

DESIGN OF MAGNETIC ACTUATOR

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Abstract

This Paper Proposes is to design a magnetic actuator to deal with the modeling and optimization of Solenoid actuator (Magnetic Actuator). The design is very important step for the study proportional solenoid valve. The magnetic actuator includes design optimization, micro analysis and calculations and experimental characterization one of the magnetic actuator. All these magnetic actuators work in sub- micron level movement used in micro system and valve applications. Proportional solenoid valve designed in find out the magnetic force (N), magnetic field intensity (A/m), magnetic flux density (Tesla or wb/m²). To enhance the magnetic force and reduction of size by magnetic field in air gap of solenoid valve. Permanent magnetic bias magnetic actuator study for bidirectional application using different permanent magnet material and optimization of size of armature.

Key Words: Electromagnet, Solenoid actuator, Modeling, Design Rules,

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1. INTRODUCTION

Actuators is defined as energy converter which convert one form of energy (electrical) into mechanical energy in a controlled form. Electromagnetic actuator which converts electrical to magnetic field is called "Solenoid". A Linear Solenoid is an electromagnetic device that converts electrical energy into a mechanical energy pushing or pulling force or motion. When electrical current applied to a conductor in generates magnetic field. The pole is determined by the direction of current flow within the conductor (wire). This wire coil becomes an Electromagnet with its own north and south poles just like the same as that for a permanent magnet. One of the reasons for using magnetic fields instead of electric fields is the higher energy density in magnetic fields. The air gap between stationary member (stator) and a moving member of an electromechanical actuator is where the electromechanical energy conversion takes place. The amount of energy per unit volume of air gap for magnetic fields can be five times the magnitude higher than that of electric fields. Lorentz's law of electromagnetic forces and Faraday's law of electromagnetic induction are the two fundamental principles that govern electromagnetic actuators. From the armature design point of view, linear solenoids are divided into four families of solenoid actuator geometries solenoids with disk, plunger, conical, and ball armatures .The variables of the optimization study are the solenoid geometry, magnetic material properties, and electromagnetic circuit including coil parameters. Utilized mathematical models would couple the electrical, mechanical, hydraulic, and from the armature design point of view, linear solenoids are such as ANSYS are available. Operating principle in [8] of Linear and Rotary Solenoid actuator. Design, finite element analysis and duty cycle [9] of all types of solenoid actuator. Divided into four families of solenoid actuator geometries solenoids with disk, plunger, conical, and ball

armatures .The variables of the optimization study are the solenoid geometry, magnetic material properties, and electromagnetic circuit including coil parameters. Utilized mathematical models would couple the electrical, mechanical, hydraulic, and Magnetic systems of these devices by taking into account the nonlinearity of the magnetic materials, eddy currents, and motion.

The increasing quantity of different novel actuator technologies being used in industrial applications along with the need for light and volume reduced system are boosting the necessity of general analysis using uniform criteria Regarding the comparison of solenoid actuators, in[1] design and analysis of various types of magnetic actuators including proportional solenoid valves, relays, high speed magnets etc.. Solenoid actuator designing for optimization in, [2] of Mechatronics and adaptronic systems .The mathematical formulation of linear solenoid in, [3] for predicting dynamic response. FEM based approach for predicting the dynamic analysis in,[4] long stroke linear actuator. The magnetic actuators in [5] for the application of aerospace, automotive, industrial applications of electromechanical actuator, brushless permanent magnet linear motors, fast acting solenoid actuators. An optimal design method in [6] on the high speed solenoid valve magnetic field by making a full consideration of the effects of various soft magnetic material's properties and geometries on the high speed solenoid valve electronic performance. A model of fast 2/2 switching valve in [7] and its experimental validation. And a number of commercial software packages In This paper introducing a new design (methodology) to analyze proportional solenoid actuator by designing and modeling their maximum output mechanical quantities (Force, Stroke) as a function of geometry and material properties and discusses and scalability.

2. DESIGN RULES

As previously stated the purpose of this work is to design rules and models for actuator optimization this section explains the general procedure introducing all the concepts which are going to provide such rules. The main steps are: Study of different plunger type Solenoid actuators.

- ❖ Design parameters. Study of the geometry and materials of the actuators.
- ❖ Optimization of Solenoid actuator by placing a non magnetic spacer, varying the plunger angle, including Bobbin as a magnetic material and Reducing bobbin thickness.
- ❖ Analysis and scalability of the actuator.
- ❖ Comparison of Theoretical, Experimental and ANSYS Results.

