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Design and ANSYS Software Based Simulation of U-I Type Actuator and Rail Used in Electromagnetic Levitation System

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Abstract: In this paper an analysis and simulation of U- I structure (actuator and rail) used in electromagnetic levitation system (EMLS) has been performed utilizing ANSYS software. For the successful implementation of any EMLS the proper selection and design of actuator and guide-way is important. The design of actuator is primarily controlled by the input power to lift power ratio and lift power magnet weight ratio. These factors are dependent on the magnet dimensions, required gap flux and hence the required current density in the winding. The magnet configurations chosen on the basis of required pole-face area and necessary window area to house the excitation coils. Electromagnetic levitated and guided systems are commonly used in the field of transport vehicles, frictionless bearings and conveyor systems In this work a FEM based analysis has done to find out the flux pattern, flux density, field intensity, working force for U-type actuator and I-type rail based levitation system at different operating condition.

Keywords: Electromagnetic levitation; FEM analysis; eddy current effect; ANSYS software; flux pattern.

1. Introduction

In manufacturing processes, working environment affects the quality of the precision products. Conventional transportation systems e.g., belt-type conveyors or articulated robots generate dusts and pollution due to the mechanical friction or lubrication, and are inadequate to satisfy the environmental demands. Magnetic levitated carrier system for the transportation systems has the advantages of being contact free, can eliminate the mechanical components e.g., gears, guide, ball bearings, reduce the mechanical alignment and maintenance cost, hence it satisfies the environmental demands [1, 2]. Therefore, research on contact-free type transportation system and actuator has been actively performed by worldwide researchers. Modern applications of levitation in equipments like magnetic bearings and magnetically levitated vehicles have given renewed impetus to research efforts in the direction of electromagnetic levitation. Advances in control electronics and superconducting materials have also contributed to further research in the area of electromagnetic levitation. In electromagnetic levitation (attraction system), the electromagnets are driven either by AC or DC source. Although several experimental systems

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using AC sources have been built, these methods are considered to be suited for applications where mass of the suspended object is small [3]. The severe constraints imposed by eddy current losses in the magnet and the rather complex control circuitry for power modulation makes the AC method of stabilization inappropriate for heavy payloads. In contrast, the explicit Dc method, technically known as the electromagnetic levitation system (EMLS), has a considerably simpler configuration with favorable power requirement. In DC EMLS, the current as well as the attraction force of the electromagnet can be effectively controlled by utilizing a switched mode power amplifier. Based on the basic principle, magnetic levitation may broadly be classified into two types, electrodynamics levitation and electromagnetic levitation. The electrodynamic system actuates through repulsive forces. In electromagnetic system, the levitation is produced due to the attractive force between electromagnets and ferromagnetic objects. Levitation process is basically a problem of feedback control system and is represented in closed-loop form with different subsystems as shown in Figure 1. Here a position transducer senses the gap between the magnet pole-face and the ferromagnetic object and the output signal is fed back to a comparator. The output of comparator is applied to a position controller which gives the reference current for the current loop. Actual coil current is sensed by the current sensor and compares with reference current. The current error process through current controller that sends a command signal to the power amplifier, which produces necessary currents in the actuator coils [5, 6]. The currents in the coils generate requisite magnetic forces. So in general there are four major components in an electromagnetic levitation system (i) Actuator and Rail (ii) Position Sensor (iii) Controller (iv) Power amplifier. In case of DC electromagnetic levitation, electric current in a wire wound coil produces the primary field while the ferromagnetic object or guide-way creates a means of shaping the magnetic flux. Generally the electromagnet is kept fixed and the ferromagnetic object is made to remain suspended under the magnet. Alternatively, the scheme is just inverted and the electromagnet is part of the levitated object under a fixed ferromagnetic guide-way (Figure 2).

Electromagnetic levitated and guided systems are commonly used in the field of transport vehicles, frictionless bearings and conveyor systems [4]. In magnetically levitated vehicle the guidance force needed to keep it on the track is obtained with the levitation electromagnets. In this work shows a simple magnetic model for the study of the levitation and guidance forces produced by an electromagnet coupled with an iron rail. The mechanical action depends not only on the structure of the electromagnet but also on the shape of the guide way. In particular, the same electromagnet coupled to guide ways of different shapes results in a change of intensity of the two forces. The shape of the guide way is important, first of all in order to get levitation and guidance force with the same electromagnet.

In this approach, the magnet-coil has been excited by a controlled current source, which is a simpler second order transfer function for the system [1]. If N is no. of turns of coil, $i(t)$ is instantaneous current through the coil, Φ_r is total flux ,R is reluctance of entire magnetic circuit,$L(z)$ is the inductance of the coil at a particular value of air-gap length (z) and z is airgap length between actuator and guide-way then.

The flux Linkage as shown Figure 2. is given as

$$(\lambda) = N\phi_r \tag{1}$$

According to Faraday's law [10]

$$e = N\frac{d}{dt}\phi_r \tag{2}$$

and due to self inductance L,

$$e_L = L\frac{di}{dt} \tag{3}$$

from equations (1), (2) and (3) $e = \frac{d}{dt}N\phi_r$ and $e = \frac{d}{dt}iL$

on equating above equations, we get $N\phi_r = iL$

So, the inductance L of the coil we get

$$L = \frac{N\phi}{i} \tag{4}$$

At any instant of time, the inductance of the coil under some simplifying assumptions is given by the following equation

$$L(Z) = \frac{\mu_0 N^2 a}{2z(t)} \tag{5}$$

Now, Energy stored in an inductor

$$E = \frac{1}{2}Li^2 \text{ and Force} = \frac{dE}{dz}$$

when the electromagnet is excited, there is a force of attraction between the magnet and the ferromagnetic body. The force of attraction between a ferromagnetic mass and the magnet is non-linear. At any instant of time, the force of attraction between the electromagnet & the ferromagnetic rail is given by [1, 2],

$$F(i,z) = -\frac{d}{dz}\left[\frac{1}{2}L(z)i^2(t)\right] \tag{6}$$

Now putting the inductance value from equation (5) into the force equation (6), one can write:

$$F(i,z) = \frac{\mu_0 N^2 a}{4}\left[\frac{i(t)}{z(t)}\right]^2 = C\left[\frac{i(t)}{z(t)}\right]^2 \tag{7}$$

where, $F(i,x)$ is the force function, $i(t)$ is the current flowing through the coil, $z(t)$ is the air-gap between the pole face of magnet and guide-way and $C = \frac{L_0 z_0}{2}$ is called the force constant. It is to be mentioned that the above expression is only valid without magnetic saturation, assuming linear material behavior, no leakage and fringing flux, no losses due to eddy currents and no permanent magnet bias flux. From the equation (5) it is clear that selecting small number of turns, smaller pole face area and larger air-gap between magnet pole-face and guide-way can reduce the magnet electrical time constant but all these factors simultaneously will reduce the lift force. So there should be a compromise between dynamic characteristics and lift-force of the actuator while selecting all the above parameters. By increasing the input dc link voltage the rate of rise of current through the coil increases which in turn reduces the effective value of time constant. This method is called voltage forcing [1, 5]. With the change of air-gap the inductance (Figure 3) and current profile (Figure 4) of levitated system changes rapidly thereby changes the transfer-function of EMLS at different operating points.

