Size Optimization of Release Assembly of Air Circuit Breaker

Major Project Report

Submitted in Partial Fulfillment of the Requirements
for the Degree of

Master of Technology

In

Electrical Engineering

(Electrical Power Systems)

By

Falak Patel
(13MEEE15)

DEPARTMENT OF ELECTRICAL ENGINEERING
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY
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Undertaking for Originality of the Work

I, **Falak Patel**, Roll. No.13MEEE15, give undertaking that the Major Project entitled **"Size Optimization of Release Assembly of Air Circuit Breaker"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Electrical Engineering (Electrical Power Systems) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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Place: Nirma University, Ahmedabad

Endorsed By:

Industry Guide	Institute Guide
Mr. Dharm Panchal	**Prof. Sarika Kanojia**
Asst. Manager - Design	Asst. Professor
Switchgear Design and Development Centre	Department of Electrical Engineering
L&T Electrical and Automation	Institute of Technology
Vadodara	Nirma University
	Ahmedabad

Certificate

This is to certify that the Major Project Report entitled ***"Size Optimization of Release Assembly of Air Circuit Breaker"*** submitted by Mr. Falak Patel (13MEEE15) towards the partial fulfillment of the requirements for the award of Degree of Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

Date:

Industry - Guide	**Institute - Guide**
Mr. Dharm Panchal Asst. Manager - Design Switchgear Design and Development Centre L&T Electrical and Automation Vadodara	**Prof. Sarika Kanojia** Asst. Professor Department of Electrical Engineering Institute of Technology Nirma University Ahmedabad
Head of Department Department of Electrical Engineering Institute of Technology Nirma University Ahmedabad	**Director** Institute of Technology Nirma University Ahmedabad

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Falak Patel

13MEEE15

Abstract

The focus of this project is on the design and construction of the fast acting linear actuator. These linear actuators are used for providing trip force to operate mechanism which close and open contact of air circuit breaker. These actuators are rated on different ranges of rating used for auxiliary supply. This project has been carried out in a manner such that it improves performance and optimization size of air circuit breaker's release assembly. The mathematical model will be created of the present design. The main problem for this type of device is that its response cannot be estimated due to magnetic property depends on the internal molecular structure of any material. This project has main aim for optimization of size and input power by making no change in its performance mainly operating time, force output and impact force. For this, the FE - model has been developed to analyze the distribution of electromagnetic force; after that, the results of the FEM analysis, the results of numerical analysis and experimental results were compared for verifying the developed mathematical-model. A 3-dimensional electromagnetic FE-model had been developed using popular FE-Analysis computer programs, like ANSYS/MAXWELL, JMAG and MAGNET. Based on this study, new optimized designs have been prepared for further study. Mathematical model have been further improved by feedback from testing of different designs. At successfully completion of this project, a new electromagnetic release assembly has been designed for air circuit breaker.

Abbreviations

DC .... Direct Current
AC .... Alternating Current
CB .... Circuit Breaker
ACB .... Air Circuit Breaker
SR .... Shunt Release
CR .... Closing Release
UVR .... Under Voltage Release
MC .... Moving Contact
FC .... Fixed Contact
FE .... Finite Element
FEM .... Finite Element Method
MMF .... Magneto Motive Force

Nomenclatures

μ_0 .... Permeability of Free Space
μ_r .... Relative Permeability of Material
i .... Current in Coil
N .... Number of turns in Coil

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 General

Air circuit breaker is a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions using air as arc quenching medium. It is also capable of making and carrying current for a specified time duration and breaking current under specified abnormal circuit conditions, such as those of a short circuit.

Breaker consists of two contacts: Fixed contact (FC) and Moving contact (MC). Moving contact is used to make and break the circuit using stored energy in the form of spring tension or compressed air. Spring, pneumatic or oil damping is used to arrest the speed of MC while closing. Operating Mechanism is of stored energy type, which operates by pre-charged springs. The springs are charged manually with the help of charging handle or with the help of charging motor, if provided. The same operating mechanism is used for the entire range of ACB of same model with different rating and size by changing spring force. Mechanism has been developed using less number of parts resulting in more reliability, longer mechanical life and requiring very less maintenance. It can be operated using manual input and remote signal which gives signal to release assembly. This release assembly is made of different type of liner actuators.

L&T U-power Omega, model of air circuit breaker can be equipped with the following auxiliary trips or releases in release assembly: 1 x Shunt trip + 1 x Closing coil + 1 x Under voltage release[17]. Which are rated at different voltage level as per required such as 24-30V DC, 48-60V DC, 110 Vac 50/60 Hz / 110 V dc, 125-127 V dc, 220-240 Vac 50/60 Hz / 220-250 V dc, 380- 415 Vac, 50/60 Hz. These releases have same dimensions. Closing coil is shown in figure 1.1.These releases are mounted on top plate

Figure 1.1: Closing Release of L&T U-Power Omega ACB

which as shown in figure 1.2. These releases apply force on flapper which convert force into torque for driving shaft which connected to moving contact as shown in figure 1.3.

1.2 Type of Releases

A shunt release (SR) is a solenoid actuator device that mechanically triggers the breaker to open. It can be triggered by any number of protective or control functions. The contacts from those devices must be normally Open such that the contacts will close when it is desired that the breaker trip. A shunt release requires an external source of power, and that power must be available at the time when the breaker is required to open - hence, for reliability, it is normal practice to operate a shunt release from some form of stored energy such as a battery.

A closing release (CR) is a solenoid actuator device that mechanically triggers the breaker to close. A closing release requires an external source of power, and that power must be available at the time when the breaker is required to close - hence, for

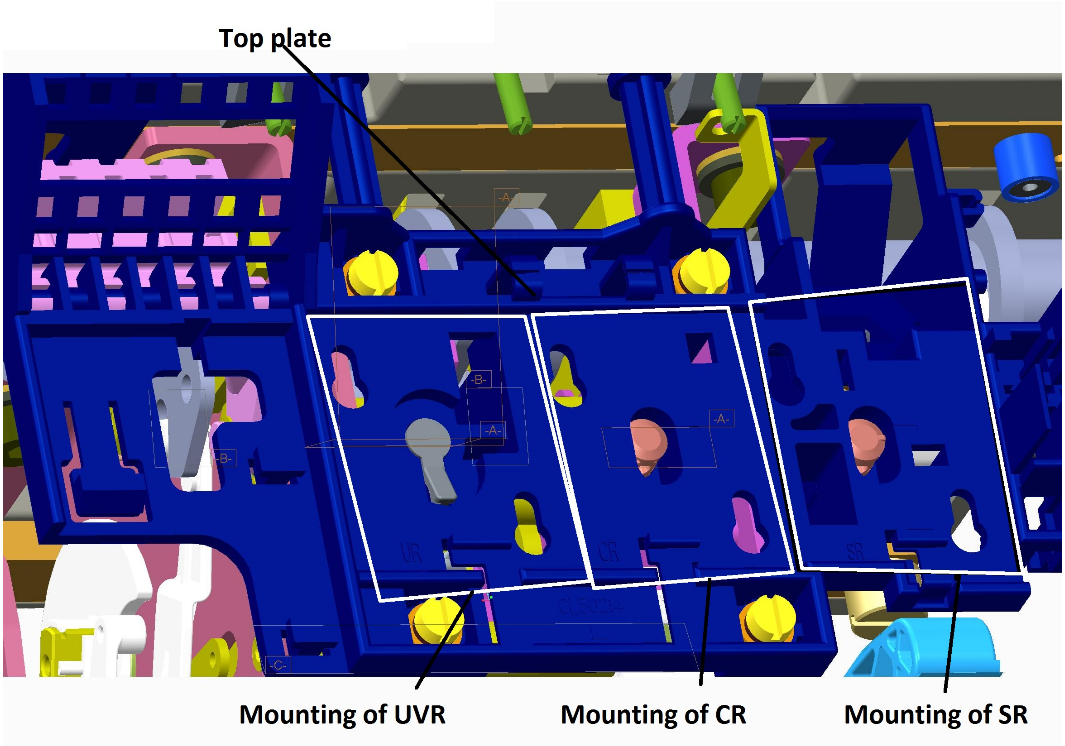

Figure 1.2: Top-Plate of ACB mechanism for mounting of Release

reliability, it is normal practice to operate a closing release from some form of stored energy such as a battery.

An under voltage release (UVR) is a device that triggers the breaker to open when the applied voltage falls below a threshold. Often, an under voltage release is operated from the system and is intended to cause the breaker to open in the event something happens to cause the system voltage to collapse. A shunt release can aggregate other protection and control functions, but the contacts from those devices must be normally Closed and wired in series with the voltage sensing element of the under voltage release such that operation of the external protection or control function opens a contact that removes voltage from the under voltage release.

1.3 Literature Review

Paper authored by QingHui Yuan et al. [1] has discussed about modeling of solenoid type actuators and also proposed a self-calibration method for determining the actuator model for dual-solenoid actuators which are common in hydroelectric valves. They have also discussed about different difficulties faced due to dual solenoid system in term of coordination.

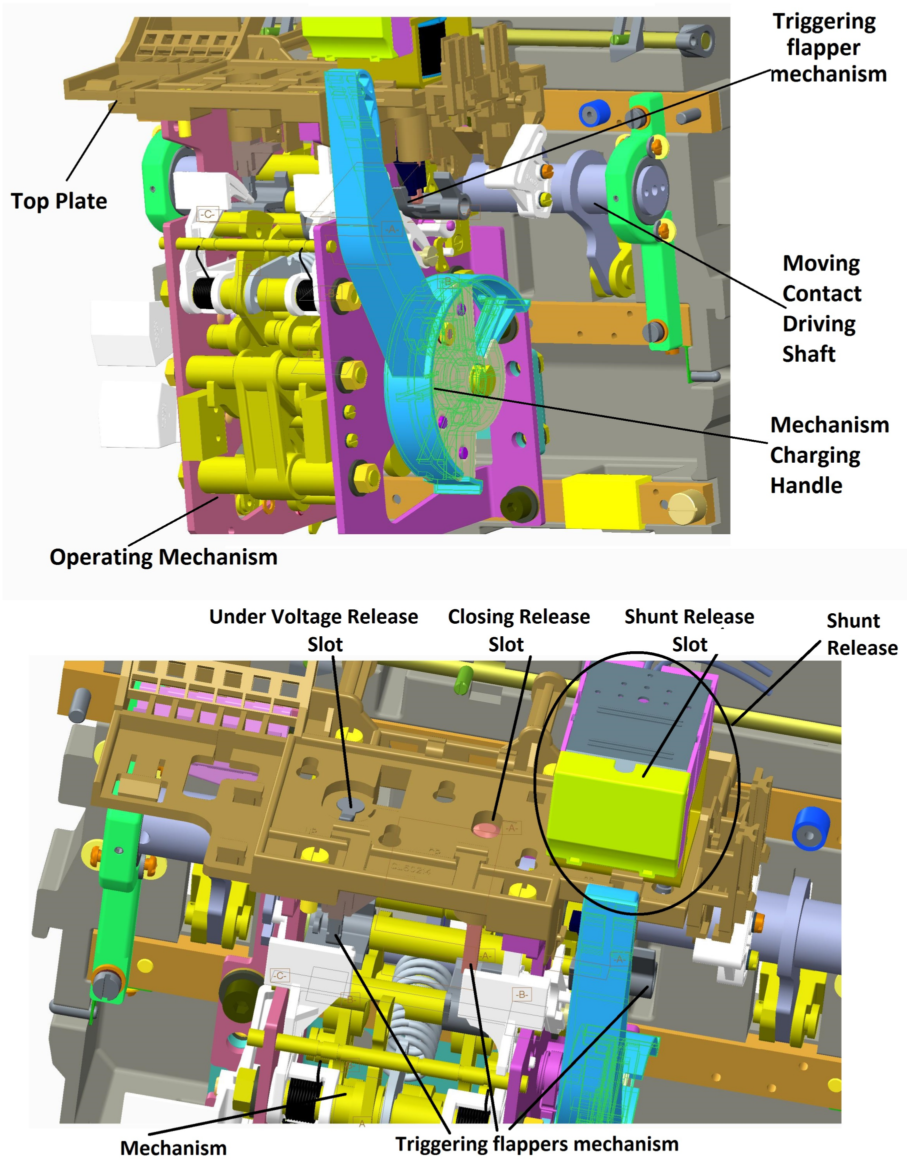

Figure 1.3: Releases on top-plate mounted on mechanism of ACB

Paper authored by Alka Verma et al.[2] has discussed about Finite Element Method Magnetic (FEMM) package which is simple, accurate, and low computational cost open source FE software tool for the solution of magneto static, harmonic low frequency magnetic and electrostatic problems and using this present FE technology, they have studied the magnetic fields inside the solenoid with ease.

Paper authored by Bruno P. Lequesne [3] has discussed about solenoid model for constant force and have done analysis by FEM tool. He have discussed about different effect of plunger profile. This shows by changing profile of plunger force is changes drastically.

Paper authored by G. A. Cividjian et al. [4] has discussed about a new method, the power approximation of boundary conditions in connected regions, is used to solve the 2-dimensional magnetic field problem within the window and the gap of the magnet, consideration taken as the core uniform saturated. It also discussed about inductance of solenoid with change in position of plunger.