The first step introduces the study of linear solenoid actuators from the armature design point of view they are divided into four families of solenoid actuator geometries, solenoids with disk, plunger, conical, and ball armature. Ball-type solenoid actuators are suitable for fluid control due to their good sealing capabilities with zero leakage. Ball type armature is not able to generate force. So it acts like a fluid flow. The disk-type is suitable for fuel injectors. The disk-type eliminates the armature and the solenoid acts directly on the flat disk through the core of the body. Disk solenoid configuration has double the main air gap for flux to cross. Long stroke (air gap) it generates less force. At the same time, it has two relatively large surfaces of inner pole and outer magnetic circuit around a coil where flux is perpendicular to its surface. This disk and seat design also results in less deposit build up at the orifice and longer service life. It is not able to lift the higher weights as plunger and conical plunger.

Plunger solenoid types are the most popular solenoid configuration with a variety of applications. This is because the plunger solenoid configuration has a single main air gap for flux to cross and one parasitic air gap that is usually perpendicular to the main one. The inner pole surface of the main air gap carries the flux that is perpendicular to its surface, especially at the small air gaps where the flux crossing a parasitic air gap does not contribute to the axial forces Conical solenoid actuators can be used in long stroke applications, such as in automotive door locks, due to their high force over long stroke capabilities. They can also be applied in situations where the armature can develop a relatively large force due to a smaller magnetic air gap than axial stroke. The conical solenoid configuration has limited applications in long stroke travel without fast response time. This is because the conical solenoid configuration has a single main air gap for flux to cross that is always smaller than mechanical travel distance and one parasitic air gap that is usually perpendicular to the direction of motion The Second step introduces a variety of geometries have mixed configurations taking advantage of armature geometry features. Each of these basic geometries is discussed separately because of their different advantages, helping to serve different purposes. The selection of geometry is the

first and most important step in the design application; therefore, thoroughly understanding the pros and cons of each solenoid type is critical. A conventional linear actuator consists of an armature, magnetic-circuit housing with a central rod serving as an armature stop, a return spring, and a coil. Coming to material properties Plunger, Cover, Core is made up of SS410 because it is having retentivity property and residual magnetism. Bobbin and Stopper is made up of SS304. The Third step introduces optimization of Solenoid actuator. Placing a non magnetic spacer is placed in the path of main flux, so that more flux is listed with plunger to exert more force on the plunger which is required. This valve is analyzed with and without a non magnetic spacer in finite element analysis. At 20mm plate of non magnetic spacer it exhibit a high force of 0.5N and flux leakage will be less and flux leakage factor is 0.85. Without non magnetic spacer it gives force 1.2N flux leakage will be high and flux leakage factor is 0.7

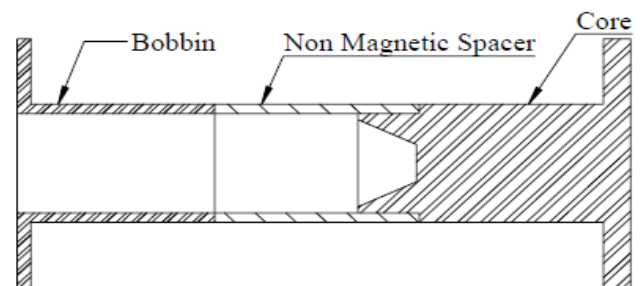


Fig.1: Bobbin indicates a Non Magnetic Spacer

By Varying Plunger angle for Stepped Conical and Conical type plunger from 200 to 700. At 600 Conical type plunger is exhibiting large force compared to other type and observed Force in FE analysis.

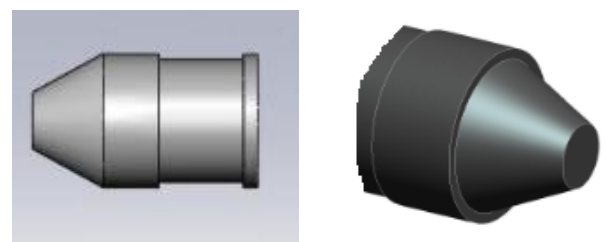


Fig. 2: Conical and Stepped Conical Plunger type

By Including Bobbin as a magnetic material exhibits force at 600 with less flux leakage and high flux leakage factor. By reducing bobbin thickness it exhibits a high force at 0.5 mm thickness.