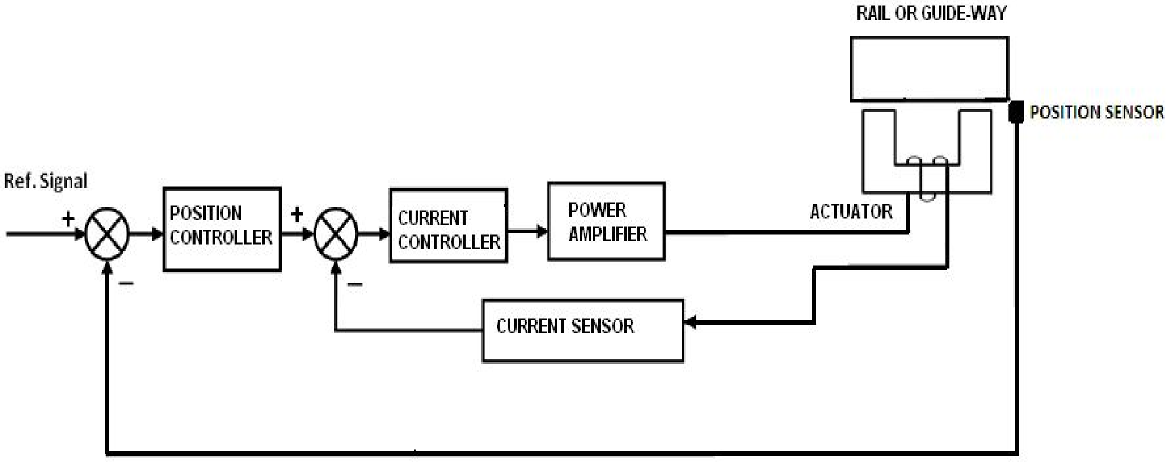

Figure 1. Simplified closed loop system of DC electromagnetic levitation system

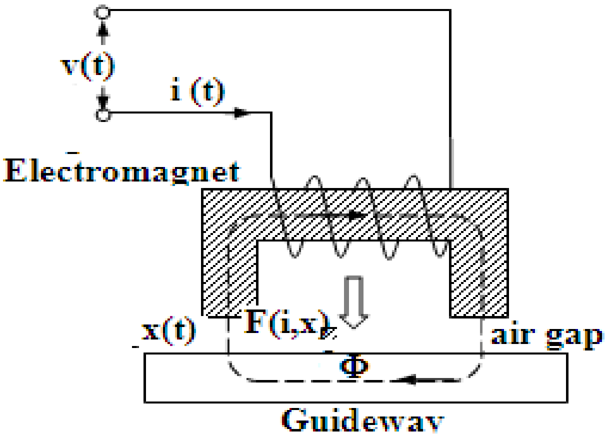

Figure 2. Simplified diagram of DC electromagnetic levitation system

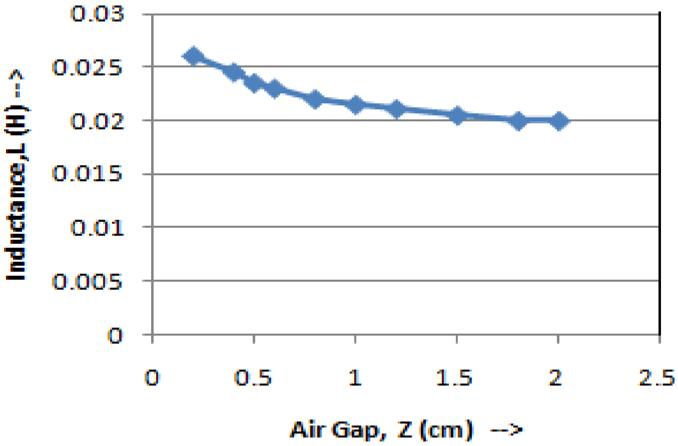

Figure 3. Inductance (H) vs. air gap (cm) characteristics

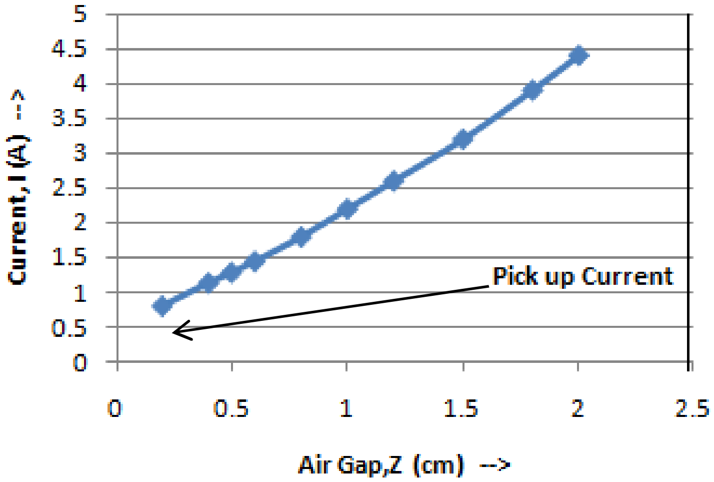

Figure 4. Pickup current (A) vs air gap (cm) characteristics

2. Finite element method (FEM) and ANSYS analysis for the proposed system

Generally electromagnetic analysis is based on finite element method (FEM). The FEM (sometimes referred to as finite element analysis (FEA) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations [11]. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically, integrated using standard techniques such as Euler's method, Runge-Kutta, etc. Finite Element Analysis (FEA) is one of these methods. In solving partial differential equations, the primary challenge is to create an equation that approximates the equation to be studied, but is numerically stable, meaning that errors in the input data and intermediate calculations do not accumulate and cause the resulting output to be meaningless. There are many ways of doing this, all with advantages and disadvantages. The Finite Element Method is a good choice for solving partial differential equations over complicated domains , when the domain changes (as during a solid state reaction with a moving boundary), when the desired precision varies over the entire domain, or when the solution lacks smoothness. In the present work, ANSYS (12.1) software has been used for electromagnetic analysis of single and multi-magnet based levitation system The ANSYS program has many finite-element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis [7-9]. Electromagnetic simulation from ANSYS provides industry leading analysis tools that enable the accurate simulation of electromagnetic fields. ANSYS Mechanical and ANSYS Multiphysics software are non exportable analysis tools incorporating pre-processing (geometry creation, meshing), solver and post-processing modules in a graphical user interface (GUI). The general flowchart for ANSYS simulation study applying above steps may be represented by the following Figure 5.