Book authored by John R. Brauer [5] has discussed about the design and application of electromagnetic actuators and sensors. It has also discussed about FE simulation using latest software tools the electromagnetic FE software package Maxwell SV, which is available to students at free of charge from Ansoft Corporation and other simulation tools like SPICE, MATLAB and Simplorer. It has also discussed about various critical perimeters of electromagnet design.

Paper authored by K R Sugavanam et al. [6] has discussed about the working of a DC solenoid along with the various applications and cost optimization by changing the winding material. It has also discussed about the use of Aluminum in place of copper in coil and it shows that its size increases by 1.37 times. By using Aluminum, its thermal property had deteriorated which reduced duty cycle of solenoid.

Paper authored by Eid Mohamed [7] has discussed about working and modeling of electromechanical valve type actuator used in automobile industry. The electromechanical valve are have good reliability and larger life span compare to the mechanical valve.

Book authored by G. Prede et al. [8] has discussed about at the structure and mode of operation of the components used for setting up an electropneumatic control in industrial applications. It has also discussed about selection of material and shape of path for magnetic flux.

Book authored by Charles R. Underbill [9]has discussed about to describe the evolution of the solenoid and various other types of electromagnets in as perfectly connected a manner as possible. It has also discussed about losses in the winding of electromagnets.

Paper authored by Muhammed Fazlur Rahman et al. [10] has discussed about solenoid actuator modeling and position estimation. This study shows that practically position estimation of linear device is more difficult compare to in the rotating machine.

Paper authored by Deepak P. Mahajan et al. [11] has discussed about improvement in force stoke output by use of different type of routers in electromagnetic linear actuators. The routers provides good conducting path for magnetic flux.

Book authored by Oriol Gomis-Bellmunt et al. [12]has discussed about model-based design rules for actuators (conventional as well as solid-state ones). In which he have discussed about following points,

- What are the necessities of the actuator's major output quantities force and stroke from the mechanical load applied by the actuator?
- For a given actuator type, which is the relationships between actuator's geometry and major output quantities?
- How scalable are actuators of a given kind?
- How active output quantities (work done and power) are related to load and geometry?
- How should actuators be designed with sized to get the best performance for the particular actuator kind and for a stated application?

He have also validated design using FEA tools like ANSYS Maxwell, MatLAB.

Paper authored by T. Lubin [13] has developed new semi-analytical expressions to compute the self-inductance and electromagnetic force for iron-core solenoid of finite length. The analytical model is based on boundary value problems with Fourier analysis. The only approximation in the modeling of this problem is in assuming infinite permeability for the iron cylinder.

Paper authored by Bruno Lequesne [14] has done dynamic model of solenoids under impact excitation, including motion and eddy currents. It has also discussed about The developed algorithm used to iterate on the core reluctivity is general and could be used in a variety of electromagnetic problems.

Paper authored by Bark-Ju Sung [15] has developed new design method for the high speed solenoid type actuator. He have derived empirical formula for design of high speed solenoid. Paper authored by N.C. Cheung et al. [16]has done dynamic modeling for linear and finite length solenoid by using first order function and second order function. Paper authored by Peiman Naseradinmousavi et al. [19] have prepared mathematical modeling which is more accurate for linear and limited travel solenoid and validated using experiments.

1.4 Problem Identification

For ACB, operation time of mechanism to open or to close breaker should be less as possible for preventing damage causes due to fault condition. So fast acting solenoid type actuators are most suited for this crucial task, but its design should fulfill IEC standards.

ACB follows IEC 60947-1 and IEC 60947-2 standard [18] for design performance. The actual design of actuators have $40N$ force output. It has large size required in L&T U-Power Omega ACB. These releases require high volume to mount and they are also short time rated. In industry, there are many competitors who have release much smaller in size and more reliable. The Major problem is to achieving optimization in size by keeping force constant. These releases are also rated for different voltage rating according to standard. So release should give reliable operation on a wide range of rating such as 24-30V DC, 48-60V DC, 110V ac 50/60 Hz / 110V dc, 125-127V dc, 220-240V ac 50/60 Hz / 220-250V dc, 380- 415 Vac, 50/60 Hz.

1.5 Objectives

The objective of this dissertation is to modify the present design and to develop a hardware prototype to derive and conclude size and force optimization of release assembly based on mathematical model. The hardware prototype will derive the power from axillary supply to operate ACB. Further, it can be realized that how the FEM tools, like JMAG, Pro-Engineer, ANSYS Maxwell and MagNet, can simplify design to improve reliability and to accomplish complete optimization. The developed modified design of prototype can also be released for production after passing its Mechanical Endurance Test (MET).

1.6 Methodology

- Brainstorming: to understand requirement of industry.
- Component study: to identify problem.
- Fish bone technique: for the understanding parameter affecting design.

- Component analysis: to get optimum area for improvement in design.
- Constraint study: for the understanding parameter to make a design which may adapt system easily .
- Modeling: to get base for new design.

- Design generation: to make optimum design by using model created and simulation in FEM tool like JMAG, ANSOFT Maxwell and MagNet.
- Design selection (War room): to check with manufacturing and design feasibility.
- Validation through prototype: to check performance of design.

1.7 Outline of Thesis

- Chapter 1 introduces solenoid type actuators which are being used as the release assembly in ACB to operate opening and closing operation. Further, it has been discussed literature survey, problem identification, objective of thesis and methodology to be adopted.
- Chapter 2 discusses about solenoid linear actuator and its modeling with the consideration of cone shape, dynamic behavior and winding.
- Chapter 3 shows actual design variables, driving current and FEM analysis of actual design with various FEM tools.
- Chapter 4 discusses about parameter affecting force output, constraint of design, proposed design modification.
- Chapter 5 comprises of conclusion and future scope.

Chapter 2

Modeling of Electromagnetic Linear Actuators

2.1 Introduction

The linear actuators are being use for converting different types of energy into linear motion such as rotary motion in electric motors. They are used in many industries such as automobile, automation systems and industrial automation. They vary in application from accurate linear measuring instrument to producing high force hydraulic actuators in earth moving machines.

Electromagnetic linear actuators are mainly consist solenoid with iron core plunger. An electrical conductor when wound in helical formation is called a solenoid, and when a current of electricity is passed through the wounded wire, it gains many of the characteristics of the bar type permanent magnet, so far as its magnetic field is concerned.

Solenoids with soft iron or magnetic steel plungers are automatic in their action, the plunger being magnetized by the field of the excited coil and mutual attraction then results between the field of the coil and the induced field of the plunger, and if the coil be fixed and the plunger be free to move, at end it will be drawn within the coil until the centre or equilibrium point of the plunger is at the centre of the coil, and force will be required to change the relative positions of the coil and plunger in either direction.

When the magnetic path is fully filled with a ferromagnetic material with high relative permeability except for a small air gap with have relative permeability of 1, the magnetic field across the air gap causes a force which tends to close that air gap by attracting plunger to yoke. This force can be calculated and used in industry to move a movable iron core which can operate a set of electrical contacts or a valve actuator or this force .

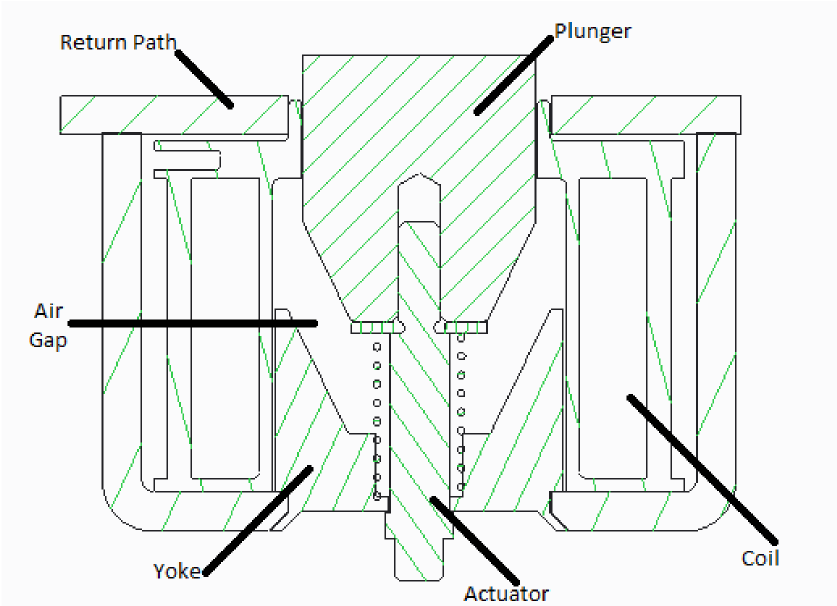

Figure 2.1: Schematic model of linear actuator

For designing a small push-pull solenoid, the following information required, schematic diagram of linear actuator in figure 2.1:

1. Force: The actual force required in the application should be higher by a safety factor multiplier of 1.33 to achieve at the force value that should be utilized in specification in design.

2. Duty Cycle: Duty cycle is the ratio of maximum ON time to total time of operation in cycle.

3. Stroke: Stroke is determined by its is effective air gap in other words displacement of moving plunger.

4. Operating Voltage: Operating DC voltage is determined based on the application and auxiliary supply voltage available.

2.2 Basics of electromagnetic

The magnetic field across the air gap can be calculated as follows (ignoring the reluctance in the ferromagnetic core)

$$B_g = \frac{F_m^2 \mu_0}{g}$$

Where, $B_g$is the magnetic field in the air gap (Tesla), $F_m$is the magneto motive force= $N\,I$ = Numbers of Turns X Current, g is the air gap.

The force across the air gap can be calculated as follows:

$$F = \frac{B_g^2 A}{2\mu_0}$$

$$F = \frac{\mu_0 (NI)^2 A}{2g^2}$$

Where, F is the force in the air gap, A is the cross sectional area of the air gap.

The more accurate force across the air gap can be calculated as follows:

$$F = \frac{\mu_0 \mu_r^2 (NI)^2 A}{2(l_2 + l_{eq} + (\mu_r - 1)x(t))^2}$$

Where, l_2 is the length of solenoid, l_{eq} is the length of effective magnetic path, μ_r is the relative permeability of effective magnetic path, A is the cross sectional area of the air gap, $x(t)$ is the length of air gap at time t.

2.3 Mathematical Model of Solenoid type plunger

The assumptions have taken for preparing mathematical model which include small air gap between the moving plunger and yoke, negligible effect of fringing, flux leakage and eddy current. Also ignoring effect of saturation and magnetic field non linearity which leads to the following expression,

$$B = \mu H \tag{2.1}$$

Where, B is magnetic flux density, μ is the magnetic permeability and H is magnetic field strength .

By taking consideration of Ampere's circuital law for MMF, the magnetic field intensity is proportional to number of conductor, N and the current, i .

Applying it to the magnetic circuit which gives,

$$\oint H\,dl = N\,i \tag{2.2}$$

Where, λ is flux linkage (Wb), l is length of close magnetic path (m), $_i$ is magnetic flux (Wb) in medium are related as,

$$\lambda = N\,\Phi_i \tag{2.3}$$

Simplifying equation (2.2)& combing with equation (2.3) with respect to stated B-H relation one has,

$$R_i = \frac{l_i}{\mu_i S_i} \tag{2.4}$$

$$\Phi = \frac{N\,i}{\sum_{i=1}^{n} R_i} \tag{2.5}$$

Where, R_i is reluctance of the medium and S_i is projected cross sectional area of surface perpendicular to magnetic flux.

Note is that magnetic flux has an inverse relation with reluctance using the principle of virtual work, the electromagnetic force can be calculated by following expression,

$$F_{mag} = \frac{dW_{work}}{dx} \tag{2.6}$$

Where, W_{work} is virtual work done by magnetic flux, F_{mag} is electromagnetic force.

By definition of work done,

$$F_{mag} = \frac{d}{dx} \int_{0}^{i} \lambda(x, i)\, di \tag{2.7}$$

The reluctance of equation (2.4) can be shown to be represented by following expression for close path is

$$\sum_{i=1}^{n} R_i = C_1 + C_2\, x \tag{2.8}$$

Where, R is the reluctance for close path, C_1 and $C_2$are upper and lower contraction coefficients.

$$C_1 = \frac{l_{eq}}{\mu_{r1}\mu_0 s_{eq}} \qquad and \qquad C_2 = \frac{1}{\mu_{r2}\mu_0 s_g} \tag{2.9}$$

Where, $\mu_{r1}$is relative permeability of magnetic path and μ_{r2} is relative permeability of gap. In this case μ_{r2} is 1 for air.

For all above relation x is displacement of solenoid plunger.

Combing equation (2.3), (2.5), (2.8), total generated electromagnetic force EMF for motion of plunger can be calculated by following relation,

$$F_{mag} = \frac{C_2\, N^2\, i^2}{2(C_1 + C_2\,(g_{max} - x)^2)} \tag{2.10}$$

It shows behavior of Force relation with Current, number of conductor in coil, air Gap$g$ is non linear.

