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ANSYS Simulation Based Comparative Study between Different Actuators and Guide-ways used in DC Electromagnetic Suspension Systems

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Abstract: Magnetic levitation is a popular topic of research over the years throughout the world due to its wide range of industrial applications. In any DC attraction type suspension system, actuator and guide-way (rail) plays most important role. In this manuscript FEM based analysis of different structures of actuator and rail (guide-way) has been carried out utilizing ANSYS software. Input power to lift power ratio and lift power magnet weight ratio are two major factors for designing actuator and rail in electromagnetic levitation system (EMLS) [1]. 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. There are various magnet and rail geometries; i.e. magnet with I, U and E profiles and various winding arrangements with flat and U-profile rail. A FEM analysis utilizing ANSYS software has done to find out the flux pattern, working flux density, field intensity, force etc. for different single actuator based levitation system at different operating conditions. Different aspects of rail and actuator have been described based on the ANSYS simulation results. The main objective is to propose a suitable configuration of actuator and guide-rail for a specific DC electromagnetic levitation system.

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

1. Introduction

The suspension of objects with no visible means of support due to magnetic force is termed as magnetic levitation or 'Maglev'. Magnetic Levitation has many fascinating applications; important among them are friction-less bearings, magnetically levitated (Maglev) trains, levitation of models in a wind tunnel, vibration isolation of sensitive machinery, levitation of molten metal in induction furnaces, levitation of metal slabs during manufacture etc.

Levitation using magnetic force is based on two different principles: attraction (or electromagnetic attraction) and repulsion (or electro-dynamic repulsion). The electromagnetic levitation system (EMLS), uses the high-power solid-state controls to regulate the current in an ordinary direct-current electromagnet, and achieves stability through active feedback. Such systems are common in most of the maglev trains where the magnets used for levitation ride below a fixed iron rail and use the attraction force for suspension of trains.

The second approach, the electro-dynamic levitation system (EDLS), generally uses high speed super-conducting magnets that are mounted on the bottom of the moving vehicle and produces the repulsive force due to eddy currents produced in the aluminum guide ways. One of the main constraints of the superconducting repulsion principle is that it cannot provide suspension force below some critical speed [1, 3]. The electrodynamics levitation system is inherently stable, but at high speed it possess stability problem due to negative damping [2]. So

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some kind of passive damper is required in elctrodynamically levitated vehicle to maintain stability at high speed. In electromagnetic system, the levitation is produced due to the attractive force between electromagnets and ferromagnetic objects.

The attraction type levitation system is simpler, relatively cheaper and has been chosen as the subject of present study. In EMLS the electromagnets are driven either by AC or DC source. Although several experimental systems using AC sources [1] have been built, these methods are considered to be suited for applications where mass of the suspended object is small. 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 DC electromagnetic levitation system (EMLS) [1, 9], 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.
EMLS requires two necessary subsystems: (i) a primary system for generating the magnetic field and (ii) a system for shaping or trapping the magnetic flux [1-3]. 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 as shown in Fig.1. Alternatively, the scheme is just inverted and the electromagnet is part of the levitated object under a fixed ferromagnetic guide-way (Figure 2). The electromagnet (actuator) and guide-way (rail) combination along with associated closed loop control will make an EMLS (Fig.3). In the Fig.2 the electromagnet is made to remain suspended under the fixed ferromagnetic guide-way. This configuration is normally used in electromagnetically levitated vehicle [10] and maglev train. The electromagnet acts as an 'actuator' which provides the basic suspension force. When the electric current is passed through a wire wrapped around a core of ferromagnetic material, magnetic flux is generated. This flux produces an attractive force on any nearby ferromagnetic material. Assuming idle condition, the magnetic force produced by the coil shown in Fig.1 can be written as [1, 2].

$$F(i,z) = \frac{\mu_0 N^2 A}{4}\left[\frac{i(t)}{z(t)}\right]^2 \tag{1}$$

Where, N = No of turns of the coil, A = Magnet pole-face area, i(t) = Instantaneous current through the coil, z(t) = Distance between the pole-face of the magnet and ferromagnetic object.
The two factors (i) input power to lift power ratio and (ii) lift power to magnet weight ratio greatly influences the design of actuator for a DC EMLS. Some important parameters like air-gap flux, magnet dimension, winding arrangement, and current density in the winding dictates the above two factors. The magnet configuration is selected on the basis of required pole face area and the necessary window area to house the excitation coils [1, 7]. There are various magnet and rail geometries; i.e., magnet with U and E profiles and various winding arrangements with flat and U-profile rails as shown in Figure 4 [4, 5]. The eddy current will generate in the magnet core as well as in the solid guide-ways and it will be different for the different structures of magnet and guide-way. This eddy current will reduce the lift force. Laminated core structure is a better option as far as eddy current losses and faster response time of the magnet are concerned [4, 5]. Another important variable that will have a direct effect on the dynamic characteristics of EMLS is the time-constant of the magnet-coil. The inductance of the coil under some simplifying assumptions is given by the equation (2).