The static magnetic field problem can be described by the following Maxwell's equations [10, 12]

$$\nabla X H = J \tag{8}$$

$$\nabla X B = 0 \tag{9}$$

$$\nabla . J = 0 \tag{10}$$

$$H = \frac{B}{\mu} \tag{11}$$

where H, B, J and μ are the magnetic field intensity, the magnetic flux density, the source current density, and the permeability, respectively. The permeability is supposed to be constant, $\mu = \mu_0$ in air.

The vector fields *B* and *H* are related through the permeability μ (in Henries/meter) of the medium as:

$$B = \mu H \tag{12}$$

In terms of the magnetic vector potential A (in Wb/meter)

$$B = \nabla X A \tag{13}$$

Applying the vector identity for an arbitrary vector F

$$\nabla X(\nabla X F) = \nabla(\nabla . F) - \nabla^2 F \tag{14}$$

To equations (8) and (11) leads to Poisson's equation for magneto static fields

$$\nabla^2 A = \mu J \tag{15}$$

Equation (15) is useful to calculate the magnetic field in magneto static cases [12]. The magnetic field will be used in the calculation of magnetic force experienced by the levitated object in EMLS.

For the present analysis, the parameters are used for the U-I type structure (which is already designed) as shown Figure 6. The parameters for the simulation are Number of turns in the coil.(N)=154, Thickness of inner leg of magnetic circuit (t_a)=1.5 cm, Thickness of lower leg of magnetic circuit (t_b)= 1.5 cm, Thickness of outer leg of magnetic circuit (t_c) =1.5 cm, Armature thickness (t_d)=1.5 cm, Width of coil (w_c)= 1.25 cm, Height of coil (h_c)= 1.25 cm, Air-gap between armature and back iron.(Z)= 0.5 cm – 2 cm, Total width of the model (W)= 8.8 cm, Total height of the structure (H)= 8.5 cm, current through the coil (I)= 2 A, Current density (J)=N*I/a_{coil}.Here we have considered the main four things to analyze the structure of U-I type using ANSYS software [9]. These are:

Armature:	Here the armature is suspended rode having different permeability (generally twice of the Iron used in the Back iron).As we using U-I type electromagnetic model, so here the armature is attracted part of the system.
Back Iron:	Back iron is the U-type electromagnet where the coil is wound around the two limbs of the C-type around bobbin insulated properly.
Coil:	Coil is generally wound around the back iron which is energized by D.C power amplifier or by A.C. The permeability of the coil is taken as unity.
Air Gap:	The distance between the armature and the back iron is taken as air gap. The permeability of the air gap is unity.