2.4 Effect of cone shape on Force

There is a cone shape of plunger in design which change behavior direction of force. This force have two components: Horizontal and Vertical to motion axis as shown in

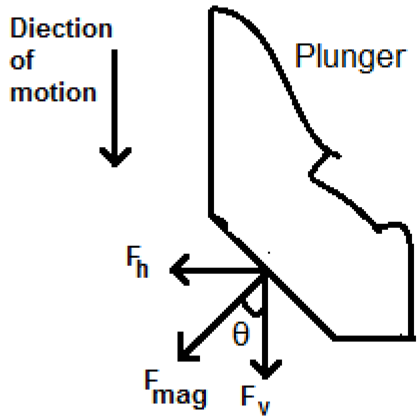

Figure 2.2: Force components due to cone shape

Figure 2.2. Due to symmetrical shape, horizontal component becomes zero but vertical force component added initiates motion. So effective force becomes,

$$F'_{mag} = F_v = F_{mag} \times cos(\theta) \tag{2.11}$$

2.5 State modeling of solenoid current

The solenoid can be modeled as electric circuit as shown in Figure(2.3)

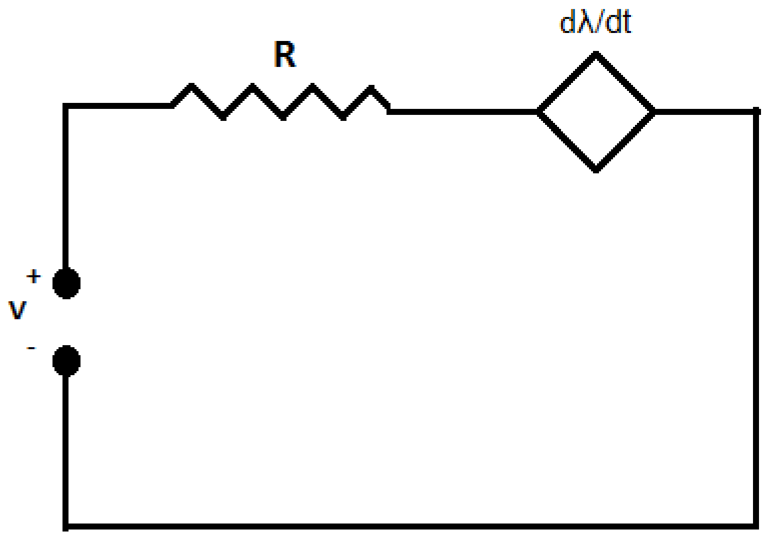

Figure 2.3: Electrical circuit of solenoid actuator

From figure(2.3) modeling of solenoid in circuit can be written as following expression in term of electrical quantity,

$$V = R\,i + \frac{d\lambda}{dt} \tag{2.12}$$

Combing equation (2.3), (2.4), (2.5) and (2.12), state equation can be written for current is,

$$\frac{di}{dt} = \frac{(V - R_i)\,(C_1 + C_2\,(g_{max} - x)}{N^2} - \frac{C_2\,i\,\ddot{x}}{(C_1 + C_2\,(g_{max} - x)} \tag{2.13}$$

2.6 Dynamic Equation

As per Newton's 2nd law of motion, "The vector sum of the forces on an object is equal

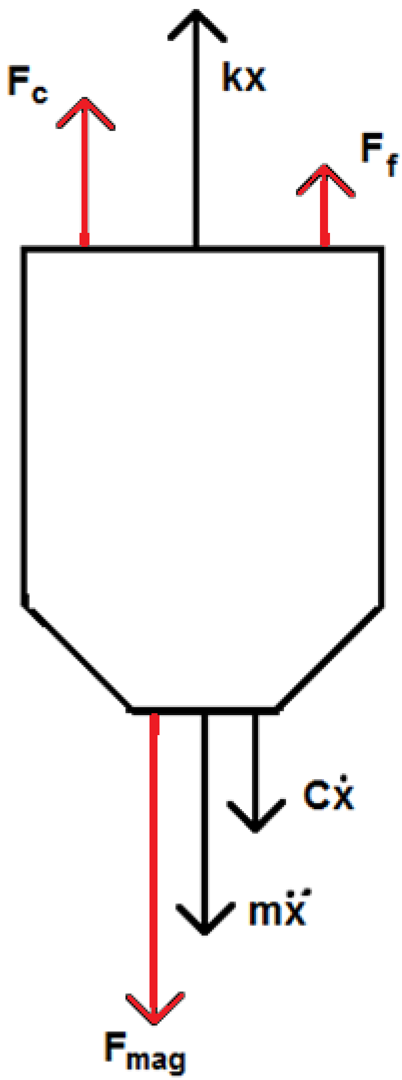

Figure 2.4: Free body diagram of solenoid actuator

to the mass of that object multiplied by the acceleration vector of the object"[20].

From figure(2.4) which shows F_c is resultant force applying due to weight of plunger and spring,F_f is force reduction due to fringing factor, kx is spring force, m is mass of plunger in dynamic equation can be written as,

$$Force\, in\, motion = Magnetic\, force\, acting$$

$$m\ddot{x} + C\dot{x} - kx = F_{mag} - F_c - F_f \tag{2.14}$$

Function of fringing is dependent on gap in magnetic path. If F is fringing factor H is height of magnetic path window then,

$$F = 1 + \frac{l_g}{\sqrt{S_g}} \times ln\left(\frac{2 \times H}{l_g}\right) \tag{2.15}$$

$$F_f = (F^2 - 1) \times Fmag \tag{2.16}$$

Hence, Final dynamic equation will become,

$$m\ddot{x} + C\dot{x} - kx = F^2 \times F_{mag} - F_c \tag{2.17}$$

2.7 Coil Design

Two of the factors determining the strength of a magnetic field generated by a solenoid are:

- The number of turns in the coil, and
- The current in the coil.

These two parameters are multiplied together to give the magneto motive force or the current density of the coil. For any given coil volume there is a limit on the current density in that coil. For instance one can increase the number of turns in a coil by decreasing the cross sectional area of the wire that is used but decreasing the wire size also increases its resistance therefore reducing the current flow in the coil for the same applied voltage potential.

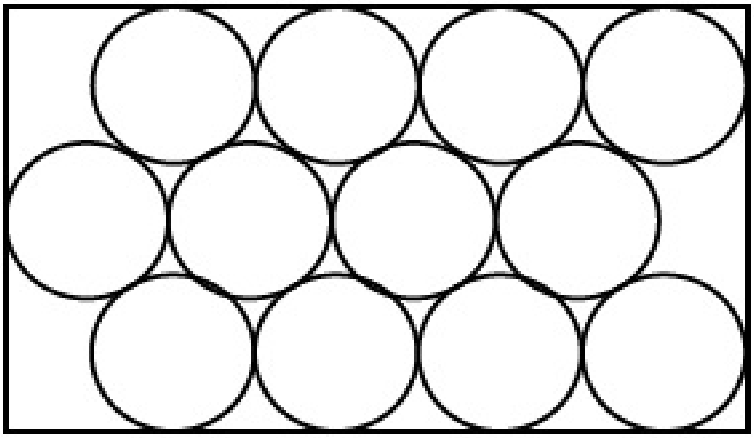

Figure 2.5: Cross Section of Multi Layer Winding

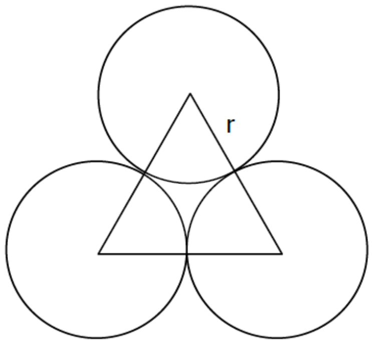

Figure 2.6: Airspace between conductors

2.7.1 Winding Factor

Small air gaps are formed when wire of a circular cross section is used for winding coils. Figure 2.5 shoes a cross section of a tightly would coil and the air gaps between the windings. Figure 2.6 shows how this airspace can be calculated with respect to the wire radius.

The area of the equilateral triangle is,

$$A_t = \frac{2r^2\sqrt{3}}{4}$$

The area of a 60 degree circular sector is,

$$A_s = \frac{\pi r^2}{6}$$

The area of the air space in the middle of the triangle is,

$$A = A_t - 3A_s$$

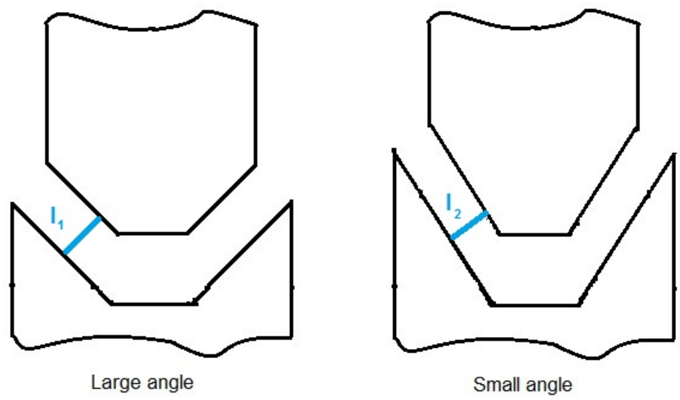

Figure 2.7: Effect of angle on air gap and cross section area

$$= \frac{2r^2\sqrt{3}}{4} - \frac{3\pi r^2}{6}$$

Therefore, since there are two air spaces per winding,

$$A_a = \frac{2r^2\sqrt{3}}{2} - \pi r^2 \tag{2.18}$$

Since the air gap equation (2.18) has terms containing the square of the radius, it can be shown that using multiple stands of smaller diameter wire in parallel results in a higher current density since there is less wasted air space between successive windings.

2.8 Effect of material on Force output

It is very clear base on equation 2.10 that force is directly proportion to relative permeability material. Relative permeability is depends on grain formation of materials. It has simple logic behind it is when relative permeability is high it gives smooth path to magnetic flux to flow same as current flow from least resistive path. For example pure Iron (99.95%) have relative permeability about 5000 give more force compare to low carbon steel (Carbon contain 0.5%) have relative permeability about 700.

2.9 Effect of angle on air gap and cross section area

The profile of plunger and seat is shown in figure 2.7 with large and small angle. It is clearly seen that as angle increases effective air gap reduces as $l_1 > l_2$ and cross section area increases.

2.10 Summary

This chapter consist of brief discussion for parts of solenoid type actuator and its uses.

It also comprises of mathematical model with cone shape plunger, dynamic equation for solenoid plunger, coil design and effect of materials.

Chapter 3

Design Data of Release Assembly

3.1 Design Data of Various Component of Release Assembly

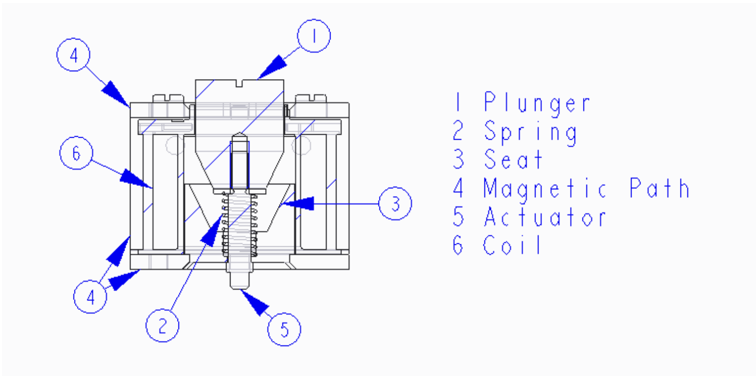

Figure 3.1: Solenoid Basic Design

Actual design is have 3 type of release: 1 x Shunt release (SR) 1x closing release (CR) and 1x Undervoltage release (UVR). This release is rated for different voltage range such as 24-30V DC, 48-60V DC, 110 Vac 50/60 Hz / 110 V dc, 125-127 V dc, 220-240 Vac 50/60 Hz / 220-250 V dc, 380- 415 Vac, 50/60 Hz.

Force Required for SR and CR is 11N and 30N respectively. CR and SR have same design and its component is shown in figure 3.1. It is measure by experiment setup as shown in figure 3.2, which showed that CR and SR is designed for 40N at initial and 80N at end of stock in which actuator is fix mounted and at different air gap force gauge placed for measurement.

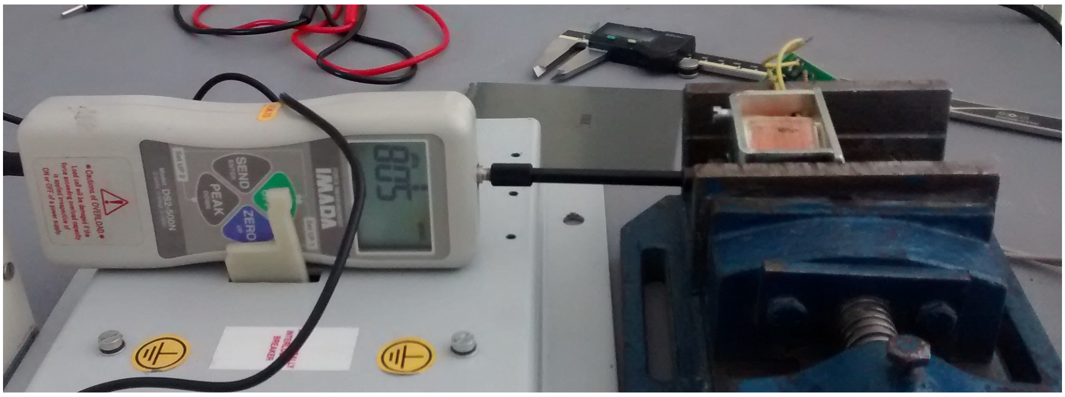

Figure 3.2: Experiment Setup for Force Measurement

Actuator have conical shape plunger design with angle of 52 degrees. Plunger is connected to actuator rod which transfer Push force to mechanism as shown earlier.