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

From the equation (2) 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].

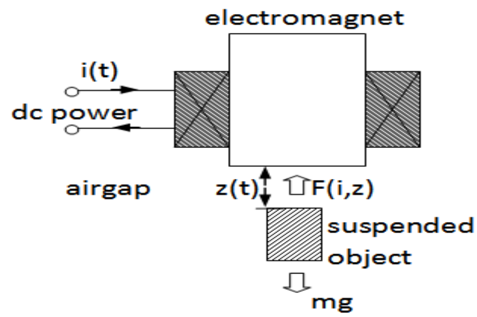

Figure 1. Simplified diagram of DC electromagnetic levitation system

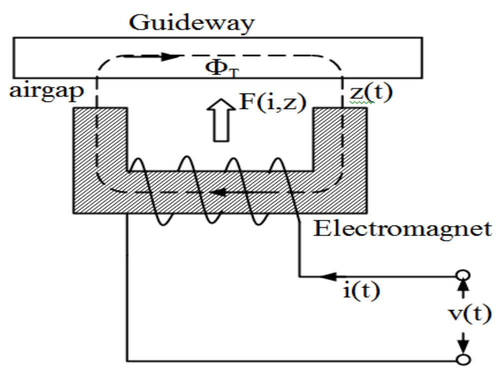

Figure 2. Simplified diagram of DC electromagnetic levitation system (inverted model)

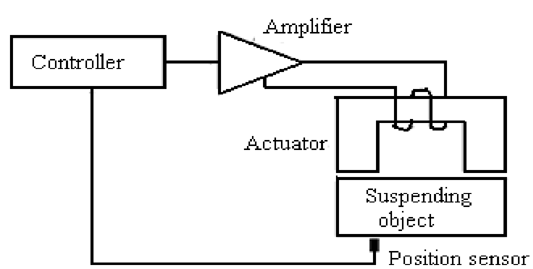

Figure 3. Basic block diagram of DC Electromagnetic levitation system

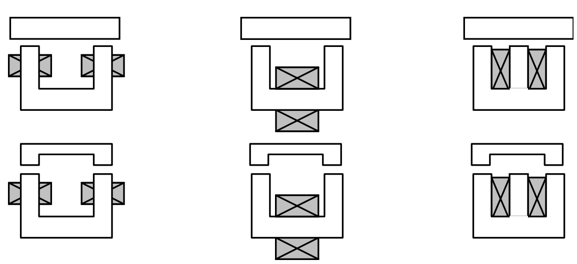

Figure 4. Different configurations of suspension systems

2. Finite Element Method (FEM) analyses

The arrangement is working on DC that is why a static magnetic field problem has been analyzed by the Finite Element Method (FEM). The static magnetic field problem can be described by the following Maxwell's equations [8]

$$\nabla X H = J \tag{3}$$

$$\nabla . B = 0 \tag{4}$$

$$\nabla . J = 0 \tag{5}$$

$$H = \frac{B}{\mu} \tag{6}$$

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 2D and 3D problem has been solved by FEM applying the ANSYS Multi-physics software.

The basic laws of such fields are Ampere's law:

$$\int H.dl = \int J.dS \tag{7}$$

Where dS are the surface element and dl is the length element. The law of conservation of magnetic flux (also called Gauss's law for magneto statics) is given as:

$$\int B.dS = 0 \tag{8}$$

Where H is the magnetic field intensity (in amperes/meter), J is the electric current density (in amperes/meter2) and B is the magnetic flux density (in tesla or Wb/meter^2). The differential forms of equation (3) and (4) are obtained as:

$$\nabla X H = J \tag{9}$$

and,

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

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

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

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

$$B = \nabla X A \tag{12}$$

Applying the vector identity for an arbitrary vector F

$$\nabla X (\nabla X F) = \nabla(\nabla . F) - \nabla^2 F \tag{13}$$

To Eqns. (3) and (6) leads to Poisson's equation for magneto static fields:

$$\nabla^2 A = \mu J \tag{14}$$

When J = 0, Eq. (14) becomes Laplace's equation:

$$\nabla^2 A = 0 \tag{15}$$

In the absence of currents (J = 0), the magnetic flux density H can be expressed in term of magnetic scalar potential V_m (in amperes/meter) as:

$$H = -\nabla V_m \tag{16}$$

The use of magnetic scalar potential reduces the three components of magnetic field H into one component V_m making computations easier and more time efficient. Appling Eq. (9) on Eq.(16) yields:

$$-\nabla X \nabla V_m = 0 \tag{17}$$

Equations (12), (14), (16) and (17) are useful tools in calculation of magnetic field in magneto static cases [8]. The magnetic field will be used in the calculation of magnetic force experienced by the levitated object in EMLS.