Fig.3: Solid Model of the Bobbin

In the fourth step the actuators performance, function of the size is analyzed and the scalability and applications are discussed. The actuators force is proportional to square of the size and the actuators displacement is proportional to the size:

$$F = i^2 / \delta^2 \tag{1}$$

The required actuator size changes with respect to the rest of the mechanical system, which can make the use of the considered type of actuator unpractical. The scalability is discussed for the considered actuator classes.

2.1 Comparison Of Optimization In Solenoid:

Table 1: Material Properties

Type Of Optimization	Force(N)	Flux Density on Plunger	Flux Density on Solenoid
Magnetic Spacer(600)	0.5 N	0.004-0.295	0.53 *10 ⁻⁴ -4.139
Non Magnetic Spacer(600)	0.8 N	0.005-0.213	0.109*10 ⁻³ -2.826
Reducing Bobbin Length(600)	1.1 N	0.007-0.30	0.742- 2.43
Stepped Conical Plunger(600)	1.2 N	0.008-0.168	0.942- 2.13
Conical Plunger(600)	1.3 N	0.019-0.11	0.842- 2.03

So if comparing the all the optimization results Conical Plunger is giving the best force compared to other one. All the results found in ANSYS

3. THEORETICAL CALCULATION

The magnetic flux flowing inside the magnetic actuator (solenoid) can be explained from the following (reluctance) expression.

$$\phi = \frac{F_{mm}}{R} = \frac{N_i \mu_r \mu_0 S}{l_2 + l_{eq} + x(\mu_r - 1)} \tag{2}$$

$$B = \frac{\phi}{A} \tag{3}$$

Where R is reluctance expressed as a fraction of the magnetic property of the iron μ_r , where l_2 , the cross section of plunger $S = \frac{\pi(D+d_1)}{2} l$, length leg is plunger length with reluctance and with equal to plates and pipe reluctance. F_{mm} is the magnetic actuator force, equal to number of turns N, current i. The solenoid force is produced for the change of the reluctance due to the change of the air gap distance. Its expression can be derived from the energy stored in solenoid.

$$F = \frac{dW_m}{dx} = \frac{SN^2 i^2 \mu_r^2 \mu_0}{2(l_2 + l_{eq} + (\mu_r - 1)x)^2} \tag{4}$$

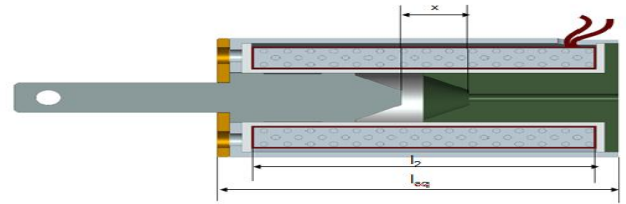


Fig .4: Solid Model of Solenoid

To Find out Flux leakage factor:

$$F = \pi \mu \left[\frac{r_1 + g}{\theta_v + g} - \frac{1}{2} \right] N_i^2 f^2 \tag{5}$$

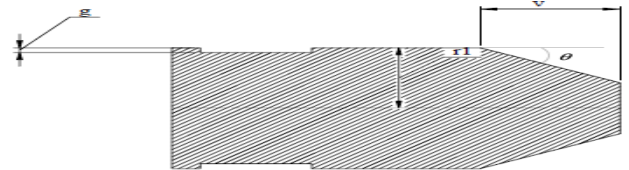


Fig .5: Drawing of Solid model area of cross section plunger

3.1 Coil Design:

To find the number of turns in the bobbin from the below formula

$$N = \frac{l_c}{d_w} \frac{d_1 - d_2}{2d_w} \tag{6}$$

To find the resistance of wire in the coil from the below formula

$$R = \frac{\rho_w l_w}{a_w} \tag{7}$$

To find the length of the wire in the coil i.e. wound to bobbin.

$$l_w = \pi \left[\frac{d_1 + d_2}{2} \right] N \tag{8}$$

Where l_c = length of the coil
 d_w = Coil wire diameter
 d_1 = inner diameter
 d_2 = inner diameter

Considering packing factor is 0.866.