3.1.1 Spring load

In design, Spring is use for maintaining initial position of plunger when supply is not provided. Spring provides force at initial position is 1 N and at end position is 4.164 N Calculated spring load data is shown in table 4.1.

3.1.2 B-H curve of material

In design of actuator, EN1A 230M07 low carbon steel is used for plunger and seat. Its B-H curve is shown in figure 3.3. This shows it have saturation on 2.1 Tesla. This B-H curve is imported in FE-software for custom material creation.

3.1.3 Current input to coil

Current for coil is supplied by driving circuit as shown in figure 3.4. This driving circuit has 555 timer IC which apply pulse to FET so circuit will be cut-off supply in 600 ms.Current waveform captured by Digital Signal Oscilloscope is shown in figure 3.6 and experiment setup is shown in figure 3.5

From figure 3.6 is,

Average current= 0.72 A

Operation time =5.91 - 5.906 s = 4ms

Table 3.1: Spring data

Loading	
Maximum True Load, $True\,F_{max}$:	6.894 N
Solid Height by Considering Maximum Load, $Solid\,Height\,F_{max}$:	4.164N
Spring constant, k:	0.306N/mm
Travel	
True Maximum Travel, $True\,Travel_{max}$:	22.514 mm
Maximum Travel Considering Solid Height, $Solid\,Height\,Travel_{max}$:	13.600 mm
Dimensions	
Spring wire Diameter, d:	0.500 mm
Outer diameter of spring, D_{outer} :	6.800 mm
Inner diameter of spring, D_{inner} :	5.800 mm
Mean diameter of spring, D_{mean}:	6.300 mm
Free length, L_{free}:	18.100 mm
No. of active coils, n_a :	7
No. of total coils, n_T:	9
Solid height, L_{solid} :	4.500 mm
Type of the ends:	closed & ground
Spring index, C :	12.6
Distance between successive coils, $Coil_{pitch}$:	2.443 mm
Rise angle of coils:	7.04
Material Type	
Type of Material :	Stainless 302 A313
Weights	
Weight of one spring, M:	0.000280 Kg
Weight per one thousand springs,M:	0.279803 Kg
Length of wire required to make one spring, L_{wire} :	178.128 mm
Stress Factors	
Material shear modulus, G:	68,599,221,789.883Pa
Maximum shear stress possible, τ_{max} :	98,51,22,922.05
Wahl correction factor, W:	1.113

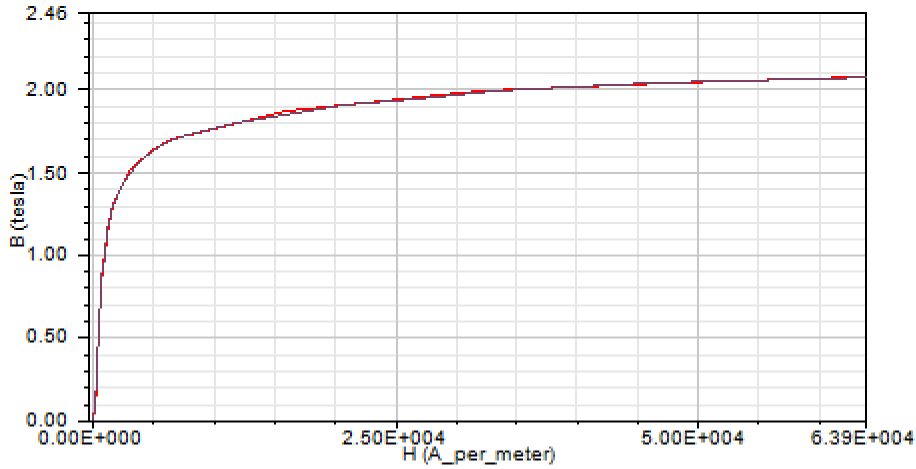

Figure 3.3: B-H curve of EN1A 230M07 low carbon stainless steel

Circuit cut-off time = 600ms.

3.2 Design calculation

No of Turns in coil = 3750,

Length of air gap = 9.15 mm,

Voltage Ratting =230V

Coil Resistance = 291 ohms

Current flowing in circuit = 0.75 A,

Length of core =32 mm,

Length of return path = 82 mm

Cut-off time = 600 ms.

Material used for seat and plunger is low carbon steel bar BS:970 En1A relative permeability 4000.

Material used for return path is low carbon steel sheet IS:415 max carbon contain 0.1% relative permeability 3000.

Now from equation (2.10) gives,

Force generated = 36.8 N,

Actuation time = 12 ms.

3.3 Results of Preliminary Analysis of Actual Design in MAGNET

Preliminary analysis is done on magnet and its model for 3-d FE analysis is shown in

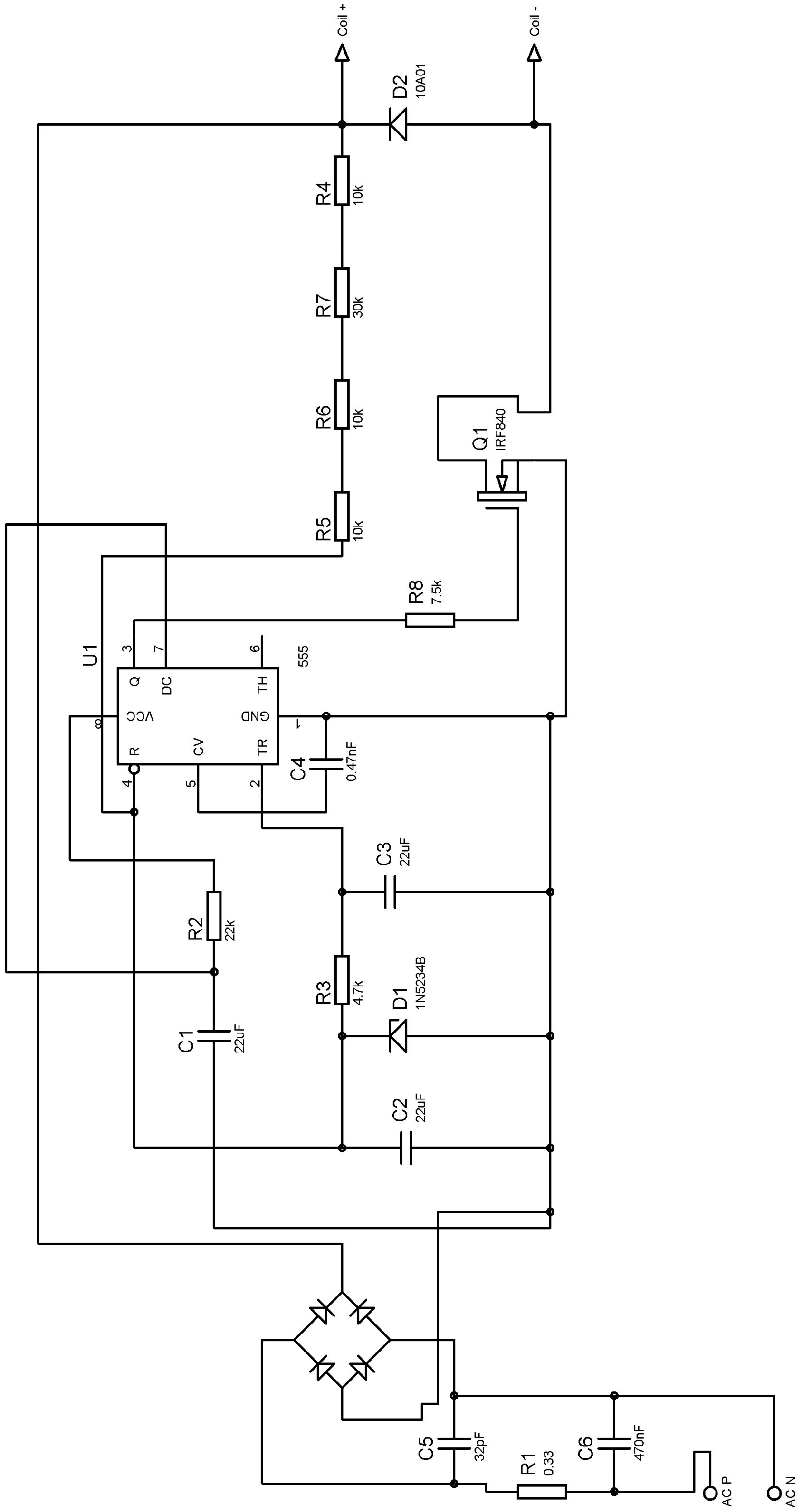

Figure 3.4: Driving Circuit for Actuator

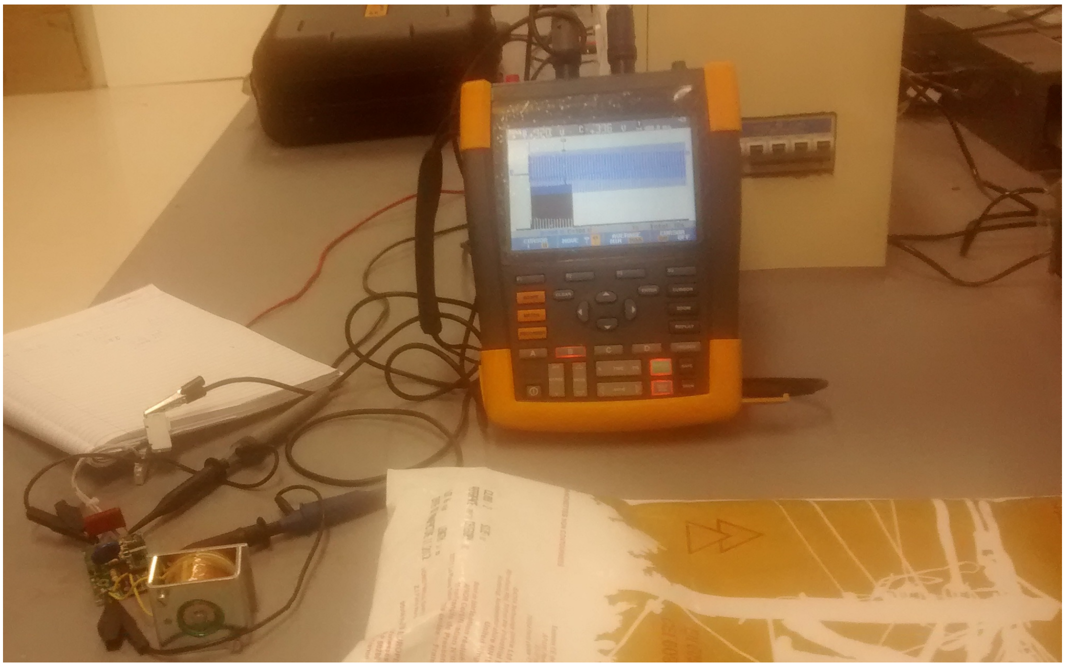

Figure 3.5: Current waveform capture experiment setup using Digital Oscilloscope

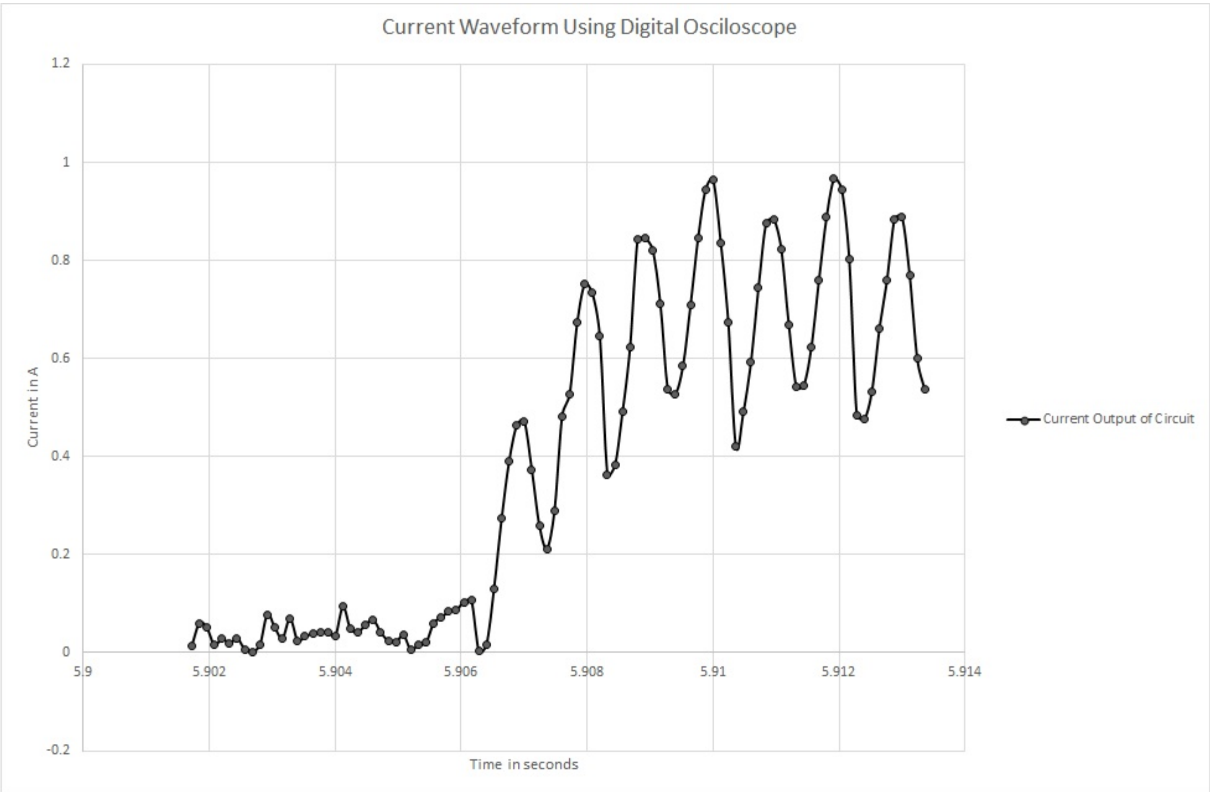

Figure 3.6: Current waveform captured by Digital Oscilloscope

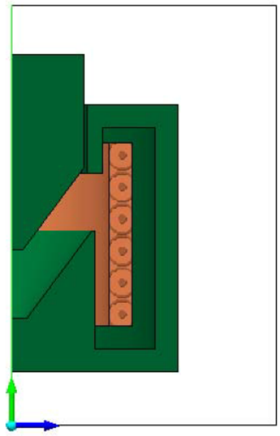

Figure 3.7: Model of actual design for simulation in MAGNET

Figure 3.8: Time Displacement Results for Actual System in MAGNET

figure 3.7. The result of simulation shows Travel-Time graph in figure 3.8.The result of simulation shows Force-Time graph in figure 3.9. In MAGNET Translation motion analysis can be done only in 2-dimational FE analysis.