3. FEM analysis and ANSYS simulation for the proposed system

The finite element method (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 [6]. 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. The Finite Element Method is a good choice for solving partial differential equations over complicated domains, when the domain changes, when the desired precision varies over the entire domain, or when the solution lacks smoothness.

ANSYS is engineering simulation software that has many finite-element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis. The analysis guides in the ANSYS documentation set describe specific procedures for performing analyses for different engineering disciplines [6]. ANSYS Mechanical and ANSYS Multi-physics software are non exportable analysis tools incorporating pre-processing (geometry creation, meshing), solver and post-processing modules in a graphical user interface. These are general-purpose finite element modeling packages for numerically solving mechanical problems, including static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems [6].

Electromagnetic simulation from ANSYS provides industry leading analysis tools that enable the accurate simulation of electromagnetic fields. ANSYS electromagnetic solutions enable engineers and designers to accurately predict the behaviour of electrical and electromechanical devices [6,7]. The ANSYS electromagnetic product suite contains both general purpose and application specific products to address a broad array of industry applications.

The flowchart for the ANSYS simulation procedure for the proposed system is shown in Figure 5.

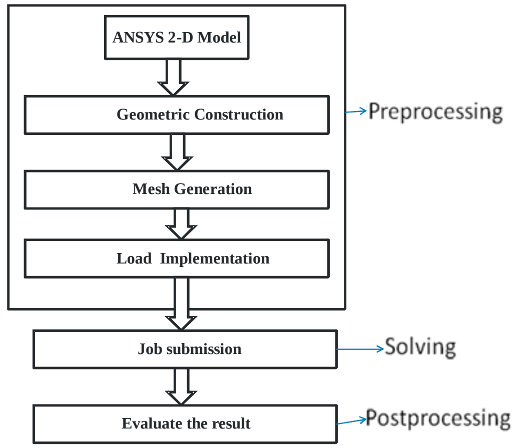

Figure 5. Flow chart for ANSYS simulation

4. Simulation Results & Discussion

Two-dimensional FEM simulation [11-13] has been carried out to determine flux pattern, working flux density, field intensity, force etc. for different structures of actuator and rail (Figure 4) Commercial FEM software ANSYS (version 12.1)has been used for this purpose. The field flux plots of different structures with air-gap of 0.5 cm are shown in Figure6 to Figure12. It has been observed that the generated flux is maximum for U-I structure and minimum for E-U structure irrespective of any air-gap. Figure12 shows flux pattern of U-I structure for 20 mm air-gap. From Figure6 and Figure12, it is clear that for any model with the increase of air-gap the generated flux reduces due to increase of leakage and fringing.

Figure 19 shows the generated flux vs. air-gap curve for six different structures as described earlier. 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 (Figure6 and Figure12) leakage flux as well as fringing is increased and the flux linkage between magnet and guide-way is decreased. Irrespective of any air-gap position the generated flux is maximum for U-I (with lower winding) structure and it is minimum in E-U structure. It has been observed that for a large operating air-gap (more than 20 mm) the generated flux is almost constant and remain same irrespective of any structure.

It has been noticed that the attractive force developed between actuator and guide-way has been decreased with the increase of air-gap (Figure13 and 14). In actual situation the force between electromagnet and rail will vary inversely proportion to the square of the air-gap. Due to this inherent force-distance characteristics one of the pole of the maglev model lies on the right half of ‘s’ plane and system becomes unstable. For closed loop stability, the force-distance characteristics have to be modified so that with the change with air-gap the required force will vary linearly. It may be seen the maximum attractive force is developed in the air-gap. Since in the present configuration the actuator is fixed and armature is movable the net acting force is downwards. With the increase of air-gap the flux density and field intensity of the levitated system have also been reduced. The direction of flux density is clear from the Figure 15 and Figure 16. As expected the flux density is more in the inner surface than the outer surface. The field intensity is mostly concentrated in the air-gap. Figure 21 shows the variation of field intensity with the change of air-gap for different rails and actuators. The pattern of flux, flux density, field intensity, force for other different structures (shown in Figure 4) are similar for U-I structure and have not been reproduced here.

For the same dimension of electromagnet and rail, it has been observed (Figure20) that any operating condition the lift force developed between the U-I structure (U-core magnet and flat guide-way) is more than the U-U structure and E-I structure . But the guidance force developed is more in U-U structure. 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. It has been noticed (Figure22-23) 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. The flux pattern for U-I structure during shifting of guide-way (both direction) has been observed in Figure17-18.