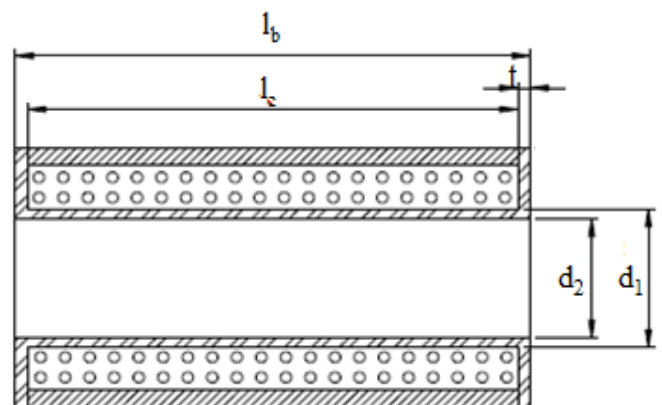


Fig .6: Solid Drawing of Bobbin

4. EXPERIMENTAL SET UP



Fig .6: Experimental set up



Fig .7: Experimental set up

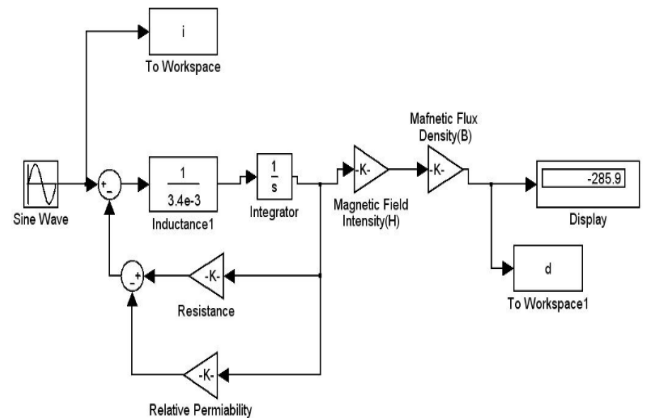
4.1 Material Selection

The model is having the following materials: air, (air gap) permeable materials and current conducting area.

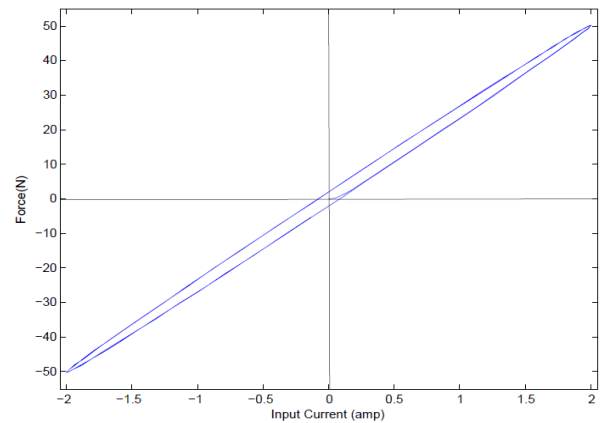
TABLE 2: Material properties

Component	Material	Relative Permeability (μ_r)
Plunger, & Cover	Stainless steel 410	1000
Bobbin, Stopper	Stainless steel 304	1.05
Free space	Air	1

4.2 Simulink Model for Solenoid Actuator To Find Out Hysteresis



4.3 Hysteresis Plot for Solenoid actuator



5.

CONCLUSIONS

The main objective of the current project is to study the solenoid actuator for the application of high force generation and to develop a design methodology for the study of optimization of solenoid actuator.

Simulation model of solenoid has been established. And simulations have been carried out for time response and Hysteresis. The Electromagnetic analysis has been established for obtained force and the magnetic force developed by plunger is correlated with experimental value.

NOMENCLATURE

- A_w = Cross sectional area of coil (m²)
- B = Flux density (wb/m²)
- d_2 = Inner diameter (mm)
- d_1 = Outer diameter (mm)
- d_w = Coil wire diameter (mm)
- F = Force (N)
- f = Flux leakage factor
- g = Clearance between plunger and bobbin
- H = Magnetic field intensity (A/m)
- i = Current (amp)
- l_c, l_2 = Length of the Coil (m)
- l_w = Length of wire in the Coil (m)

L = the coil's Inductance (H)
 N = Number of turns
 R = coils Resistance (Ω)
 S, v = Area of cross section of plunger (m²)
 V = Voltage (v)
 x = Stroke length (mm)
 ρ_w = Resistivity of wire
 Φ = Magnetic flux (Weber)
 μ_0 = Permeability
 μ_r = Relative permeability
 θ = Angle of plunge

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