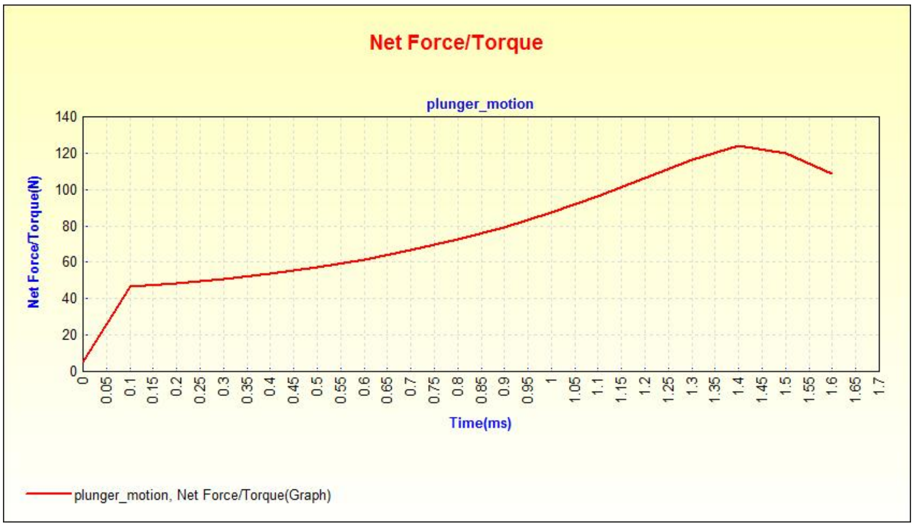

Figure 3.9: Force Time Results for Actual System in MAGNET

3.4 Results of Preliminary Analysis of Actual Design in ANSYS MAXWELL

Transient analysis is done on ANSYS MAXWELL and its model for simulation is as shown in figure 3.10. The result of simulation shows contour graph of flux density at initial position in figure3.11. The result of simulation shows force at initial position as shown in figure 3.12. In MAXWELL, Translation motion region can be apply to only cylindrical region.

In actual design, plunger have non cylindrical shape so it make very difficult to create motion region in ANSYS Maxwell.

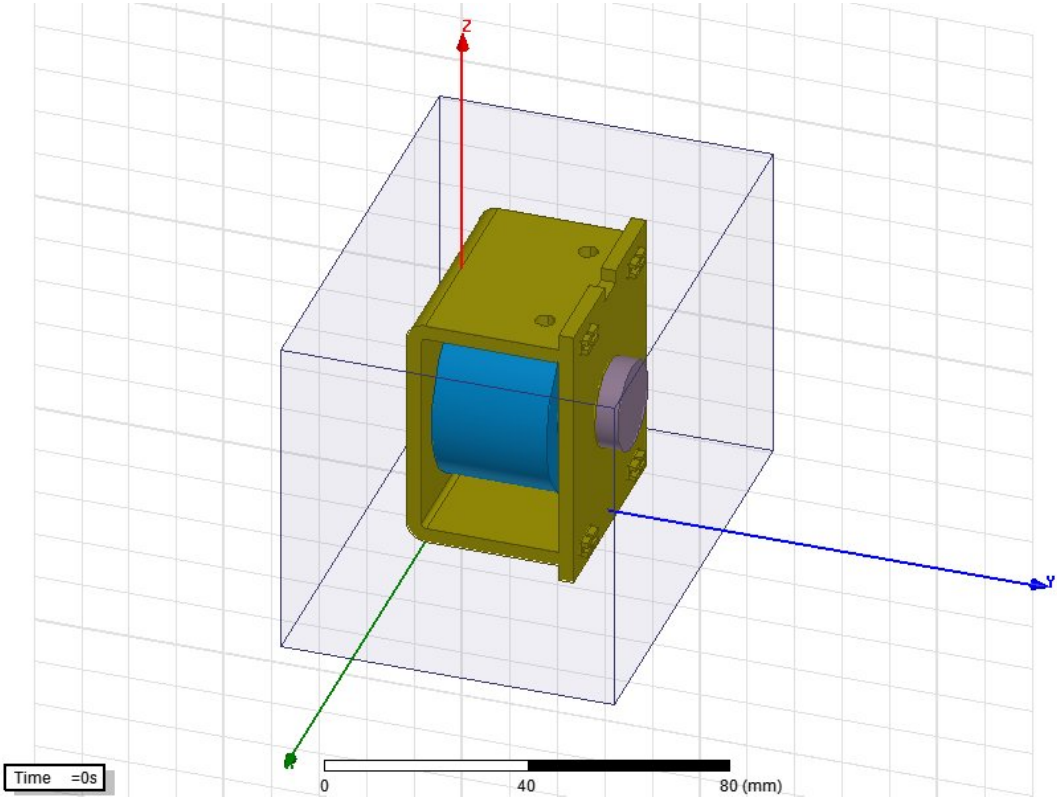

Figure 3.10: Model for Actual Design in MAXWELL

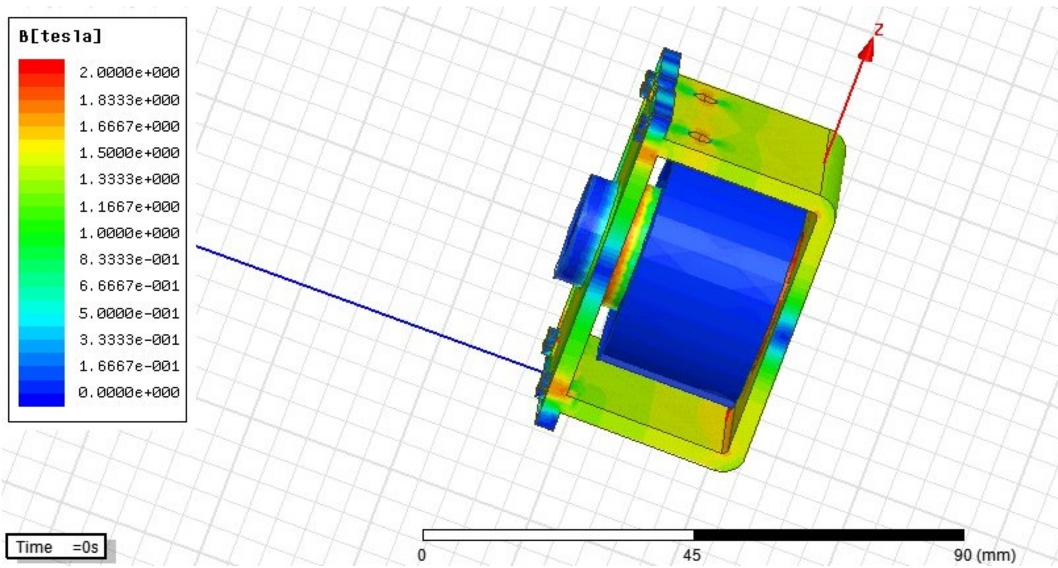

Figure 3.11: Contour of Flux Density

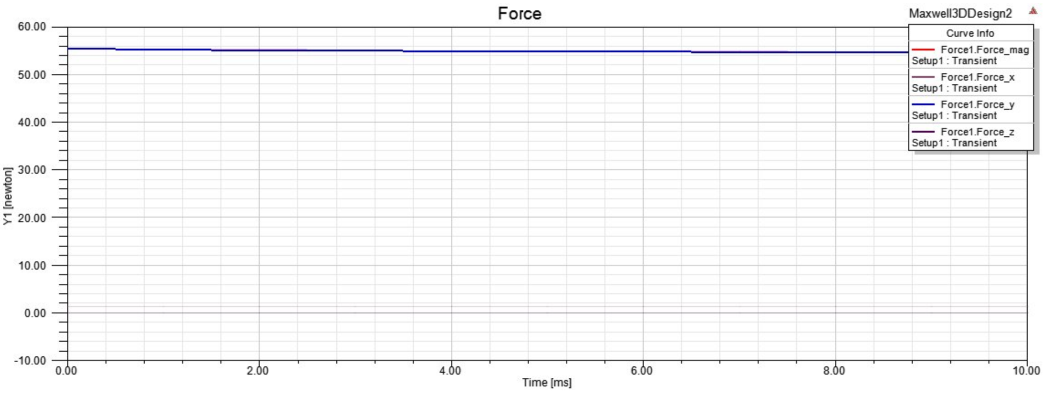

Figure 3.12: Force output of MAXWELL

3.5 Results of Preliminary Analysis of Actual Design in JMAG

Preliminary analysis is done on JMAG and its model of actual design for simulation is as shown in figure (3.13). The result of simulation shows contour graph of flux density at initial position in figure(3.14). The result of simulation shows contour graph of flux density at final position in figure (3.15). The result of simulation shows Displacement-Time graph in figure (3.16). The result of simulation shows Force-Time graph in figure (3.17). This FE tool have advantage over other tools by it have provision for input of dynamic equation of motion for motion region.