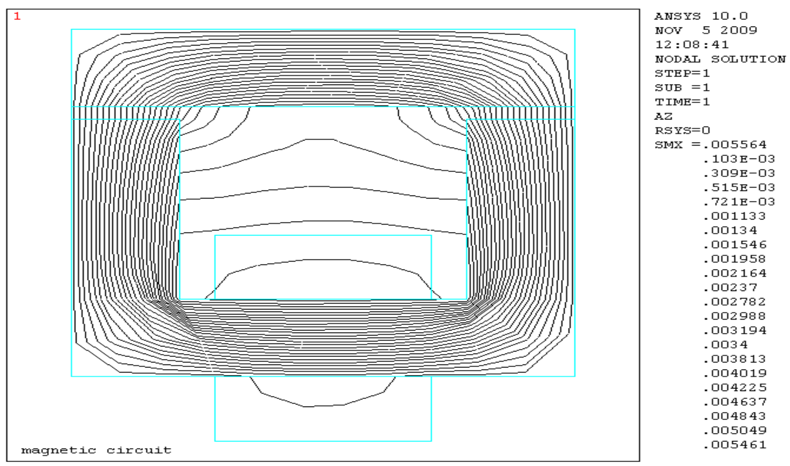

Figure 6. Flux pattern of U-I structure for 5mm air-gap

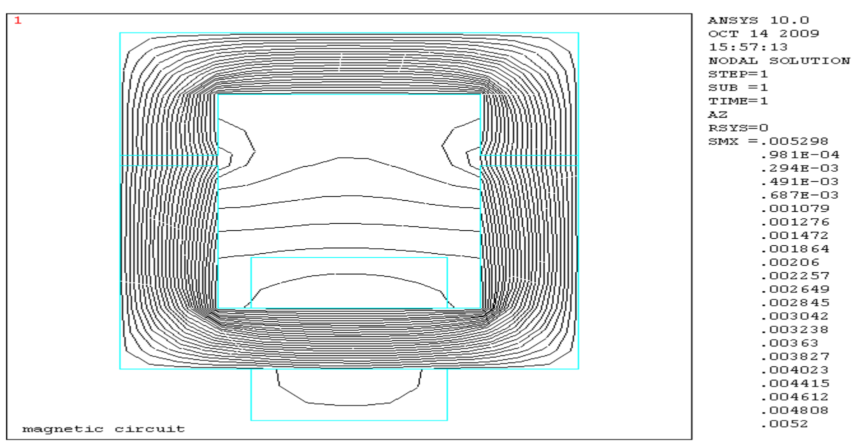

Figure 7. Flux pattern of U-U structure for 5mm air-gap

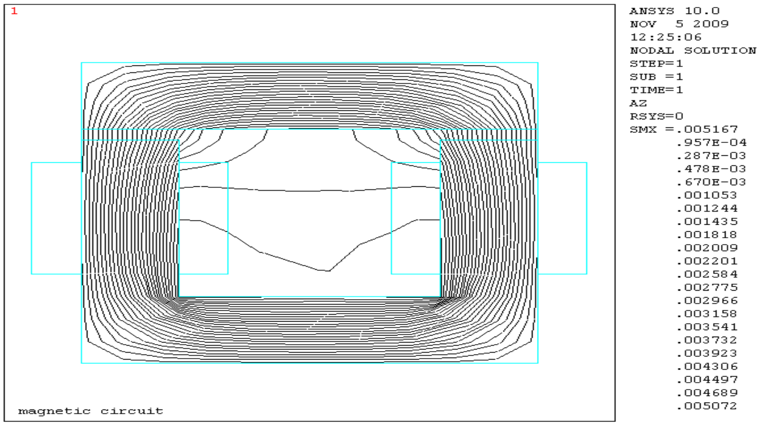

Figure 8. Flux pattern of U-I structure with two coils (upper side) for 5mm air-gap

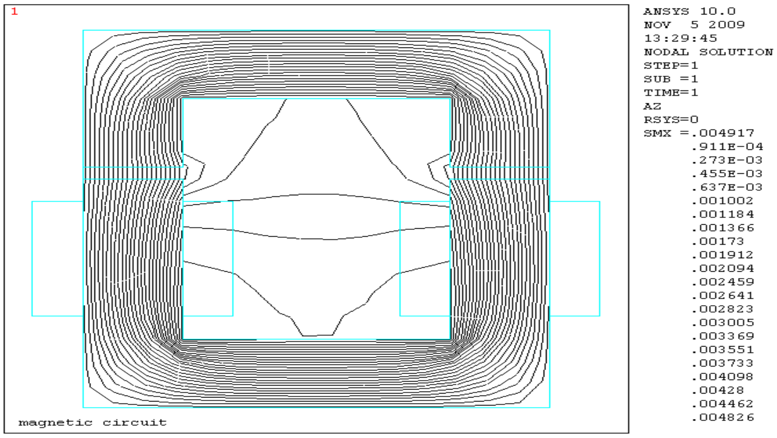

Figure 9. Flux pattern of U-U structure with two coils (upper side) for 5mm air-gap

