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(Full length research article)

Analysis of Multi-Magnet Based DC Electromagnetic Levitation System using ANSYS Simulation Software

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Abstract

In this paper an overview of finite element analysis for multi-magnet based DC electromagnetic levitation system has been presented. The proposed multi-magnet based single axis levitation scheme has been described. This paper reports ANSYS software based simulation of an electro magnetically levitated platform (vehicle structure) that uses three attraction type magnets fixed at the three corners of the platform. The magnet configurations chosen on the basis of required pole-face area and necessary window area to house the excitation coils. FEM based analysis has done to find out the flux pattern, working flux density, field intensity, force etc. for three actuators based levitation system at different condition. . The effect of different parameters like coil-current, no of turns of coil has been studied.

***Keywords**: Electromagnetic levitation, Multi-magnet system, FEM analysis, ANSYS software, flux pattern and force.*

1. Introduction

Magnetic levitation which has no contact between the moving object and fixed part is one of the good tools for a micro-machine because mechanical friction disappears, which increases the resolution and accuracy of the positioning device. A magnetic levitation system has another advantage that the manipulator can operate as a rigid body rather than using jointed parts such as robots, which means that position errors do not compound and the dynamic behavior is simple to model [1, 2]. In addition, the system is compatible with clean room operation due to frictionless movement. The major disadvantage of levitation is that the system is inherently unstable, and hence feedback control is usually required for stabilization.

Magnetic levitation systems are widely used in various fields such as frictionless bearings, high-speed maglev passenger trains, levitation of wind tunnel models etc., and it is an important task to construct a high performance feedback controller to control the position of the levitated object since a magnetic levitation system is usually unstable in the case of open-loop. Since the-electromagnetic force is a strongly nonlinear function associated with the coil current and the air gap length, the control problem is usually quite complicated. Advances in control electronics and superconducting materials have also contributed to further research in the area of electromagnetic levitation. Based on the basic principle, magnetic levitation may broadly be classified into two types, electrodynamic levitation and electromagnetic levitation [1]. The electrodynamic system actuates through repulsive forces. Most of such systems utilize superconducting magnets to generate the forces. In electromagnetic system, the levitation is produced due to the attractive force between electromagnets and ferromagnetic objects. In electromagnetic levitation (attraction system), the electromagnets are driven either by AC or DC source [1, 2]. Although several experimental systems using AC sources 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 [2]. In contrast, the explicit DC method, technically known as the DC electromagnetic levitation system (EMLS) [1,3], 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. In case of DC electromagnetic levitation, electric current

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in a wire wound coil produces the primary field while the ferromagnetic object or guide-way creates a means of shaping the magnetic flux. The electromagnet (actuator) and guide-way (rail) combination along with associated closed loop control will make an EMLS. 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. 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 [2].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. The three magnet-coils used in this work are identical to each other, having almost the same mechanical and electrical parameters. Assuming a uniform distribution of the load, the upward lift force to be generated by each magnet is same weight, and this leads to the magnet parameters being derived by the technique used in single magnet levitation.

Assuming all the flux generated by the electromagnet passes through the ferromagnetic guide-way, the instantaneous coil inductance may be expressed as

$$L(z) = \frac{N}{i(t)}\phi_T = \frac{N^2}{R_T} \tag{1}$$

Where, N = No of turns of the coil,
$i(t)$ = Instantaneous current through the coil,
Φ_T = Total flux in the magnetic circuit,
R_T = Reluctance of the entire magnetic circuit.

If the reluctance of the magnetic core is assumed to be negligible when compared to the two air gaps, we have

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

At any instant of time, the force of attraction between the electromagnet and the ferromagnetic rail is given by

$$F(i,z) = -\frac{d}{dz}\left[\frac{1}{2}L(z)i(t)^2\right] \tag{3}$$

Now putting the inductance value from Eq. (2) into the force equation (3), one can write:

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

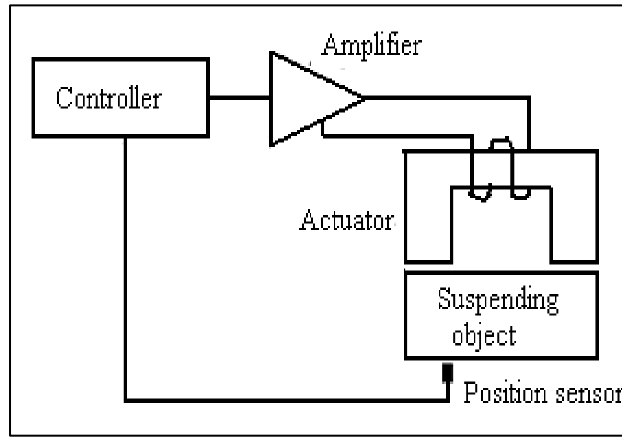

Fig.1.Basic block diagram of DC Electromagnetic levitation system

Description of proposed Multimagnet based single axis Levitation system

Though the single magnet, single axis levitation scheme may be useful for some industrial applications, majority of the applications require multi-axis levitation control where one may need to use a multiple-magnet based levitation system. This paper reports ANSYS simulation of an electro magnetically levitated platform [6] that uses three attraction type magnets fixed at the three corners of an equilateral triangle of the platform. Three attraction type (U-I structure) magnets fixed in same distance from each and other at the three corners of the platform for the stable levitation around 10 mm air-gap is shown in Fig.2. The overall structure of the electromagnetically levitated vehicle may consist of independent levitation, guidance and propulsion systems. However, this work considers only the single axis magnetic levitation part. The prototype consists of three identical electromagnets placed at the three corners of an equilateral triangle (Fig.2) and the structure is made to remain suspended at different air-gap positions under a ferromagnetic guide-way - the arrangement that is normally used for electromagnetic MAGLEV system. The minimum number of actuators required to levitate such a platform is three, but more than three actuators may be used for better reliability. In each case the current of the electromagnet is controlled through a single switch based DC to DC switched mode chopper circuit utilizing an outer position control loop and an inner current feedback control loop as shown in the block diagram of Fig. 1. In this work, a U-core type magnet and flat guide-way have been chosen, for a better lift /drag ratio [3]. The laminated rail and magnet-core is advantageous not only in reducing the magnetic drag force caused by eddy currents in the iron rail, but also to make a quicker control response of the air-gap between the magnet and the rail. For simplicity and rigidity in the structure, a solid iron rail and core have been used.

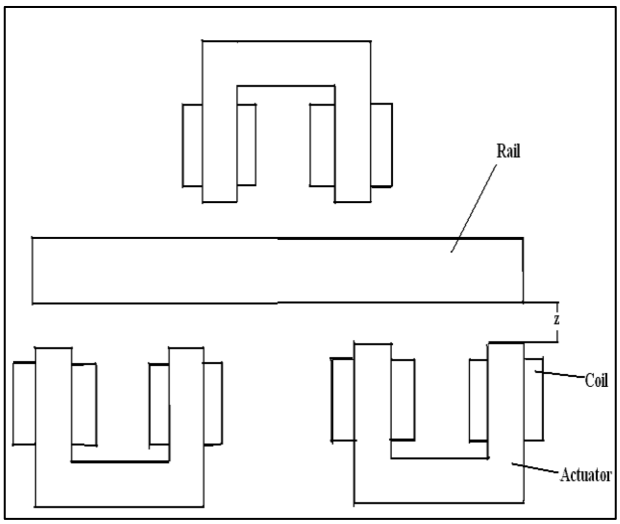

Fig.2. Basic structure of Multi-magnet

Finite Element Analysis and ANSYS Simulation for Multi-Magnet Levitation 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. 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 [6,7]. The finite element method (FEM) as a tool for solution of magneto static problems. In this method, the solution region is discretized into simple geometric shapes called finite elements. For each element, a stiffness matrix is calculated so as to relate the material properties and applied loads to the values at the nodes of the element as [6]:

$$[K^e][x]=[f] \quad (5)$$

where, [$\mathbf{K^e}$] is the element stiffness matrix, [**x**] is the vector of unknown nodal values and [**f**] is the element's force vector. The element stiffness matrix depends on the geometry and properties of the element. For each type of problem, i.e. magnetic, structural or thermal, a specific element stiffness matrix has to be used. The element stiffness matrices will all be inserted into a global stiffness matrix [$\mathbf{K}^G$] which relates all the unknown nodal values of the solution domain to the applied loads, and material properties as[6,7]:

$$[K^G][X]= [F] \quad (6)$$

Where [**X**] is the global unknown nodal values and [**F**] is the global force vector [6]. In magnetic problems, the two most common solution types are the magnetic scalar potential and the magnetic vector potential. As stated earlier in this chapter, the magnetic scalar potential is suitable for the solution domains in which there is no external source of current density available. On the other hand, the magnetic vector potential solution is suitable for the cases in which there is an external current density available in the solution domain. The vector fields B and H are related through the permeability (in henries/meter) of the medium as [4]:

$$B = \mu H \quad (7)$$

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

$$B = \nabla X A \quad (8)$$

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 [4]:

$$H = -\nabla V_m \quad (9)$$

For the analysis of magnetic levitation systems, the source of the magnetic field is the external current density in the electromagnets and thus the magnetic vector potential formulation is used.

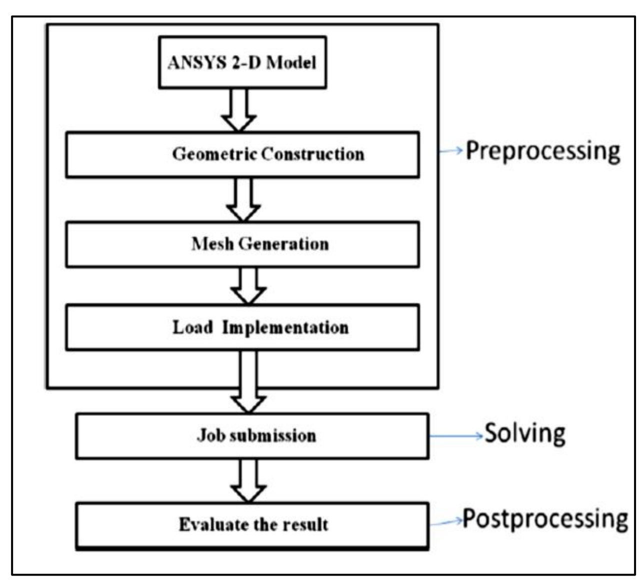

Fig.3. Flow chart for ANSYS software

ANSYS program 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 electromagnetic model.

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 behavior of electrical and electromechanical devices. The ANSYS electromagnetic product suite contains both general purpose and application specific products to address a broad array of industry applications, different engineering disciplines. 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 [5]. 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.ANSYS Mechanical technology incorporates both structural and material non-linearities. ANSYS Multiphysics software includes solvers for thermal, structural, CFD, electromagnetic, and acoustics and can sometimes couple these separate physics together in order to address multidisciplinary.

Simulation Results and Discussions

FEM simulation has been carried out to determine flux pattern, working flux density, field intensity, force etc. in the actuator and guide-way. FEM software ANSYS (Ver.12.1) has been used for this purpose.

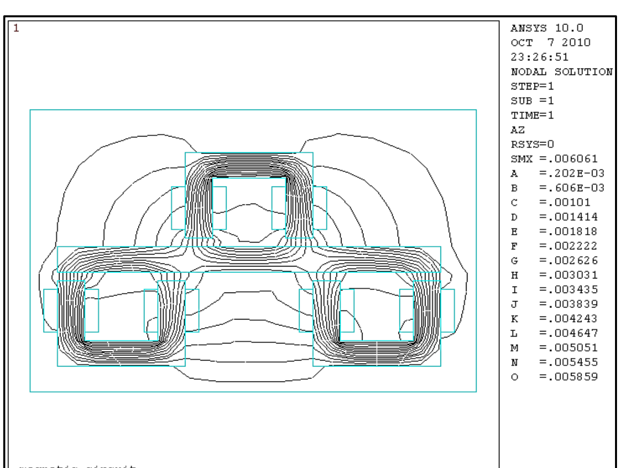

Fig.4. Flux pattern for three magnet fixed at three corner for z=1cm, N=500 and i=5A

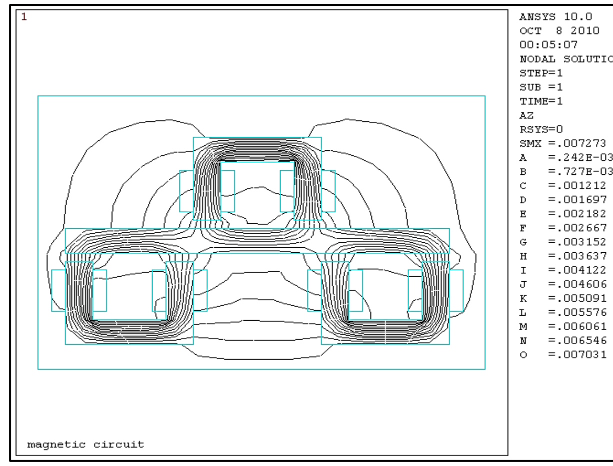

Fig.5. Flux pattern for three magnet fixed at three corner for z=1cm, N=500 and i=6A

