
4.50	14.50	2.00	3.00	1,053.00	0.86	(5.87)
4.50	14.50	2.00	2.00	1,048.00	0.93	(11.22)
4.50	15.50	5.00	5.00	1,024.00	0.89	(3.37)
4.50	15.50	5.00	4.00	976.00	0.90	(2.42)
4.50	15.50	5.00	3.00	1,196.00	0.58	(5.40)
4.50	15.50	5.00	2.00	945.00	0.99	(10.23)
4.50	15.50	4.00	5.00	1,038.00	0.81	(3.59)
4.50	15.50	4.00	4.00	1,205.00	0.86	(2.93)
4.50	15.50	4.00	3.00	1,007.00	0.91	(5.79)
4.50	15.50	4.00	2.00	944.00	0.98	(10.82)
4.50	15.50	3.00	5.00	934.00	0.96	(3.71)
4.50	15.50	3.00	4.00	1,302.00	0.68	(3.28)
4.50	15.50	3.00	3.00	991.00	0.97	(6.04)
4.50	15.50	3.00	2.00	1,028.00	0.82	(11.35)
4.50	15.50	2.00	5.00	1,002.00	0.98	(3.43)
4.50	15.50	2.00	4.00	1,271.00	0.84	(3.14)
4.50	15.50	2.00	3.00	1,039.00	0.92	(5.62)
4.50	15.50	2.00	2.00	1,265.00	0.64	(11.12)
5.50	11.50	5.00	5.00	946.00	0.94	(7.66)
5.50	11.50	5.00	4.00	1,182.00	0.93	(10.50)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter Core 3	Length of Connecting Shaft	Distance Between core 2 and shell	Distance Between Core 1 and Core 2	Triangles	Error(%)	Force(N)
5.50	11.50	5.00	3.00	1,152.00	0.85	(14.39)
5.50	11.50	5.00	2.00	1,274.00	0.95	(21.23)
5.50	11.50	4.00	5.00	911.00	0.95	(7.71)
5.50	11.50	4.00	4.00	1,226.00	0.70	(10.64)
5.50	11.50	4.00	3.00	1,231.00	0.78	(14.70)
5.50	11.50	4.00	2.00	1,161.00	0.98	(21.86)
5.50	11.50	3.00	5.00	975.00	0.88	(7.75)
5.50	11.50	3.00	4.00	1,313.00	0.62	(10.65)
5.50	11.50	3.00	3.00	1,138.00	0.77	(14.85)
5.50	11.50	3.00	2.00	1,274.00	0.79	(22.56)
5.50	11.50	2.00	5.00	1,005.00	0.89	(7.43)
5.50	11.50	2.00	4.00	920.00	0.97	(10.11)
5.50	11.50	2.00	3.00	1,223.00	0.80	(14.52)
5.50	11.50	2.00	2.00	1,258.00	0.82	(22.54)
5.50	12.50	5.00	5.00	922.00	0.99	(7.52)
5.50	12.50	5.00	4.00	1,201.00	0.88	(9.48)
5.50	12.50	5.00	3.00	1,212.00	0.73	(12.22)
5.50	12.50	5.00	2.00	1,274.00	0.79	(16.17)
5.50	12.50	4.00	5.00	933.00	0.97	(7.55)
5.50	12.50	4.00	4.00	1,204.00	0.64	(9.67)
5.50	12.50	4.00	3.00	1,272.00	0.81	(12.53)
5.50	12.50	4.00	2.00	1,158.00	0.89	(16.93)
5.50	12.50	3.00	5.00	977.00	0.88	(7.45)
5.50	12.50	3.00	4.00	1,004.00	0.82	(9.57)
5.50	12.50	3.00	3.00	1,195.00	0.75	(12.75)
5.50	12.50	3.00	2.00	1,250.00	0.80	(17.79)
5.50	12.50	2.00	5.00	1,005.00	0.79	(7.12)
5.50	12.50	2.00	4.00	1,152.00	0.84	(9.26)
5.50	12.50	2.00	3.00	1,221.00	0.87	(12.52)
5.50	12.50	2.00	2.00	1,252.00	0.79	(17.89)
5.50	13.50	5.00	5.00	1,206.00	0.78	(6.76)
5.50	13.50	5.00	4.00	1,203.00	0.84	(7.91)
5.50	13.50	5.00	3.00	1,223.00	0.68	(8.96)
5.50	13.50	5.00	2.00	1,226.00	0.80	(9.63)
5.50	13.50	4.00	5.00	944.00	0.97	(6.77)
5.50	13.50	4.00	4.00	1,208.00	0.92	(8.15)
5.50	13.50	4.00	3.00	1,275.00	0.73	(9.42)
5.50	13.50	4.00	2.00	1,097.00	1.03	(10.64)
5.50	13.50	3.00	5.00	975.00	0.93	(6.72)
5.50	13.50	3.00	4.00	1,004.00	0.87	(8.14)
5.50	13.50	3.00	3.00	1,152.00	0.74	(9.80)
5.50	13.50	3.00	2.00	1,252.00	0.83	(11.69)
5.50	13.50	2.00	5.00	1,007.00	0.87	(6.41)
5.50	13.50	2.00	4.00	1,137.00	1.03	(7.86)
5.50	13.50	2.00	3.00	1,273.00	0.84	(9.70)
5.50	13.50	2.00	2.00	1,254.00	0.74	(11.96)

Force on core 2 when it should be resting against stops

Various initial values for distance of core 2 from the shell are given (mm)