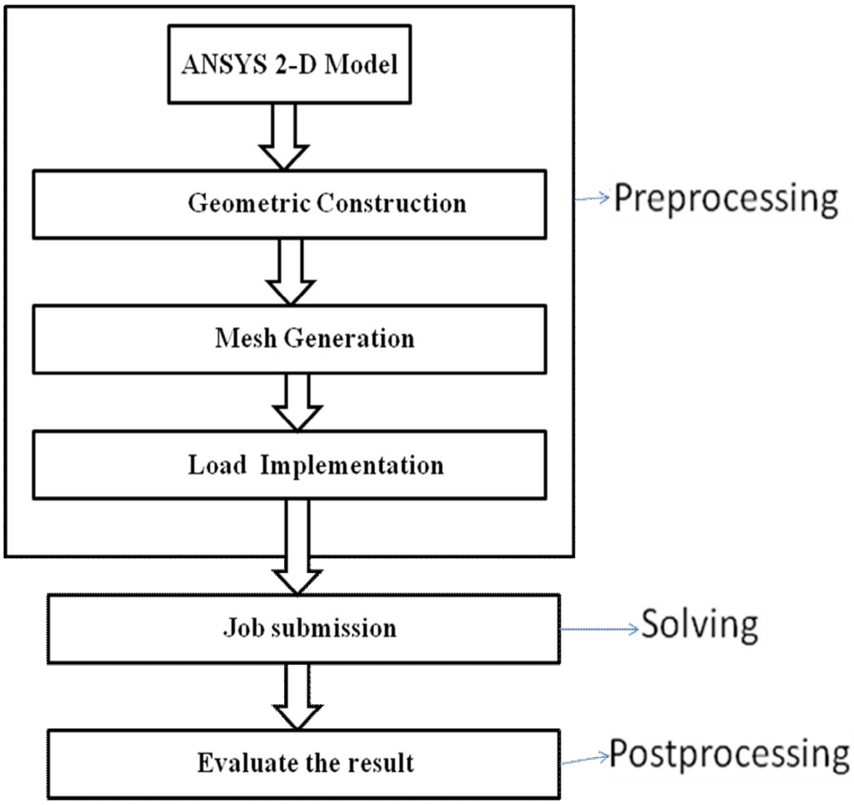

Figure 5. Flow chart for ANSYS simulation

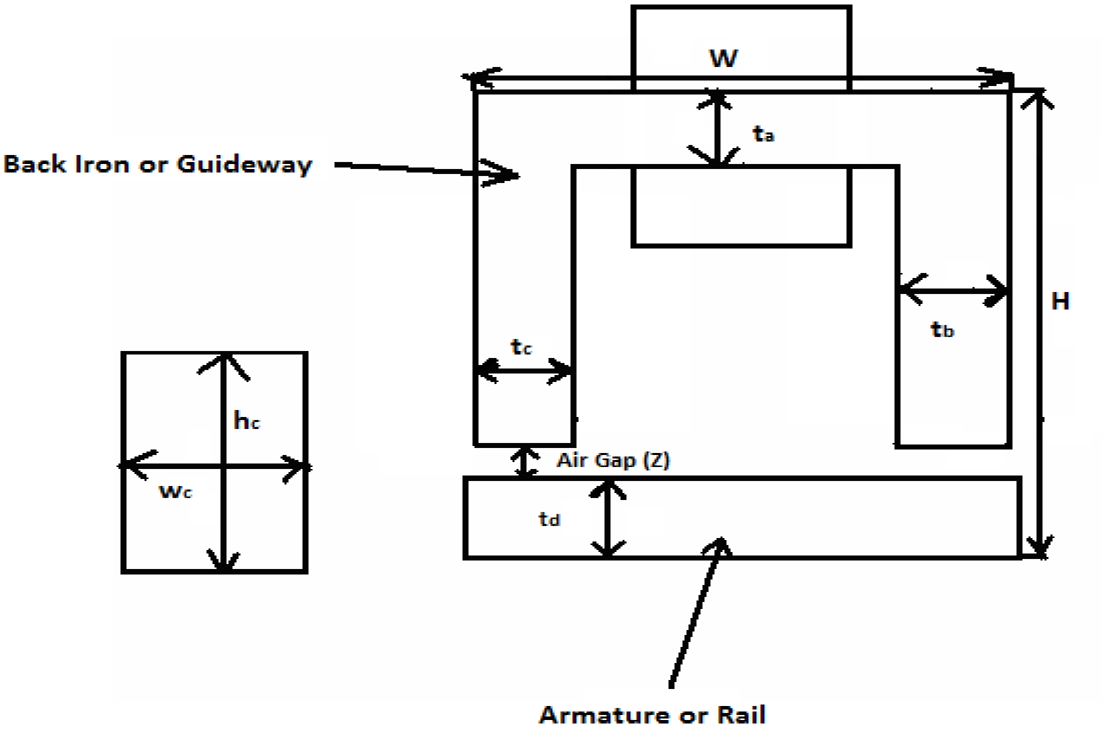

Figure 6. Basic diagram of U-I structure

3. ANSYS simulation results and discussions

There are lots of applications of electromagnetic levitation systems in industry; important among them is electromagnetically levitated vehicle system. In electromagnetically levitated vehicle and maglev train different configurations of rails and actuators are used. Two-dimensional FEM simulation has been carried out to determine flux pattern, working flux density, field intensity, force for U-type (actuator) and I-type (guide-way) structure varying air-gaps (5mm to 20mm) under similar operating condition. Commercial FEM software ANSYS has been used for this purpose. The ANSYS simulation plots of U-I structure at two different air-gap positions keeping other parameters constant are shown in Figure 7. to Figure 12. It has been noticed that the generated flux of the actuator decreases with the increase of air-gap between the pole-face of electromagnet and guide-rail. With the increase of air-gap the leakage as well as fringing flux is increased and the flux linkage between magnet and guide-way is decreased as Figure 15. It has been observed that for a large operating air-gap (more than 20 mm) the generated flux is almost constant and remain same of U-I type structure.With the increase of air-gap the flux density, field intensity and force of the levitated system have also been reduced (Figure 16 to Figure 18). The flux pattern for U-I structure during shifting of guide-way (both direction) has been observed in Figure 13-14. It is to be mentioned that the levitation force is maximum when the electromagnet is placed centrally with the guide-way, whereas the guidance force is zero. In the EMLS, other than levitation force, guidance force is also developed between actuator and rail. In ANSYS simulation both the guidance and levitation force is observed. In actual Maglev rail system there will be always a relative change in distance between guide-way and rail. Here the effect on levitation and guidance force with the shifting of rail (guide-way) has been studied through FEM analysis in Figure 19. It has been noticed (Figure 19) the levitation force is maximum when the electromagnet is placed centrally with the guide-way, whereas the guidance force is zero. The shifting of rail has been done both directions with respect to central position. With the change of rail position in either direction, the levitation force has been reduced and the guidance force has been increased.