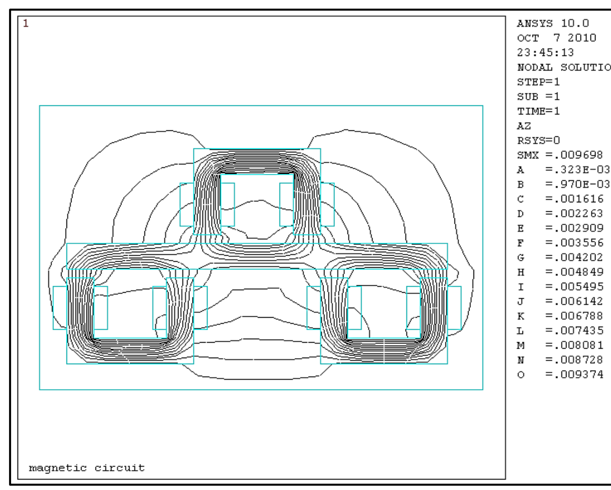

Fig.6. Flux pattern for three magnet fixed at three corner for z=1cm, N=800 and i=5A

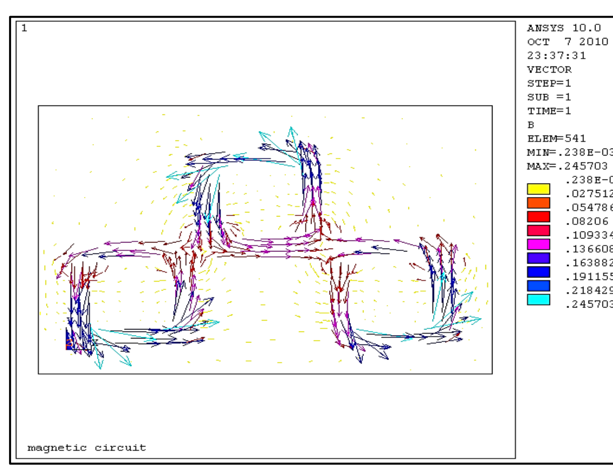

Fig.7. Flux density for three magnet fixed at the three corner for z=1cm, N=500 and i=5A

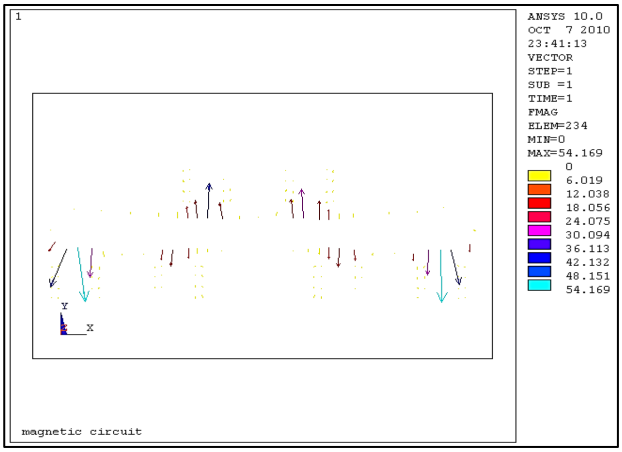

Fig.8. Force for three magnet fixed at three corner for z=1cm, N=500 and i=5A

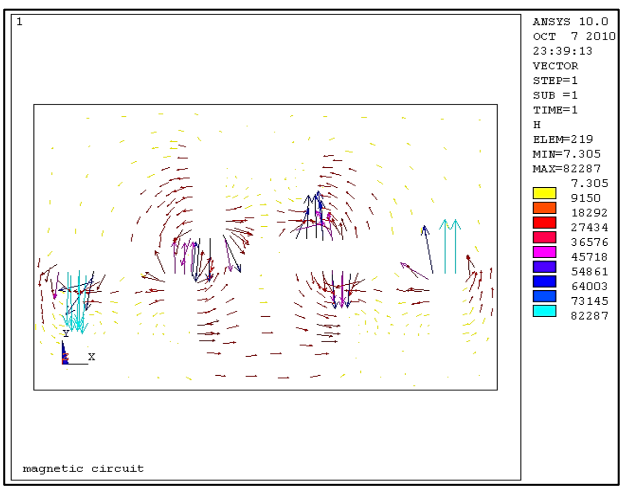

Fig.9. Field intensity for three magnet fixed at the three corner for z=1cm, N=500 and i=5A