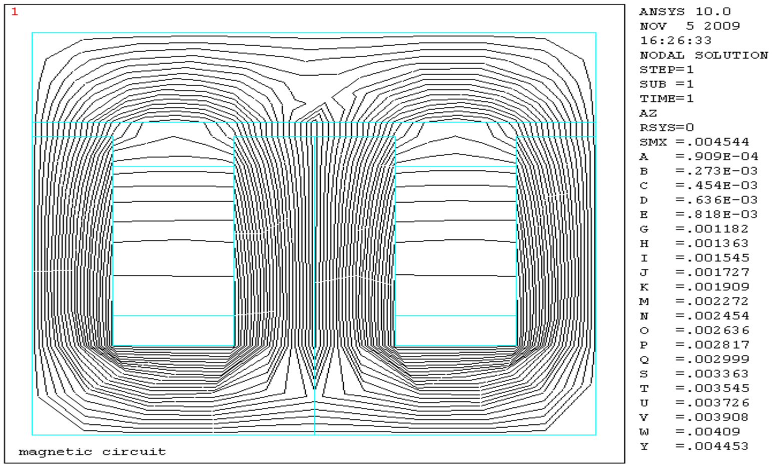

Figure 10. Flux pattern of E-I structure with single coil for 5mm air-gap

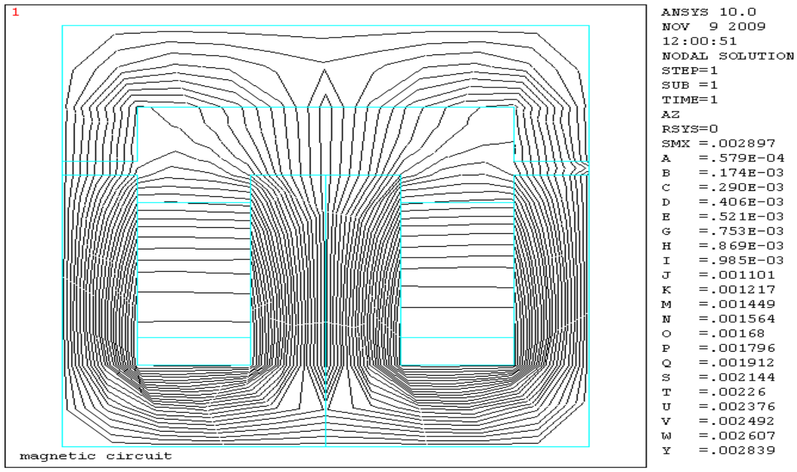

Figure 11. Flux pattern of E-U structure with single coil for 5mm air-gap

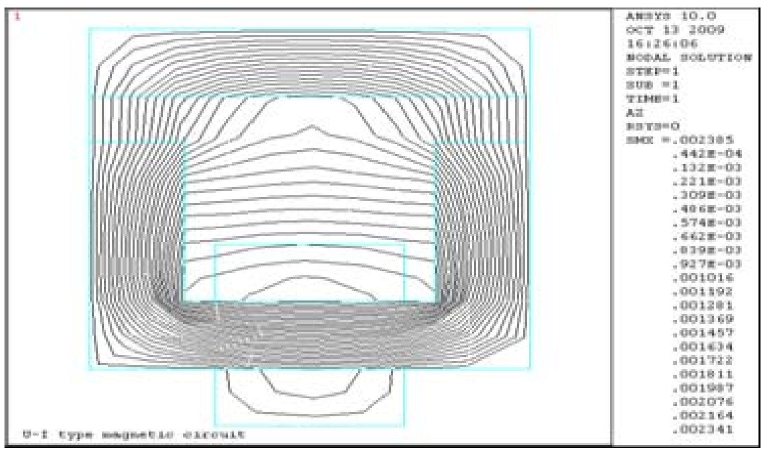

Figure 12. Flux pattern of U-I structure for 20 mm air-gap

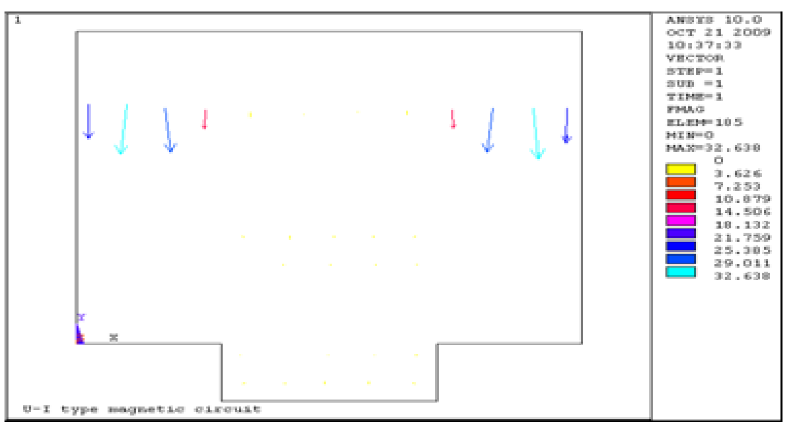