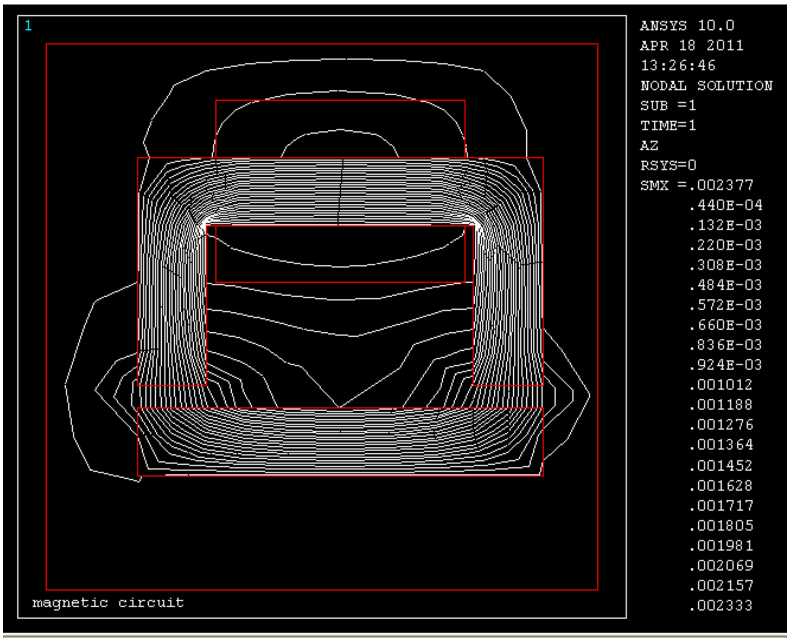

Figure 7. Flux pattern of U-I structure for No. of turn 154 and 0.5 cm air gap

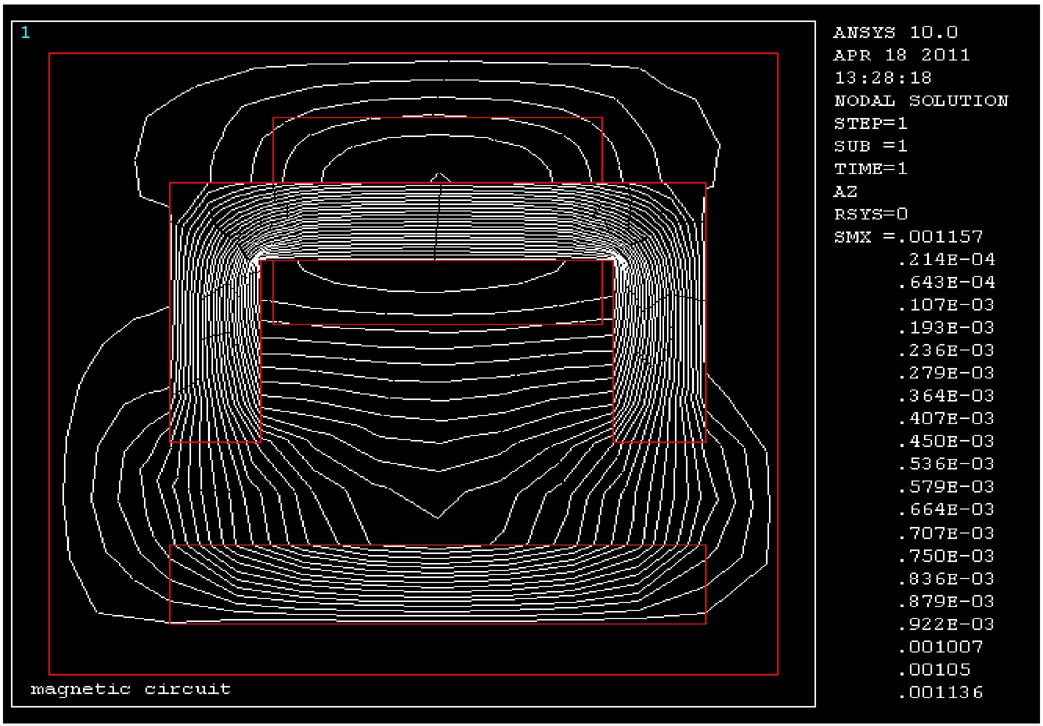

Figure 8. Flux pattern of U-I structure for No. of turn 154 and 2 cm air gap

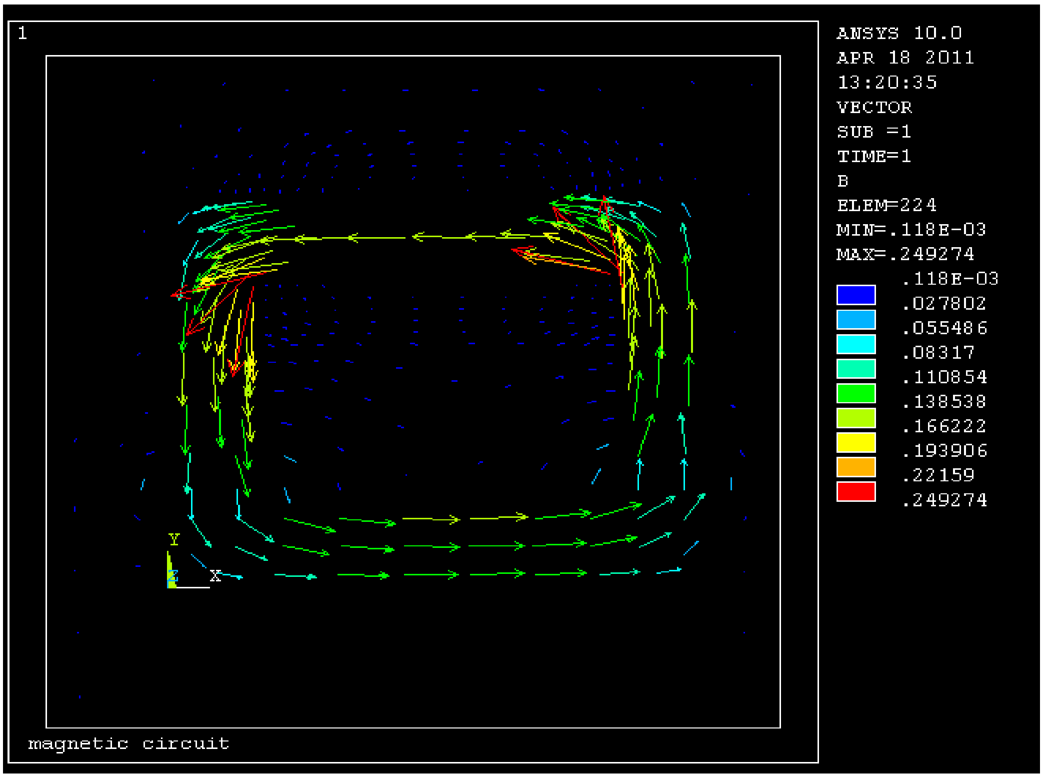

Figure 9. Flux density of U-I structure for No. of turn 154 and 0.5 cm air gap

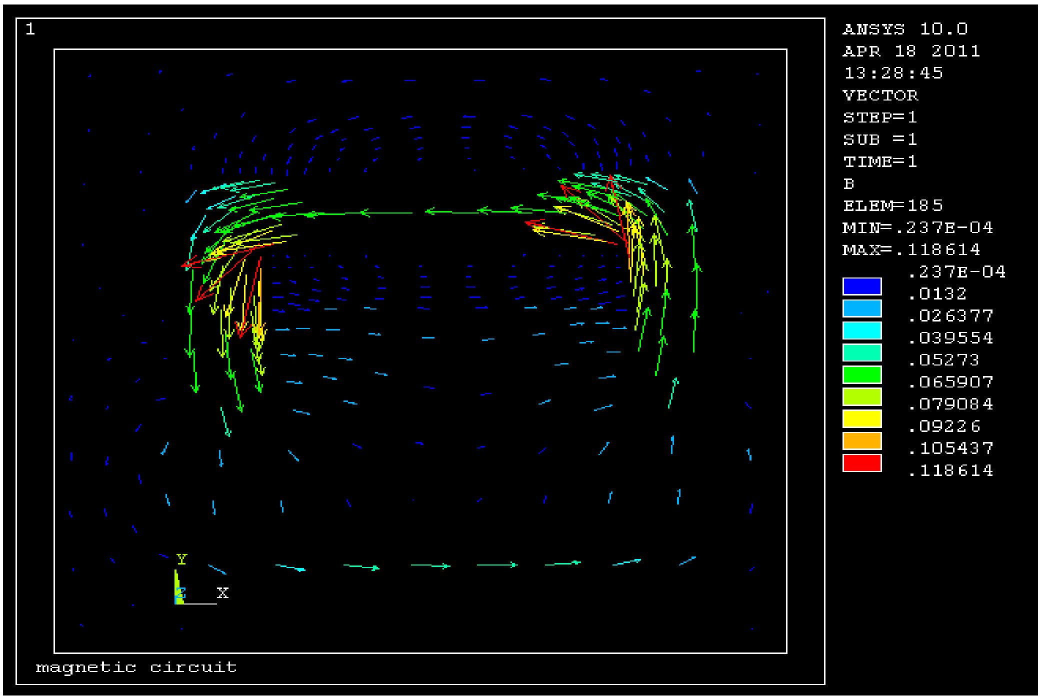

Figure 10. Flux density of U-I structure for No. of turn 154 and 2 cm air gap

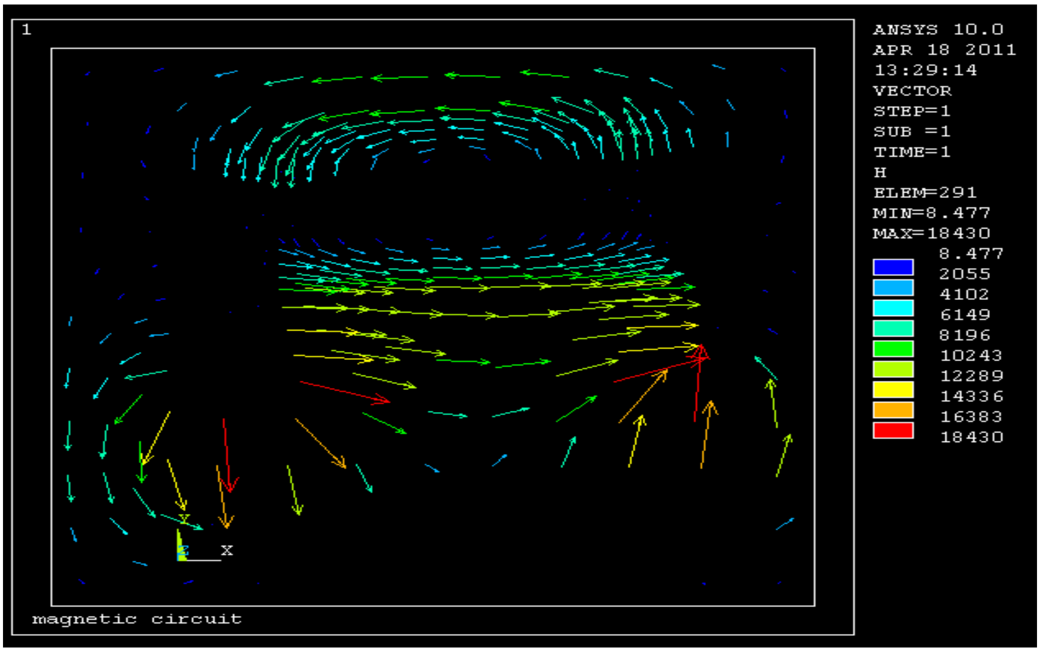

Figure 11. Field intensity of U-I structure for No. of turn 154 and 0.5 cm air gap