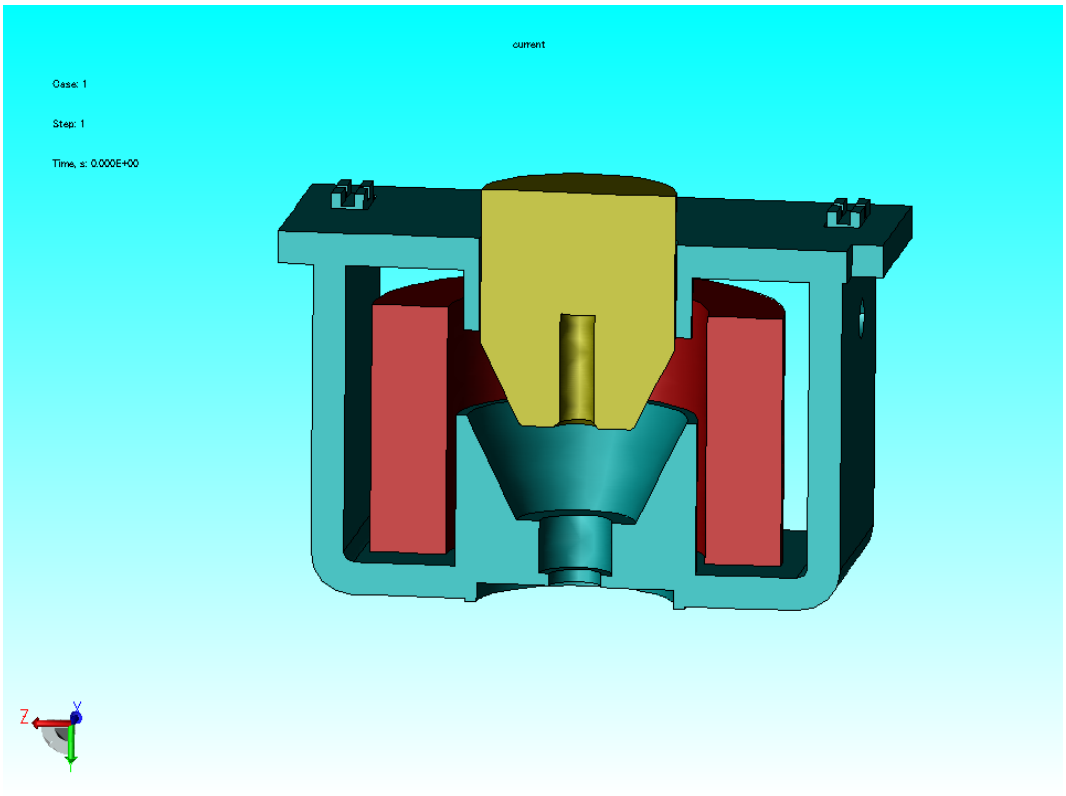

Figure 3.13: Model for present design in JMAG

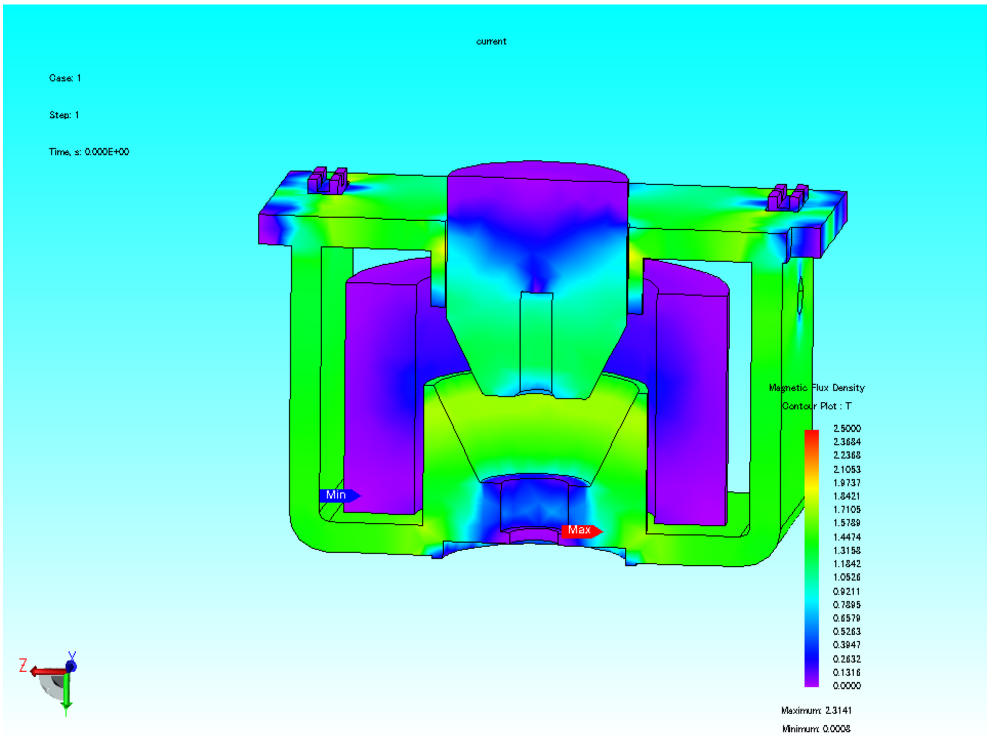

Figure 3.14: Flux Density in Actual Design at Initial Position

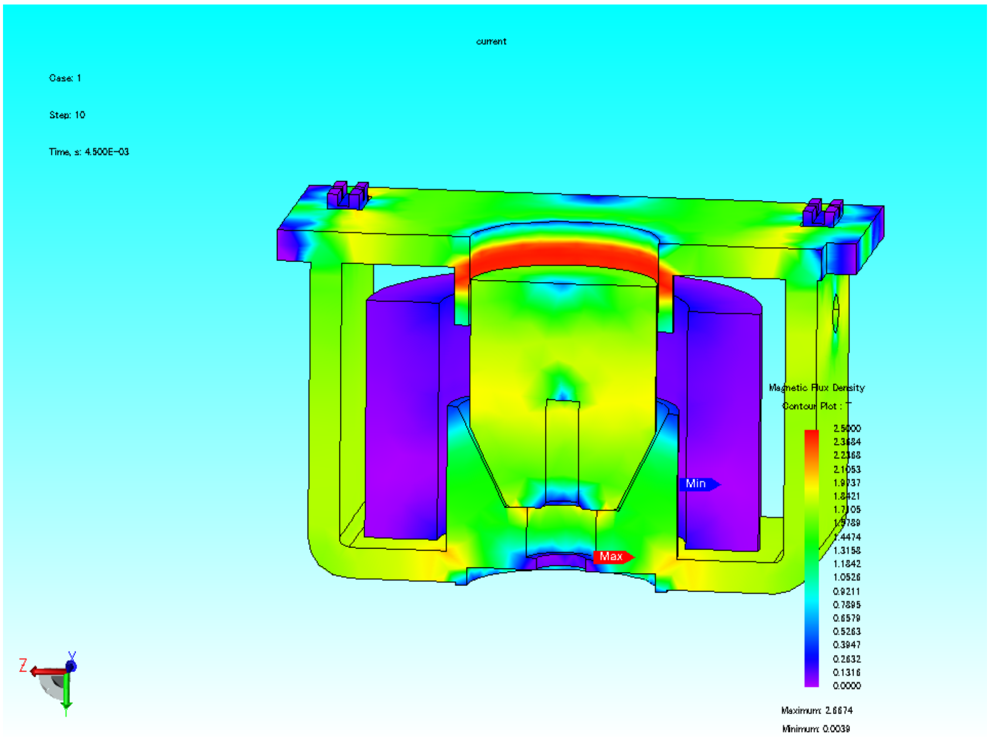

Figure 3.15: Flux Density in Actual Design at Final Position

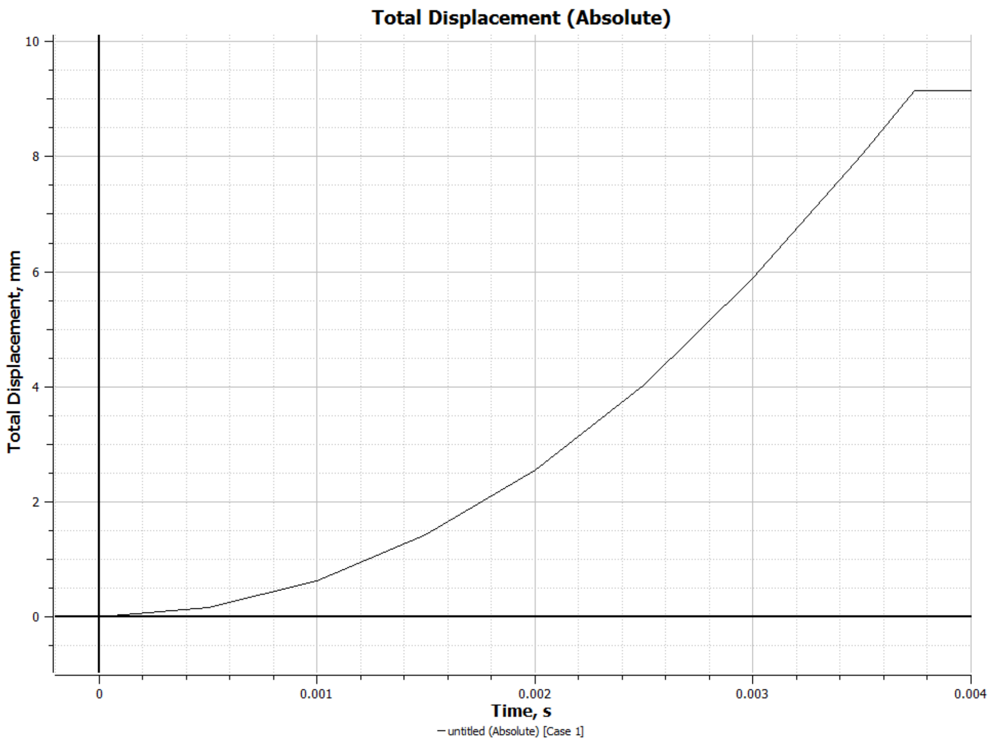

Figure 3.16: Displacement-Time Result of Actual Design in JMAG

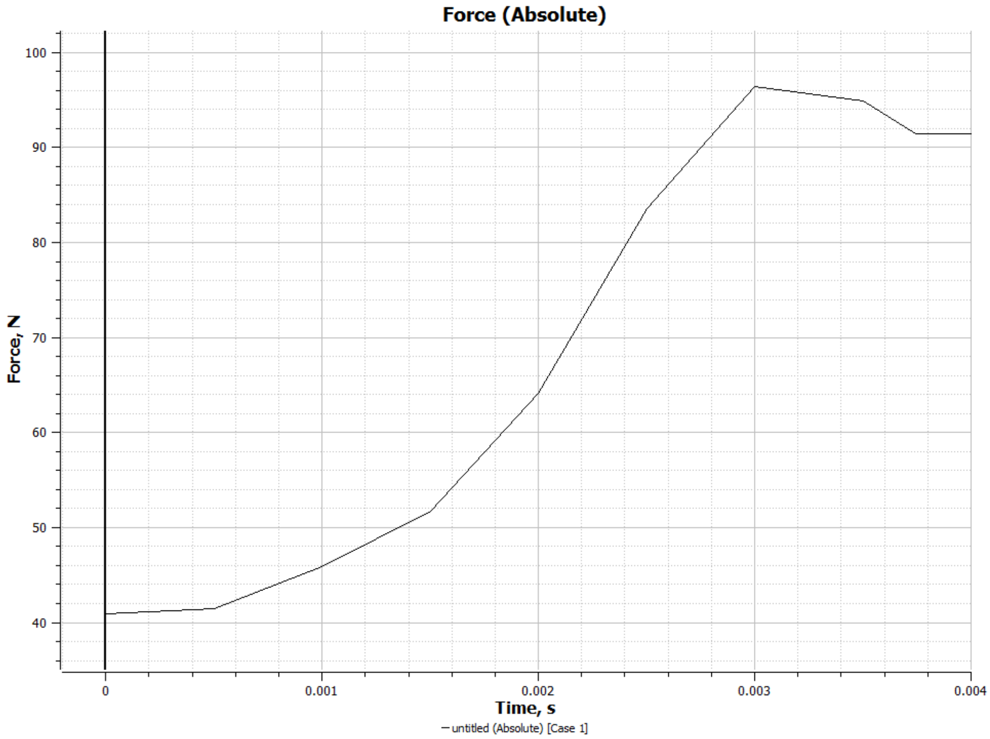

Figure 3.17: Force-Time Result of Actual Design in JMAG

3.6 Summary

This chapter comprises of data of the actual design like rating, spring load, B-H curve of soft magnetic material, driving circuit & current input, No of turns and wire gauge. It also consists of graph of driving current which was recorded by DSO. It shows FEM simulation for actual design in different FEM tools like MagNet, ANSYS Maxwell and JMAG. The one which gives result nearer to the practical result is selected for further analysis is ANSYS Maxwell.

Chapter 4

Design generation and selection

4.1 Parameters effecting force output

Magnetic force generated by actuator is depends on many parameter which are inter-related. The equation of force, equation 2.10, helped to derive relation between force and shows the major parameters as,

- Number of turns
- Current
- Relative permeability of material
- Effective length of air gap
- Length of magnetic path
- Area of cross section

These parameters are also inter dependent. If number of turns reduces, length of wire reduce which led to reduction in resistance so current increases. If wire gauge reduces, size of coil reduces led to reduction in resistance so current reduction but increases number of turn in same confine space.if plunger seat profile angle increases, effective air gap reduces and effective cross section area increases which led to reduction in number of turns which gives size reduction.

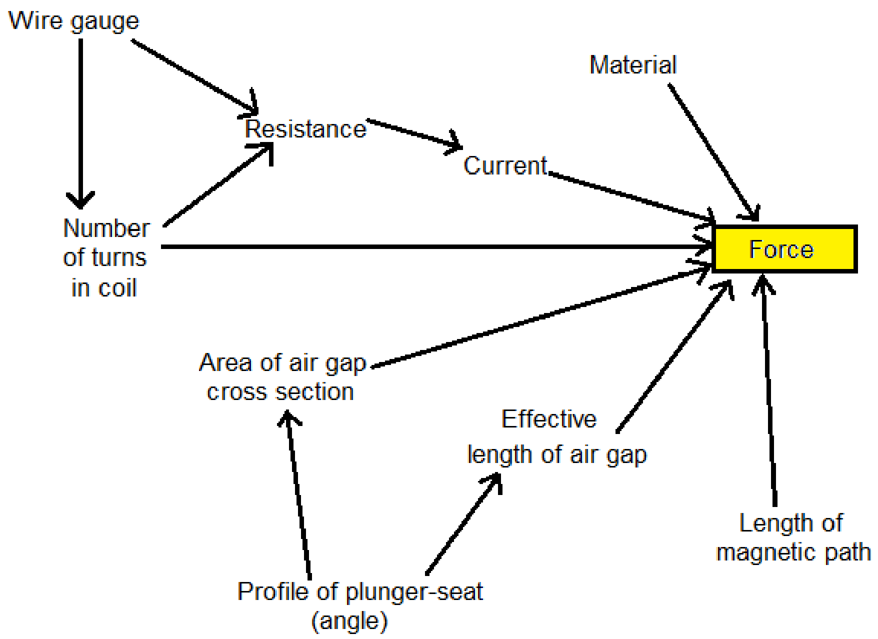

Figure 4.1: Parameters effecting force output

4.2 Constraint study

There are 4 constraint to be considered for new design.

1. Mounting space should be same as 48.0833 mm as shown in figure 4.2.
2. Total vertical motion should be same as 9.15 mm as shown in figure 4.3.
3. Initial force should be at least at 40 N.
4. Input power should not more then 200 VA.