Figure 13. Force for U-I structure for 5 mm air-gap

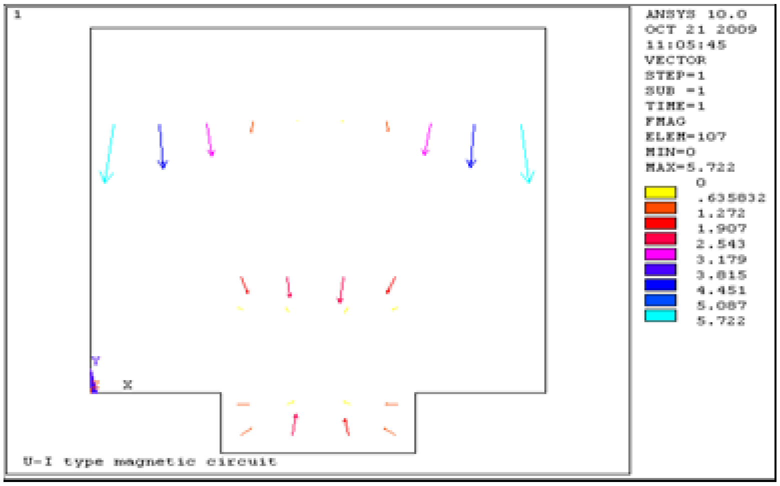

Figure 14. Force for U-I structure for 20 mm air-gap

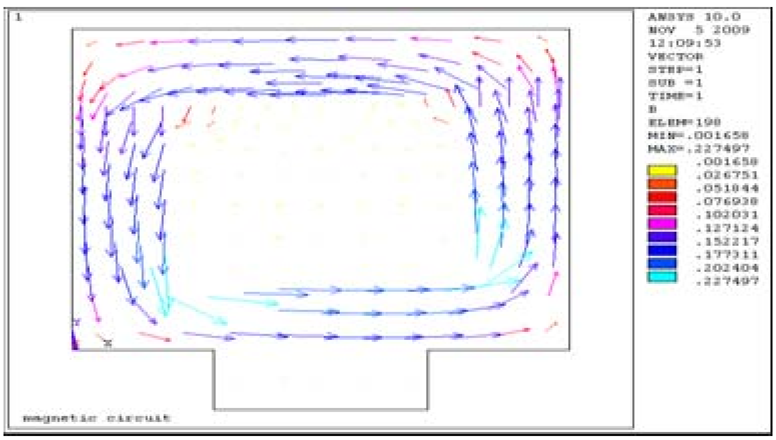

Figure 15. Flux density for U-I structure for 5 mm air-gap

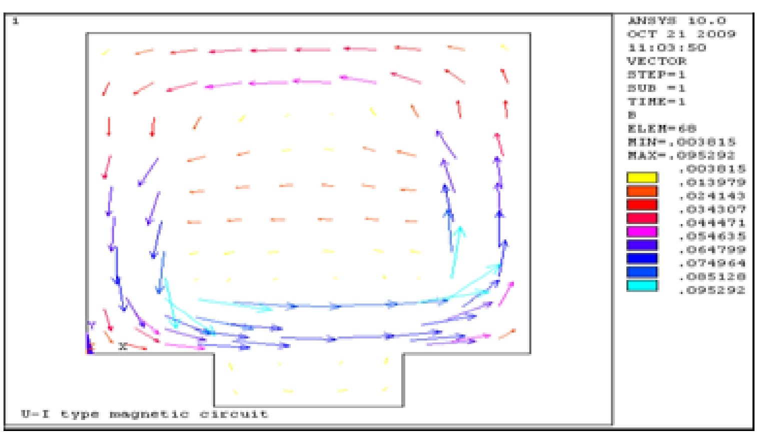

Figure 16. Flux density for U-I structure for 20 mm air-gap

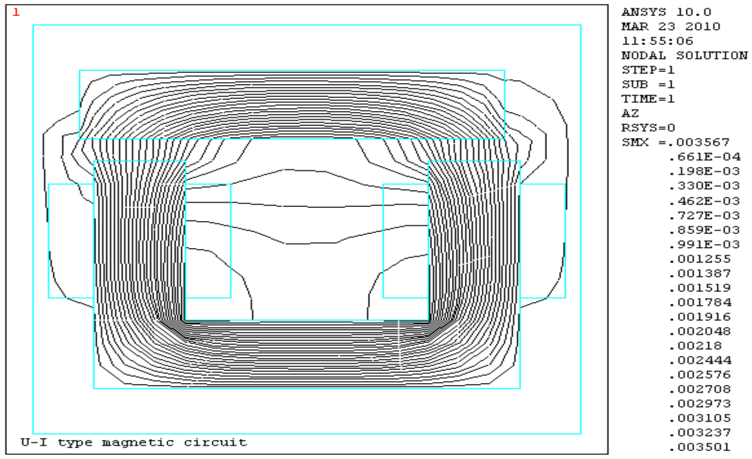