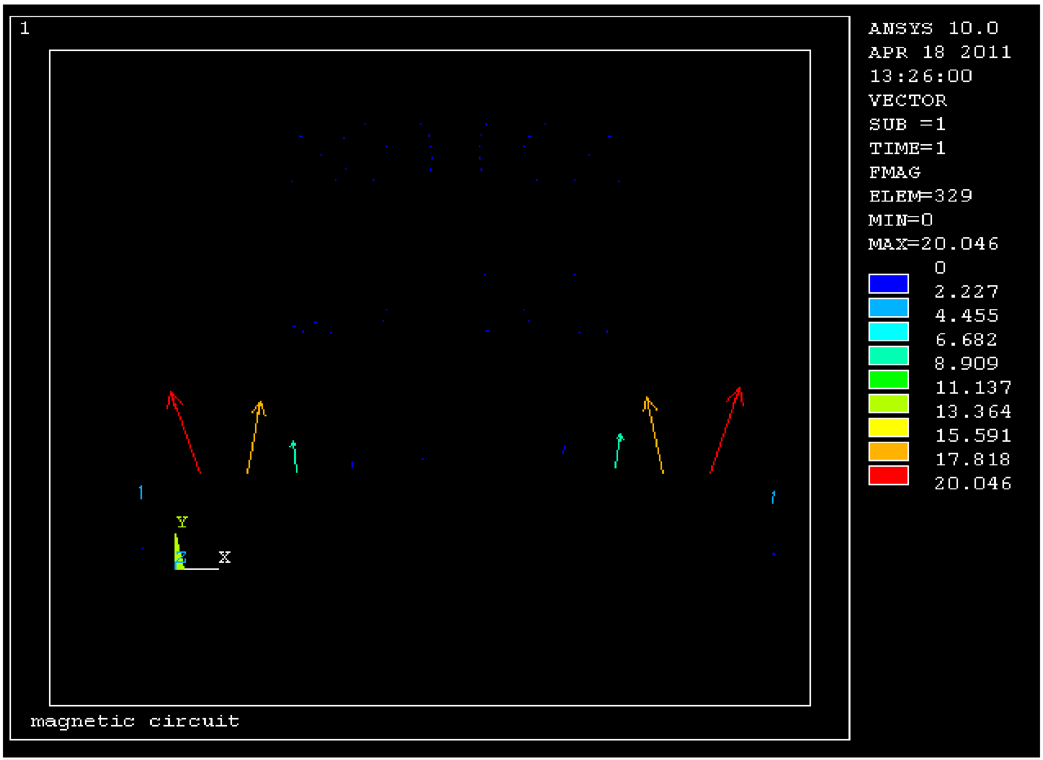

Figure 12. Force of U-I structure for No. of turn 154 and 0.5 cm air gap

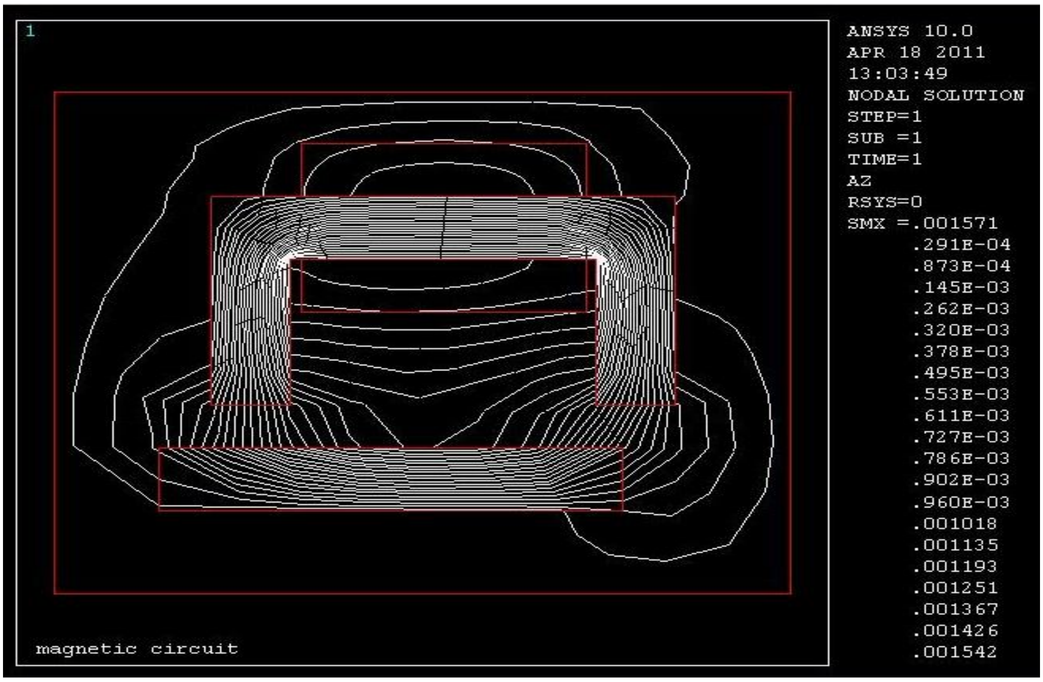

Figure 13. Flux pattern for U-I structure N=154, D=1cm and Z=1 cm for left shifting of object

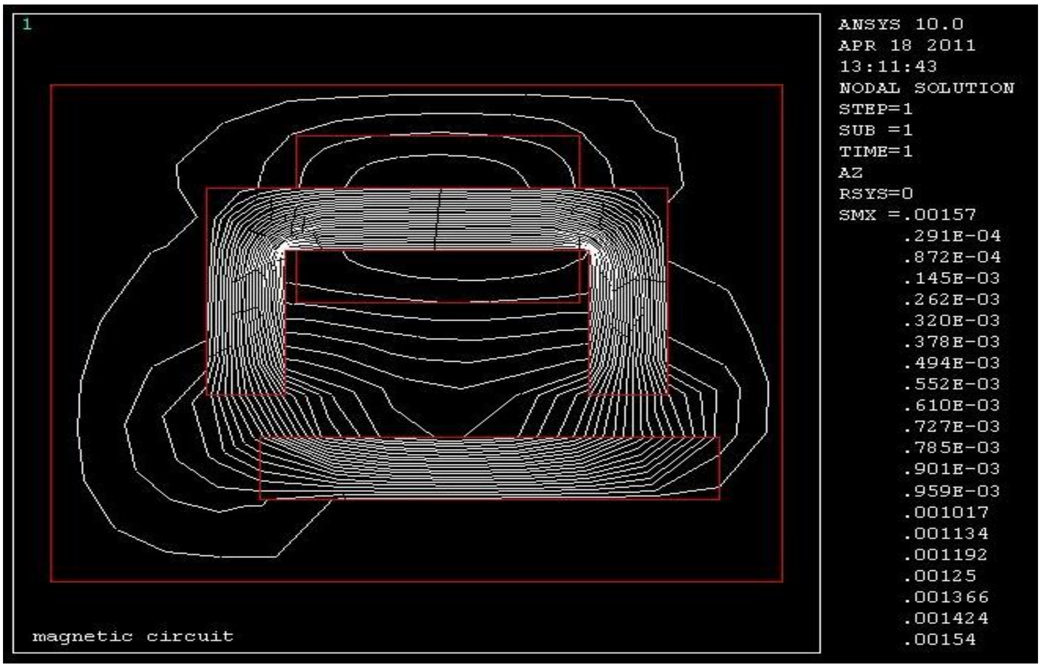

Figure 14. Flux pattern for U-I structure N=154, D=1cm and Z=1 cm for right shifting of object