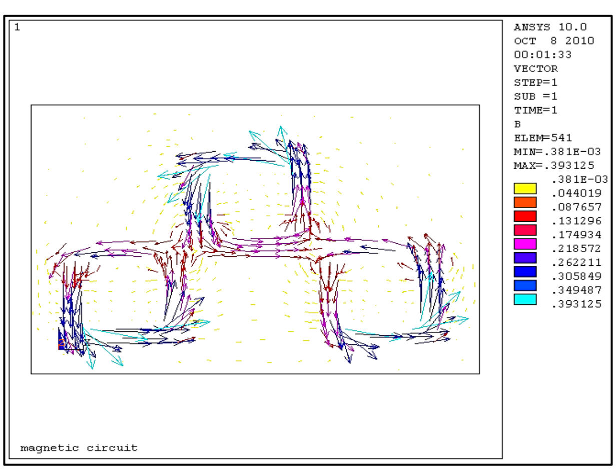

Fig.10. Flux density for three magnet fixed at three corner for z=1cm, N=800 and i=5A

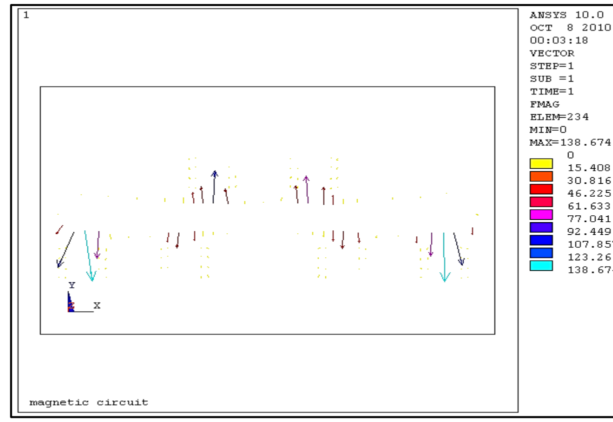

Fig.11. Force for three magnet fixed at three corner for z=1cm, N=800 and i=5A

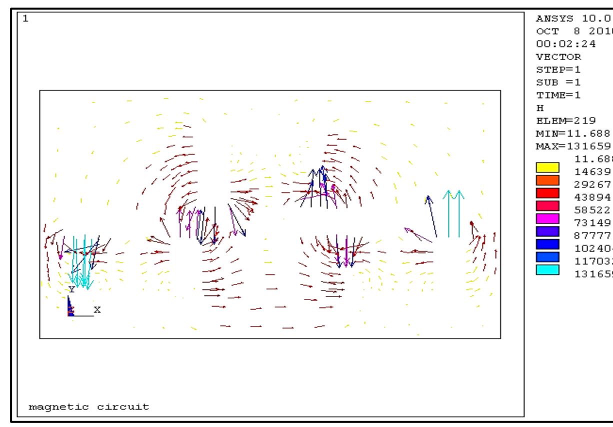

Fig.12. Field intensity for three magnet fixed at three corner for z=1cm, N=800 and i=5A

From Fig.4. to Fig.12 represents the flux pattern, flux density, and force and field intensity of Ansys simulation plot for different number of turns of coil and different coil-current value for multi-magnet levitation system. It has been noticed that the generated flux of the actuator decrease with the increase of air-gap between the pole-face of electromagnet and guide-rail and the flux increases with the increase of number of turns of coil as shown Fig. 4 and Fig.6. With the increase of air-gap leakage flux is increased and the flux linkage between magnet and guide-way is decreased. The flux patterns are mutually linked with each other magnet as shown Fig. 4. The flux, flux density, force characteristics for different coil-current and different air gap for multi-magnet levitation system are shown in Fig.13, Fig.14 and Fig.15 respectively. It has been noticed (Fig.13 to Fig.15) that the flux, flux density and force is decreased with increase the air gap, but as expected with the increase of coil-current flux, flux density and force is increased irrespective of any operating air-gap. Fig.18, Fig.19 and Fig.20 represents flux, flux density and force characteristics respectively for different number of turns of the coil (N=500 to N=800). The flux, flux density and force of the actuator increases with the increase of number of turns of the coil