Important thing to see is that force is always negative

Diameter	Length of	Distance Between	Distance Between			
Core 3	Connecting Shaft	core 2 and shell	Core 1 and Core 2	Triangles	Error(%)	Force(N)
5.50	14.50	5.00	5.00	1,186.00	0.79	(5.56)
5.50	14.50	5.00	4.00	928.00	0.99	(5.46)
5.50	14.50	5.00	3.00	1,157.00	0.64	(4.70)
5.50	14.50	5.00	2.00	1,173.00	0.81	(9.96)
5.50	14.50	4.00	5.00	1,206.00	0.69	(5.68)
5.50	14.50	4.00	4.00	1,217.00	0.84	(5.86)
5.50	14.50	4.00	3.00	1,242.00	0.84	(5.38)
5.50	14.50	4.00	2.00	1,147.00	0.72	(10.81)
5.50	14.50	3.00	5.00	945.00	0.90	(5.68)
5.50	14.50	3.00	4.00	1,265.00	0.60	(6.11)
5.50	14.50	3.00	3.00	1,162.00	0.74	(5.92)
5.50	14.50	3.00	2.00	1,231.00	0.68	(11.44)
5.50	14.50	2.00	5.00	979.00	0.89	(5.39)
5.50	14.50	2.00	4.00	1,160.00	0.81	(5.88)
5.50	14.50	2.00	3.00	1,255.00	0.79	(5.94)
5.50	14.50	2.00	2.00	1,269.00	0.65	(11.27)
5.50	15.50	5.00	5.00	936.00	0.92	(3.62)
5.50	15.50	5.00	4.00	1,138.00	0.82	(2.37)
5.50	15.50	5.00	3.00	1,151.00	0.68	(5.34)
5.50	15.50	5.00	2.00	1,195.00	0.69	(10.23)
5.50	15.50	4.00	5.00	943.00	0.97	(3.86)
5.50	15.50	4.00	4.00	1,136.00	0.89	(2.85)
5.50	15.50	4.00	3.00	985.00	0.83	(5.76)
5.50	15.50	4.00	2.00	1,102.00	0.70	(10.77)
5.50	15.50	3.00	5.00	922.00	0.94	(4.04)
5.50	15.50	3.00	4.00	1,268.00	0.64	(3.28)
5.50	15.50	3.00	3.00	1,170.00	0.63	(6.06)
5.50	15.50	3.00	2.00	1,212.00	0.64	(11.39)
5.50	15.50	2.00	5.00	979.00	0.93	(3.82)
5.50	15.50	2.00	4.00	1,154.00	0.92	(3.20)
5.50	15.50	2.00	3.00	1,251.00	0.73	(5.64)
5.50	15.50	2.00	2.00	1,152.00	0.69	(10.88)

Instructions for Basic Model Construction and Analysis in Maxwell 2-D Field Solver

Make sure Key is inserted in Parallel port
Go to control panel under start -> settings
Click on Flexlm License Server
Start the server click OK

Open the Maxwell Control Panel program under start
Click on Projects
Click on New
Name the file Click OK
Open the file by clicking on the file and clicking open (if it doesn't automatically open)

Set the solver to Magnetostatic
Set Drawing to RZ plane

Click on Define Model->Draw Model
Go to window->grid
Set the grid to the increment you want to draw in (smallest distance in the drawing being made)
Don't make grid visible if you choose a very small number
Click OK

Click Model->Drawing Units
Pick the units you want to use
Click OK

Click Model-> Drawing Size
Choose min and max values to give you room to draw the drawing

(NOTE)
(($r_{\max}$ and $z_{\max}$ is the size of the drawing box
r is u
z is v))

Click Object-> Polyline
Click left button where you want to start line..
Continue around until you have a closed object...
Double click
To backup right click
Each object can be named and the color changed

You can also type in du or dv values to get specific distances without clicking

Object-> Rectangle is used to create rectangles.

Continue until entire drawing is complete

Go to File-> Exit

Save changes to drawing

Click Setup Materials

Choose each object

Pick the material you want to use

Click assign

Continue until all objects are chosen

Click exit

Save changes

Click set boundary sources

Go Edit->Select->Object-> By Clicking

Click on the object you are assigning (background)

After you have chose background right click

click assign->Boundary->Ballon

Click Assign

Go Edit->Select->Object-> By Clicking

Click on the object you are assigning (coil)

After you have chose coil right click

click assign->source->solid

Click current, and total enter the total amps (amps*turns)

Click Assign

Go File->Exit

Save changes

Go Setup Executive Parameters

Click Force

Choose the object you want to know the Force on

Click yes

Exit Save

Click Set up solution
Click options
Click suggested values
Enter percent error you want
Click OK

Click Solve
Nominal Problem
Wait

After calculation Is complete
Go to post process (Here you can see flux lines and magnitude of B and H)
Click nominal problem
Click post-> plot

Choose what ever you desire
Click execute
To do another click Global->Refresh
Repeat the above
When done click File->exit

To see the force calculated
Click Solutions->Force

Vita

Jeremy Myers began his engineering studies at the University of Tennessee in the Fall Semester of 1995. He was the top graduate of the spring 1999 class. At that time he received a Bachelor's degree in Mechanical Engineering with a minor in Education. In the spring of 2001, he completed his Master's degree in Mechanical Engineering with a concentration in Machine Design. He also received minors in Mathematics and Physics. This thesis is presented as partial fulfillment of that degree. Mr. Myers' funding was the combination of fellowships from Tau Beta Pi, the national engineering honor society, and The University of Tennessee. He was also funded by the Engineering Fundamentals Division of UTK. Here, he worked as a graduate teaching assistant, teaching freshman engineering. Future plans involve teaching at the college level, while sharing in the Bible ministry work of Jehovah's Witnesses (Matthew 28:19,20).