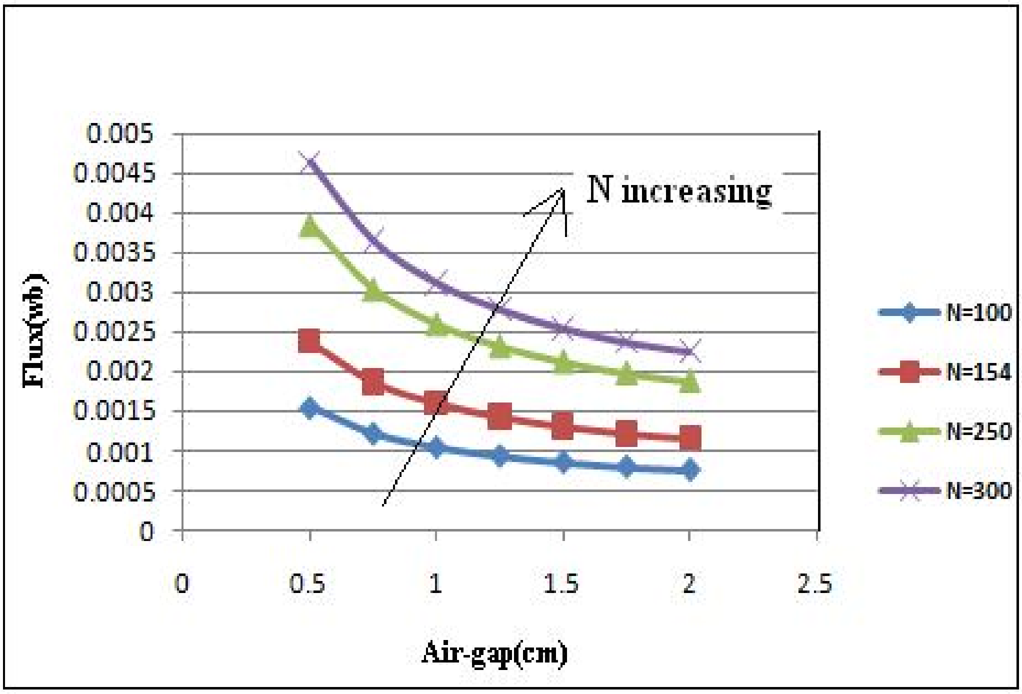

Figure 15. Magnetic flux (wb) vs. air gap (cm) for different number of turns of coil

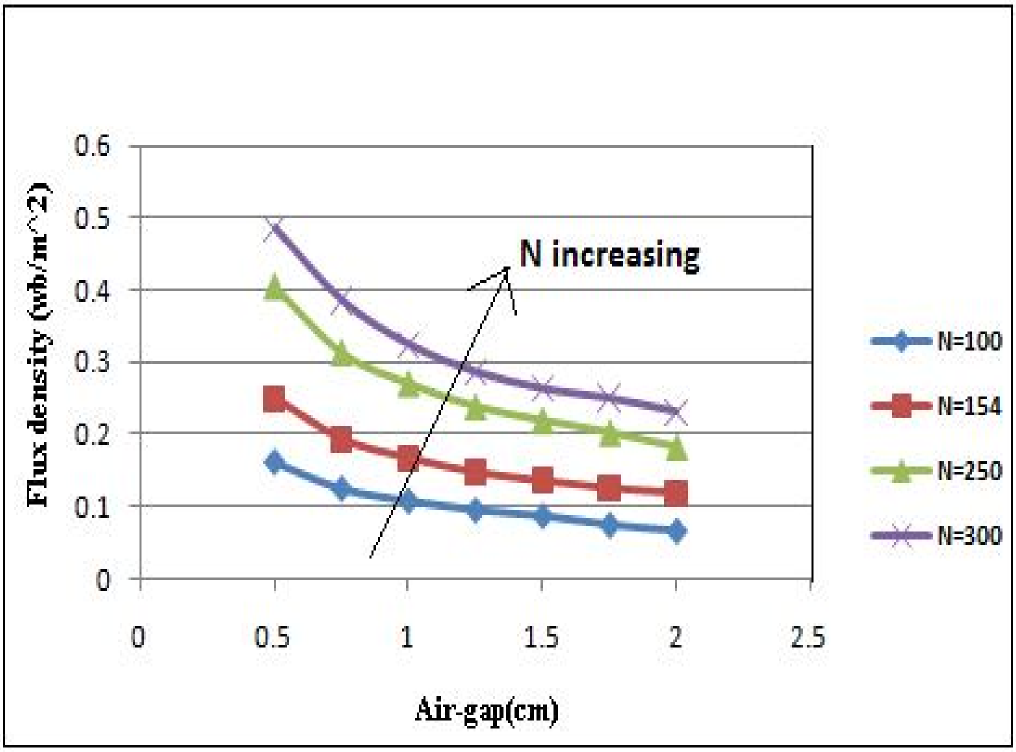

Figure 16. Magnetic flux density (wb/m2) vs. airgap (cm) for different number of turns of coil