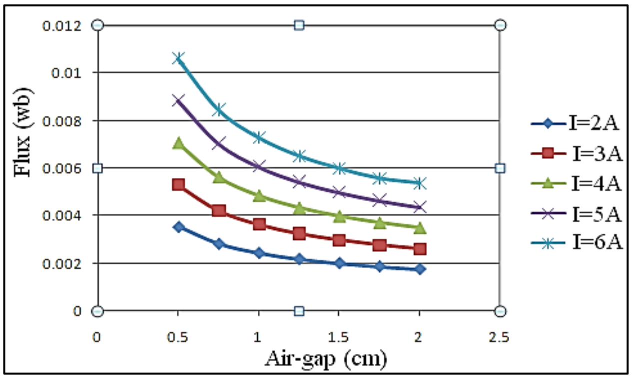

Fig.13. Flux vs. air-gap for different coil-current (corresponding air-gap) of proposed multi-magnet based levitation

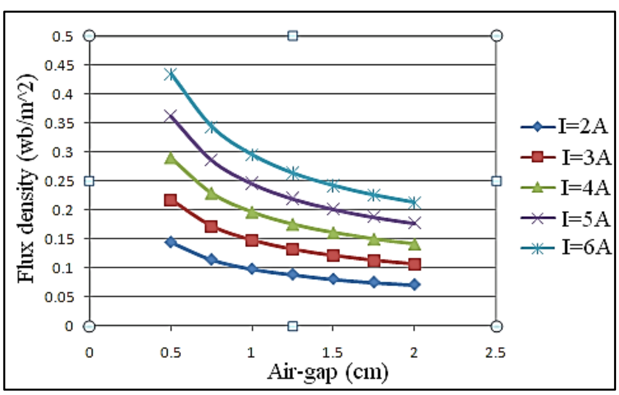

Fig.14. Flux density vs. air-gap for different coil-current (corresponding air-gap) of proposed multi-magnet based levitation

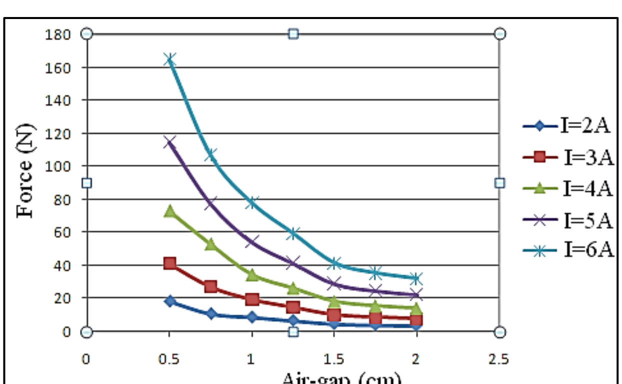

Fig.15. Force vs. air-gap for different coil-current (corresponding air-gap) of proposed multi-magnet based levitation

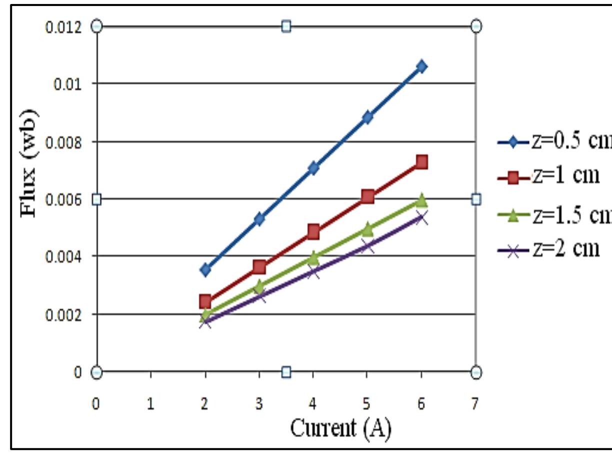

Fig.16. Flux vs. coil-current for different air-gap of the proposed multi-magnet levitation