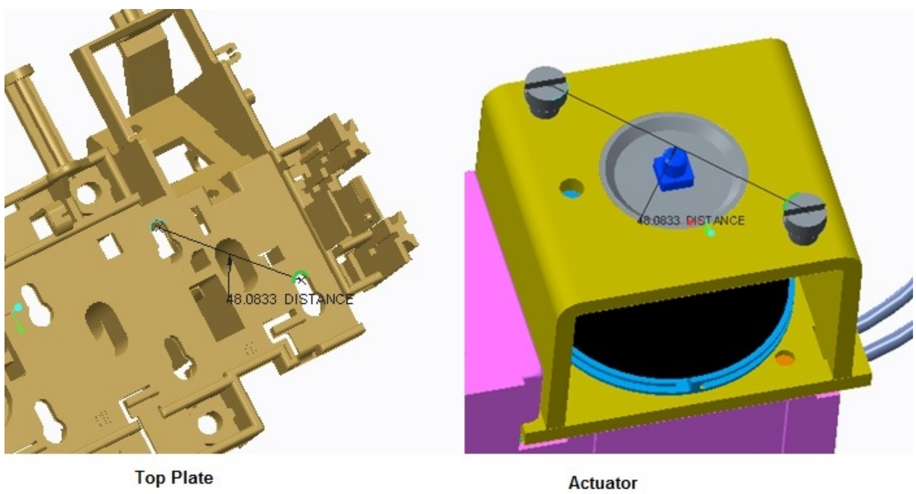

Figure 4.2: Mounting Space Constraint Study

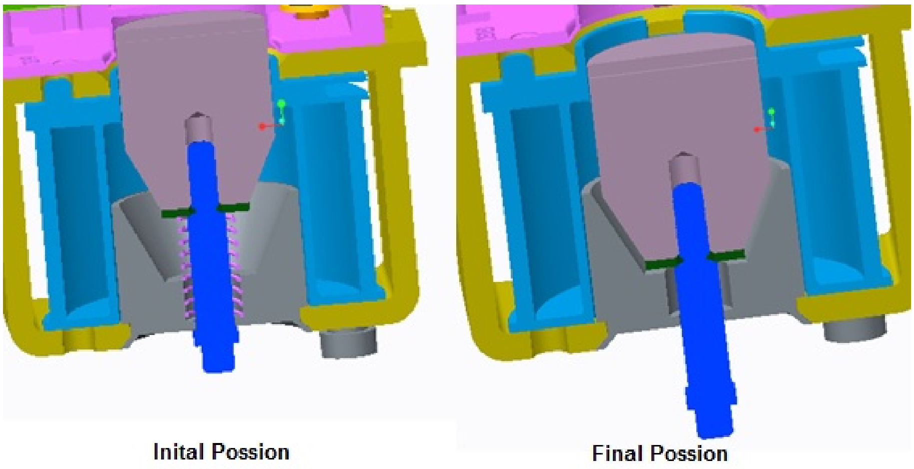

Figure 4.3: Total vertical Motion Constraint Study

4.3 Design generation

By considering parameters effecting force, there are major 5 designs design to analyze as ,

- Design 1: Plunger and seat profile change.
- Design 2: All components redesign.
- Design 3: All components redesign with different materials.
- Design 4: Double coil design in actual system.
- Design 5: Round shape design.

4.3.1 Evaluation of Design 1 : Plunger and seat profile change

Changes: angle of plunger and seat profile, number of turns, current

As angle of plunger and seat profile become smaller, air gap reduces and area of cross section increases thus the output force increases. For keeping output force constant at specified, number of turns have to reduces so resistance of coil reduces which led to increase in current. So it is boundary condition for this design coil wire gauge to withstand current, minimum height required and coil size.

Size reduction is 0% in this design.

Learning: angle of plunger and seat profile have great impact on design.

4.3.2 Evaluation of Design 2 : All components redesign

Changes: angle of plunger and seat profile, number of turns, current, size of components.

As angle of plunger and seat profile become smaller, air gap reduces and area of cross section increases thus the output force increases. For keeping output force constant at specified, number of turns have to reduces so resistance of coil reduces which led to increase in current. So it is boundary condition for this design coil wire gauge to withstand current, minimum height required and coil size which led to reduction in overall size. size reduction also led to smaller length of magnetic path which gives good output force.

Size reduction is about 20% in this design.

Learning: coil design, angle of plunger and seat profile have great impact on design.

4.3.3 Evaluation of Design 3 : All components redesign with different materials

Changes: angle of plunger and seat profile, number of turns, current, size of components, materials of different parts.

This design is same as design 2 except material use in components. Material used for components is high grade material with very high relative permeability. If the high relative permeability is high then it led to high output force.

Size reduction is about 26% in this design but material is not easily available.

Learning: Material have great impact on output.

4.3.4 Evaluation of Design 4: Double coil design in actual system

Changes: number of turns, current, size of components.

This design is modification in actual coil by split into two and connecting into parallel. This increases current by double by this limited by wire gauge size which increases. In this design force increase by 3-4 times but its behavior become sluggish.

Size increment is about 6% in this design because of second coil former and increase in wire gauge.

Learning: Material have great impact on output, this design is not compatible with problem statement.

4.3.5 Evaluation of Design 5 : Round shape design

Changes: angle of plunger and seat profile, number of turns, current, Return path.

This design is modification in Return path by making it from round bar. This increases flux flow in Return path. In this design, design is fully enclosed so heat dissipation in less.

Size reduction is 12% in this design.

Learning: This design have heating problem.

4.4 Final design selection and simulations

The design 2 is more promising then other design when manufacturing constrains, material availability and cost is consider. Plunger angle is set to 36° It also shows good behavior in simulations done in JMAG.It shows same force characteristic as actual design as shown in figure 4.4. These results shows that its have initial force output is about 48N.