Figure 17. Flux for U-I structure where z=10 mm, x=5 mm (-ve shifting)

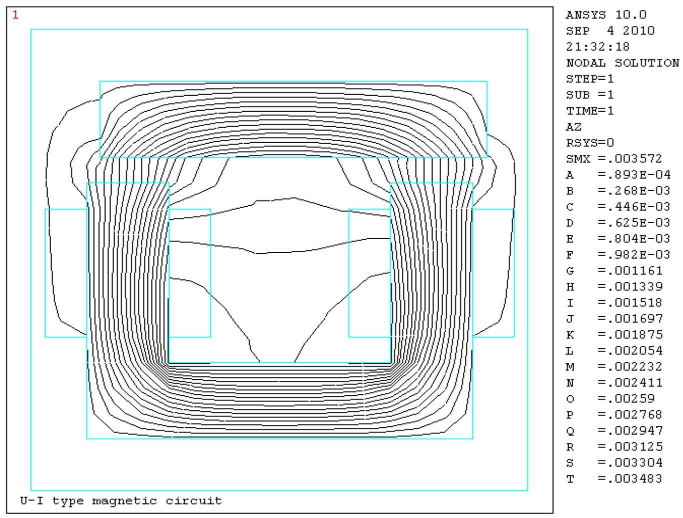

Figure 18. Flux for U-I structure where z=10 mm, x=5 mm (+ve shifting)

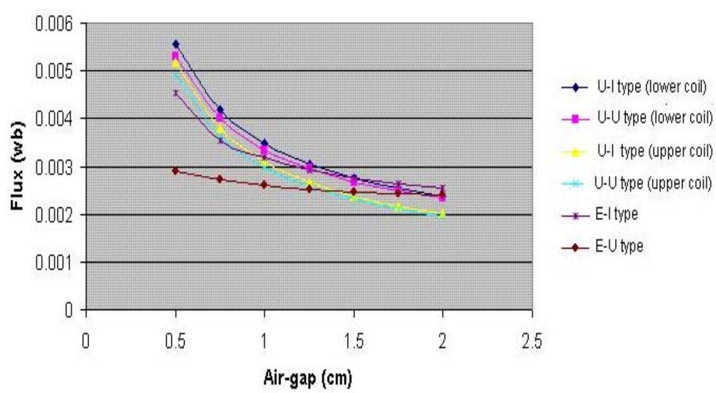

Figure 19. Flux vs. air gap curve for different structures for different air-gap

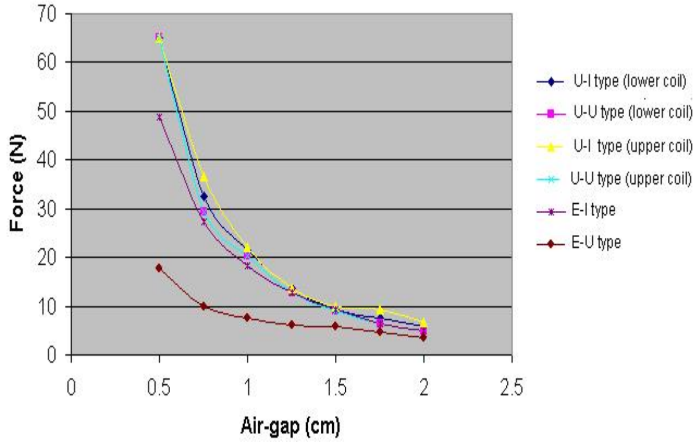

Figure 20. Force vs. air gap curve for different structures for different air-gap.