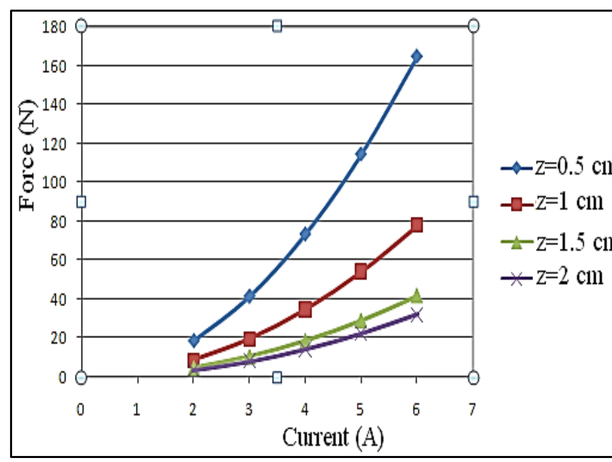

Fig.17. Force vs. coil-current for different air-gap of proposed multi-magnet levitation

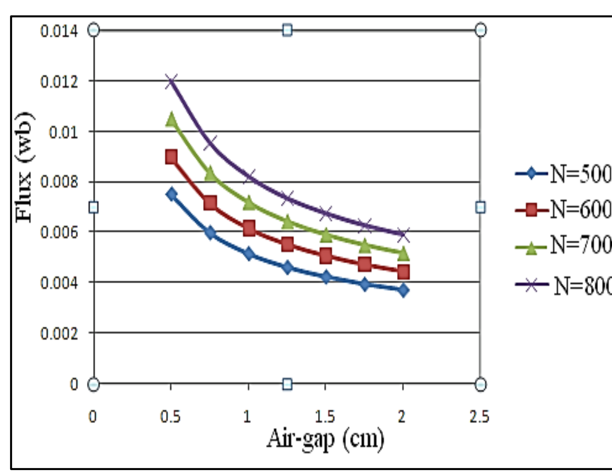

Fig.18. Flux vs. air-gap for different no. of turns of coil of proposed system

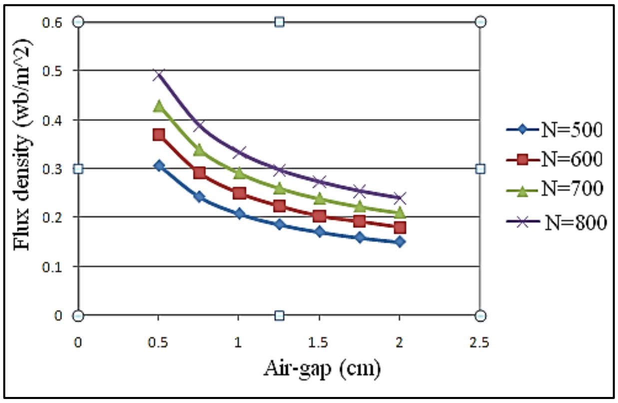

Fig.19. Flux density vs. air-gap for different no. of turns of coil of multi-magnet Levitation

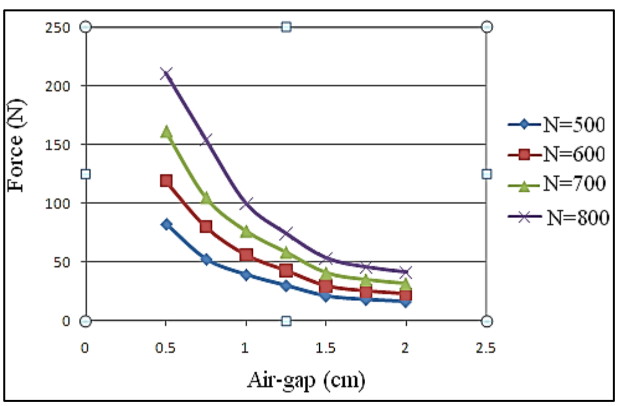

Fig.20. Force vs. air-gap for different no. of turns of coil of Multi-magnet Levitation

Conclusions

In this paper an overview of ANSYS software based simulation for multi-magnet based DC EMLS has been presented. ANSYS simulation for multi-magnet based EMLS results are given for different air gap and current flowing through the coil. ANSYS simulation plots and results are presented. The simulated results of flux, flux density and force are determined by FEM-based analysis using the Maxwell's stress tensor and virtual work.This idea will be utilized for the design and fabrication of electromagnetically levitated vehicle as a future extension of work.

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