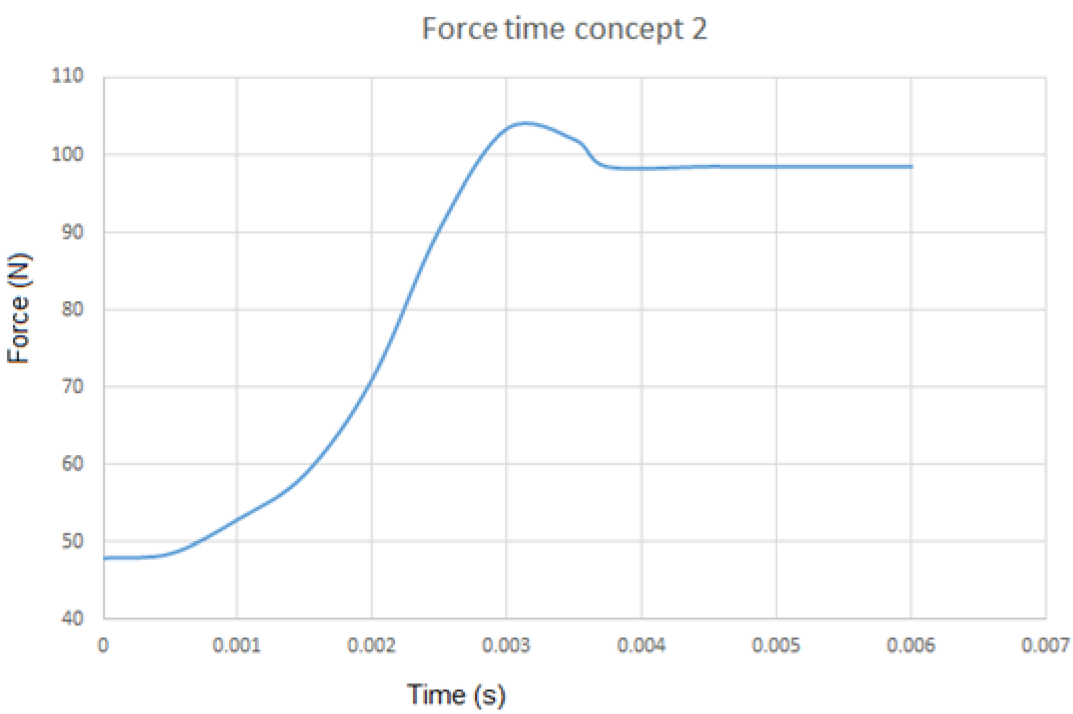

Figure 4.4: Force time response of design 2

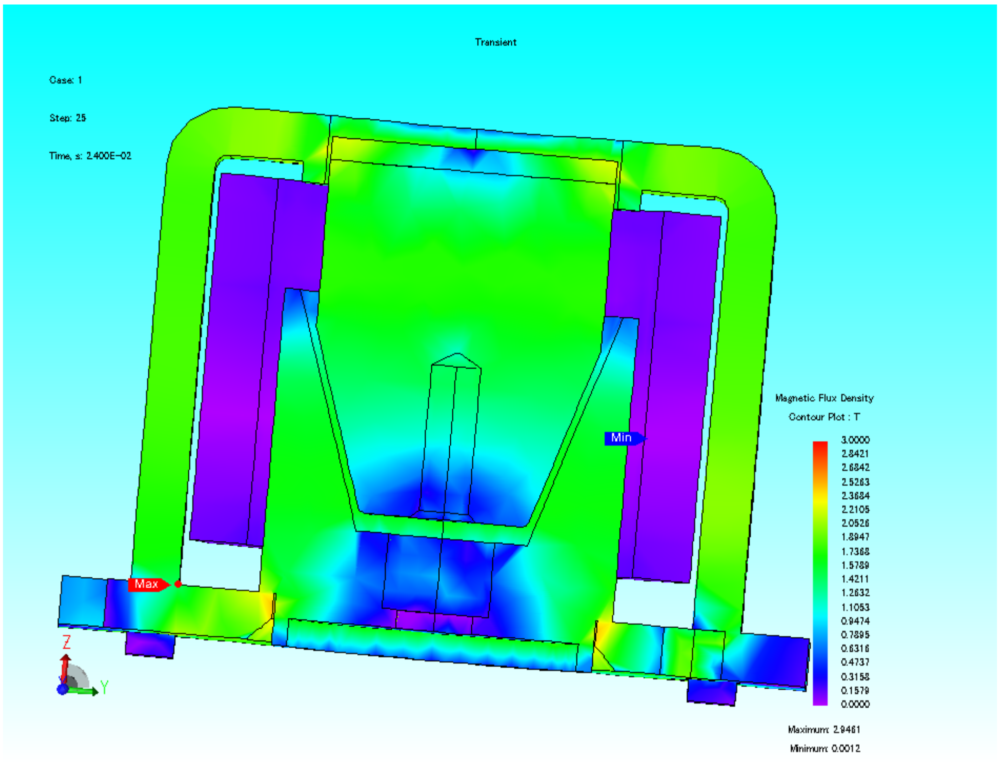

Figure 4.5: Flux density in design 2

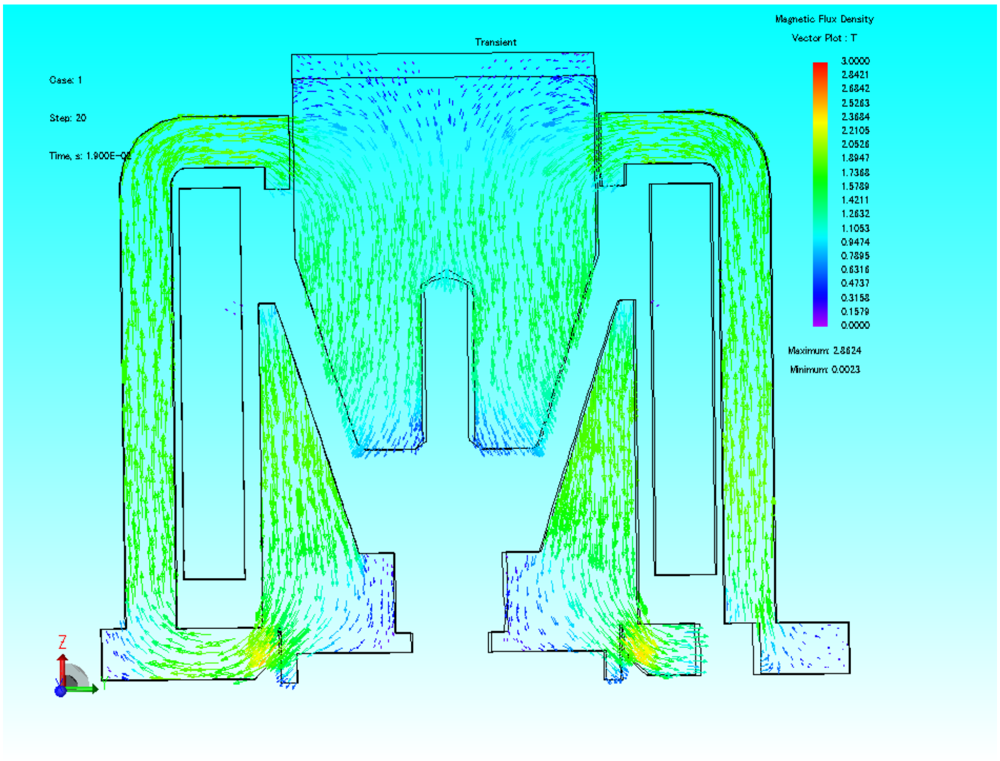

Figure 4.6: Flux vector in body of design 2

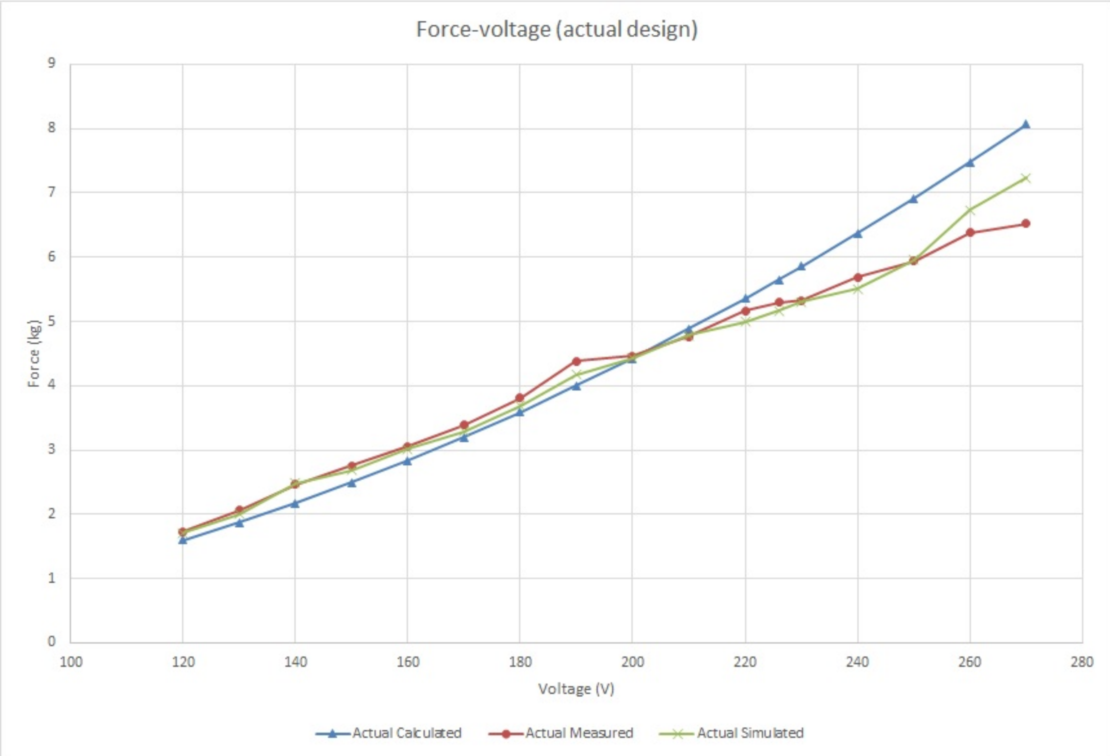

Figure 4.7: Force-voltage response for actual design with 26° half angle with 3750 turns

4.5 Final design prototype and comparison with simulation and mathematical results

Let the design 2 is divided further in two parts as one have change in design but cone half angle is same 26° and other has change in design with cone half angle is 18°. These releases have to operate for different voltage so comparing with actual design.

Figure 4.7 shows Force value of calculated, simulated and testing at different voltage for actual design with 26° and 3750 turns. Figure 4.8 shows Force value of calculated, simulated and testing at different voltage for design with 26° and 2160 turns. Figure 4.9 shows Force value of calculated, simulated and testing at different voltage for actual design with 18° and 2450 turns. Both design gives similar output as actual design, however, design with 2160 turns draws 2 time of actual current which is higher then allowed VA but it gives 35% size reduction. So it required current control circuit for this purpose. however, the design with 2450 turns draws 1.5 time of actual current which give in allowed VA and it gives 30 % size reduction. So it dose not require current control circuit for the said purpose.

Figure 4.10 shows % change in force by selecting different design over actual design. Figure 4.7, 4.8 and 4.9 shows that this model gives good results in limited range, beyond range this give larger error.

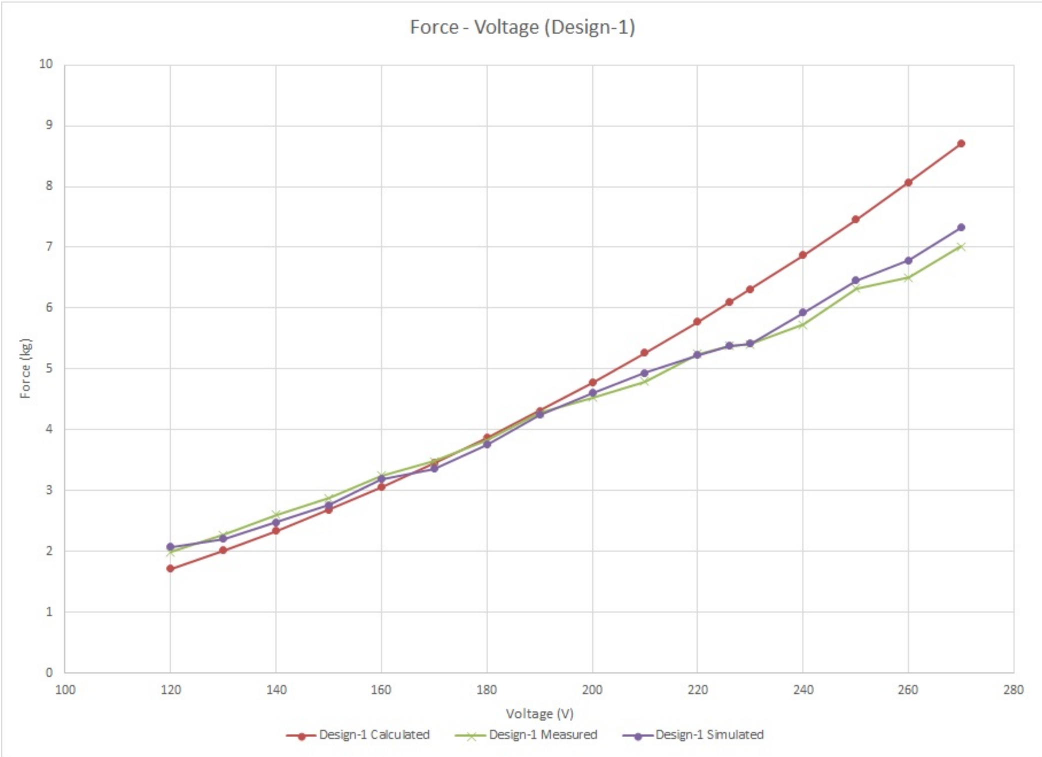

Figure 4.8: Force-voltage response for design with 26° half angle and 2160 turns

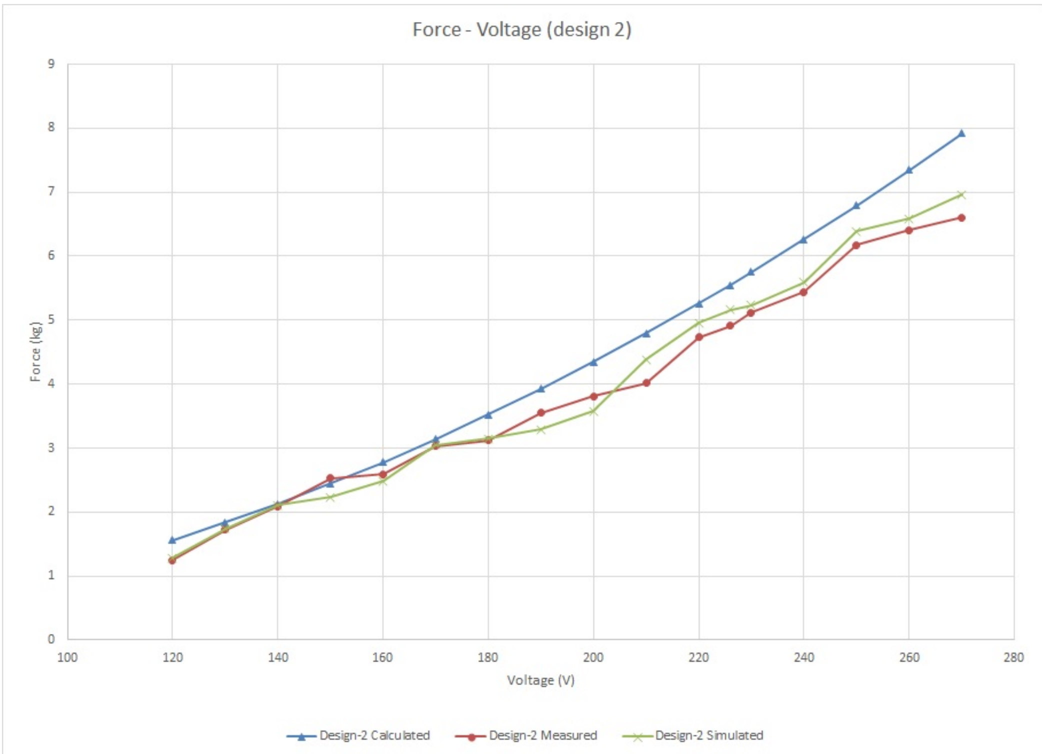

Figure 4.9: Force-voltage response for design with 18° half angle and 2450 turns

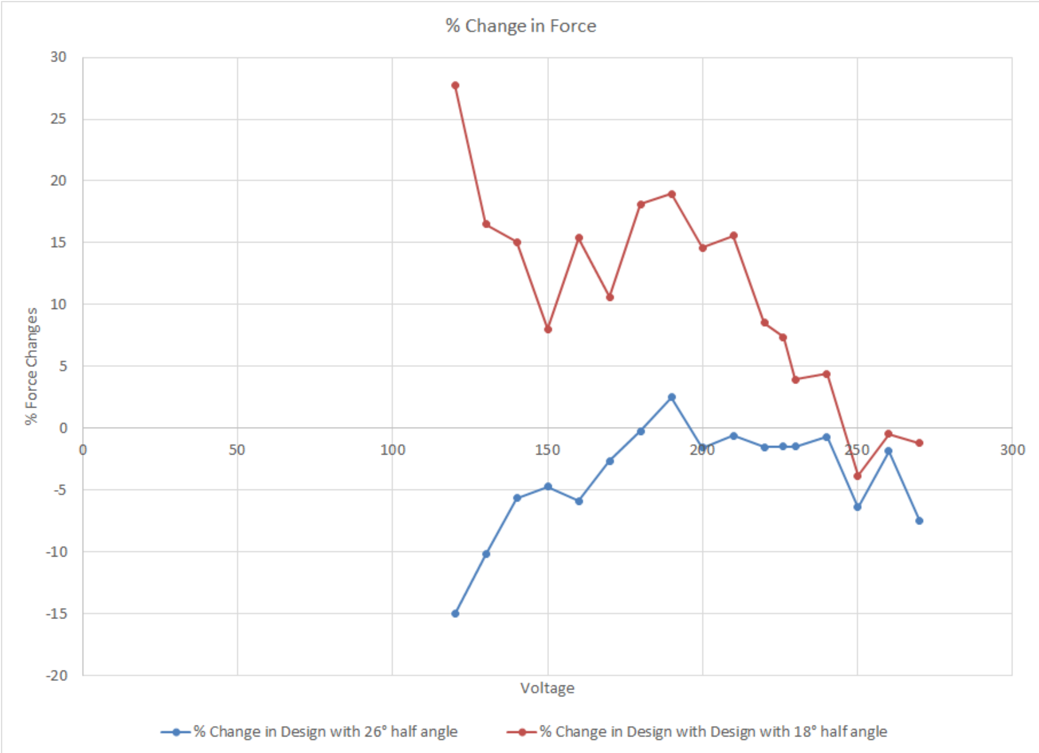

Figure 4.10: % Change in force with compare to actual design to prototypes

4.6 Summary

This chapter comprises of study on parameter affecting to the force output and size with inter relation with each other. Based on study, new modification in designs are generated which satisfy all design constraint. The detailed study of these designs are carried out to get the best optimized design.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

The effective area for the force to act on is increased due to the plunger's conical face instead of the flat surface. The existing coil size was too large for the present requirement to generate a force so reduction in size of the coil results into overall size reduction of the actuator. The force produced in the actuator is dependent on permeability of the material, which in turn, depends on the molecular arrangement of material.

The mathematical model suggests that calculation of force is accurate, but fringing factor will reduce accuracy of the calculated force, which can only be approximated. An assumption is made that the flux entering and leaving the material is perpendicular to the surface of the material having high permeability medium. The disadvantage of the conical shape actuator is that it generates less holding force than the flat surface actuator for the same required effective area, but gives more actuating force as output for the larger air gap. The derived mathematical model can be used for designing the solenoid actuator. An error margin of 10% should be considered in the calculated force output due to the approximation of fringing factor, which can be rectified by taking feedback from the prototype itself.

The design with 2450 turns in coil gives more promising results for the size reduction by 20% with cost reduction by 18%. This design also satisfies constraints. Surface-mount technology based PCBs can reduce overall actuator size significantly compare to through-hole technology.

5.2 Future scope

The accurate model can be created by performing number of experiments. By performing more number of experiments with different design, empirical formula can be derive to understand affecting parameters.

The duty cycle of actuator can be control by designing appropriate electronic control circuit i.e. SPWM technique. The duty cycle can be decrease in order to get less heat dissipation while the solenoid actuator output remain same. This design should be tested a number of time to get desired result.

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