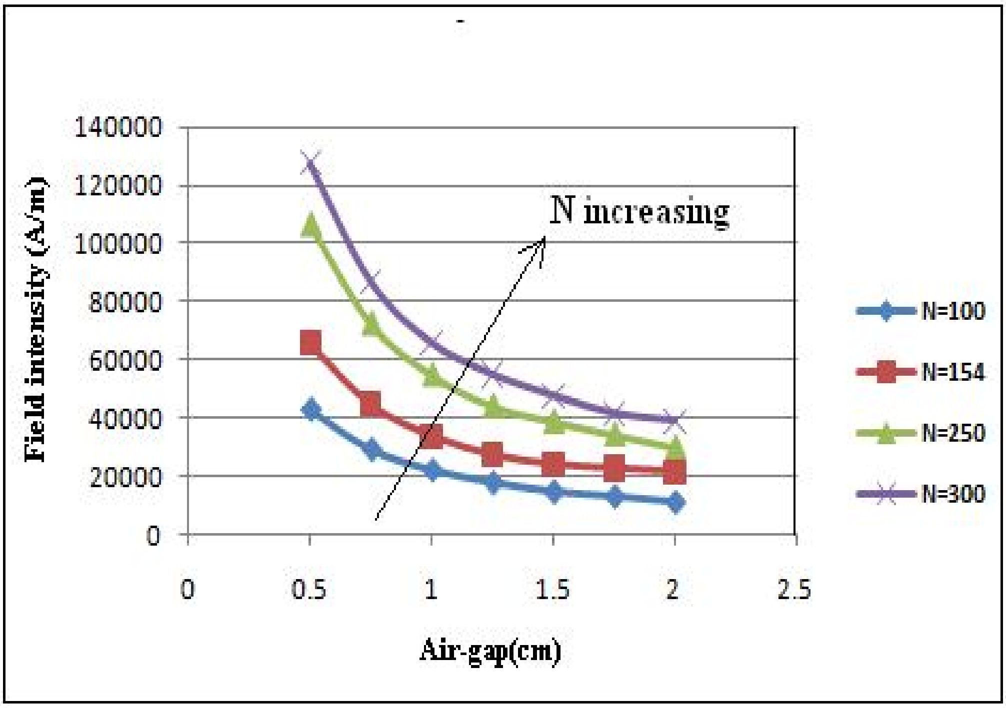

Figure 17. Magnetic field intensity (A/m) vs. air gap (cm) for different number of turns of coil

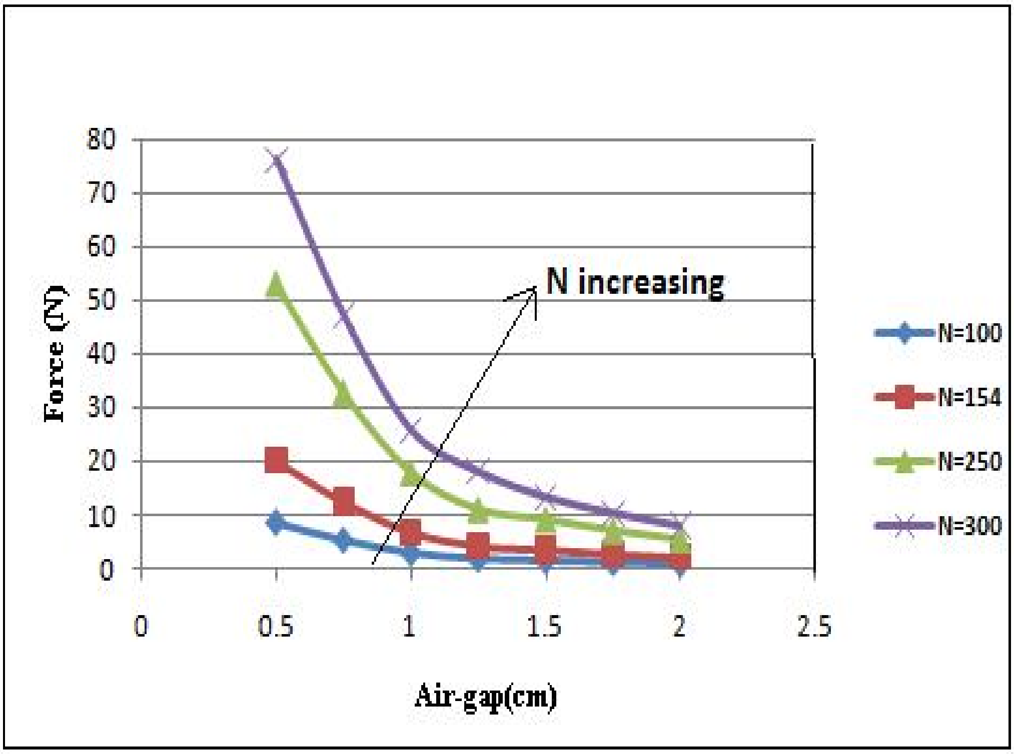

Figure 18. Magnetic force (N) vs. air gap (cm) for different number of turns of coil

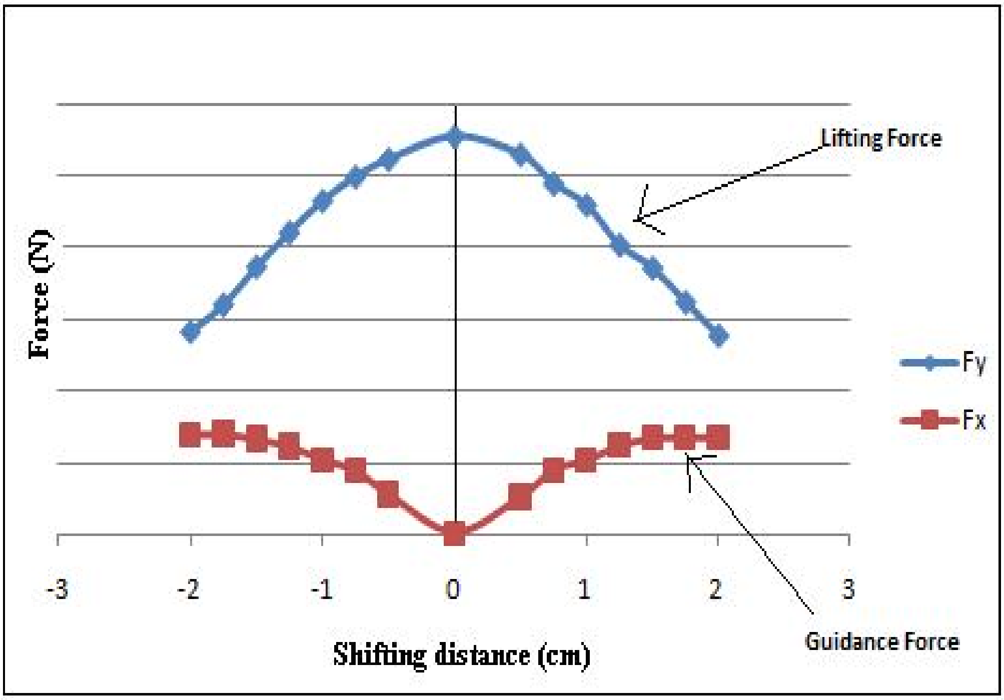

Figure 19. Variation of guidance force (Fx) and lifting force (Fy) with change in displacement (or shifting)

4. Conclusions

In this simulation of U-I structure of rail and actuator used in EMLS has been presented. A two dimensional FEM analysis has been carried out utilizing ANSYS software. The reduction of lift force due to eddy current effect very much depends on the magnet and guide-way geometry. Because of better lift force, a U-core magnet with a flat guide-way may be suitable for both low and high speed DC attraction type levitation systems. The effect of change with different parameters of rail and actuator on magnetic behaviour of levitation system has been studied. In the EMLS, other than levitation force, guidance force is also developed between actuator and rail. In ANSYS simulation both the guidance and levitation force is observed. In actual Maglev rail system there will be always a relative change in distance between guide-way and rail. Here the effect on levitation and guidance force with the shifting of rail (guide-way) has been studied through FEM analysis.

Acknowledgments

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