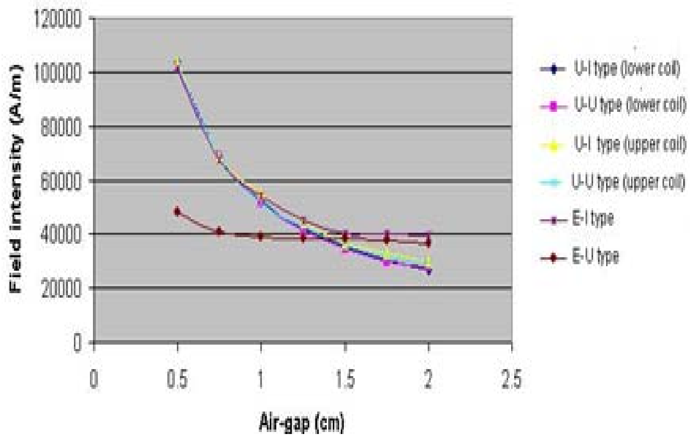

Figure 21. Field intensity vs. Air-gap of different structures

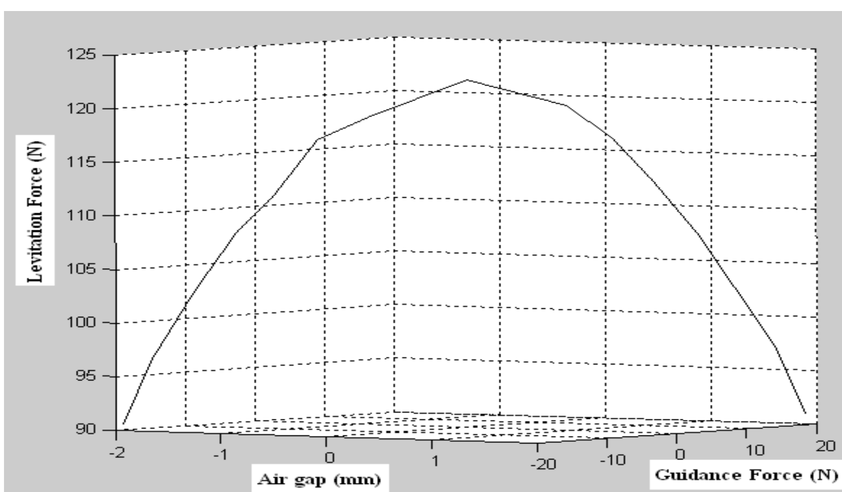

Figure 22. Levitation and guidance force vs. shifted distance (3D) for U-I structure

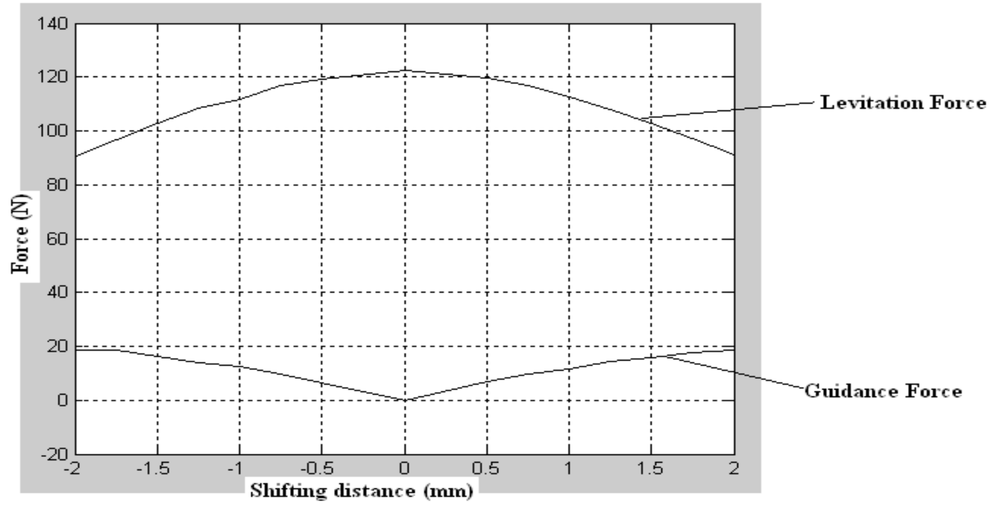

Figure 23. Levitation and guidance force vs. shifted distance (2D) for U-I structure

5. Conclusions

A comparative study between different structures of rail and actuator used in EMLS has been presented. A two dimensional FEM analysis has been carried out utilizing ANSYS software.

Different structures of electromagnet and guide-way and their relative advantages and disadvantages have been discussed. 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. This idea will be utilized for the design and fabrication of electromagnetically levitated vehicle as a future extension of work. The effect of shifting of guide-way (rail) on levitation and guidance force has also been studied.

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