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Research paper

Modeling and simulation of Electromagnetic Fields on a Floating Aluminium

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Abstract

The electromagnetic field calculation for a floating aluminum disc is difficult to calculate since the equation involved does not produce a closed solution. The numerical, analytical, semi-analytical techniques that are already developed to find these magnetic fields have no proper mathematical formulation when the disc is disturbed from its coaxial position. The stabilization of disc is going to be effected when the disc moves away from its coaxial position due to a change in inductance between the disc and coils, due to change in magnetic flux linkage, etc. In this paper, a 2D FEM model is developed to determine the magnetic fields on a floatingaluminum disc when it is moved away from its coaxial position. The 3D FEM model developed is simulated in both COMSOL-Multiphysics and ANSYS-Electronics. The results obtained by simulation are compared, for accuracy, with the numerical solution developed earlier using Finite Difference method (FDM) and also discussed.

Keywords: *ANSYS-Electronics; COMSOL-Multiphysics; Electromagneticfieldanalysis; FiniteDifferenceMethod; Inducedcurrents.*

1. Introduction

Electromagnetic levitation using repulsion principle [1,2] is an interesting phenomenon and has been used by scientists and engineers in several electrodynamic applications. Levitation can be either due to attractive force or due to a repulsive force, whereas here the repulsion principle is used. The disc after levitation can be stabilized by using a secondary coil, coaxial with the primary coil and also the magnitude and phase of the current has to be adjusted in these coils. To avoid the difficulty of change in current by that of the other coil (as the coils and disc are mutually coupled), the primary and secondary coils are connected in series phase opposition. Also, the turns of the secondary coil have to be adjusted for better stabilization.

The repulsive magnetic levitation as shown in Fig.1 primarily has an aluminum disc of very small thickness above a primary coil, placed concentrically and carrying AC current of frequency 220Hz. The axis-symmetric time-varying flux produced by the current in the primary coil links with the current induced on the disc which is in phase opposition to the current in the primary coil. Hence, the disc experiences a repulsive force and lifts itself off from the coil, only when the repulsive force is greater than the disc weight.

The disc lifts up from the coil until the repulsive force is equal to the gravitational force or the weight of the coil. This causes the increase in leakage flux thereby increasing the effective inductance. Suppose if there is any disturbance or if the disc is slightly tilted from the axis of the coil, the disc will throw off from the center either towards right or left due to the repulsive force based on the direction of the disturbance.

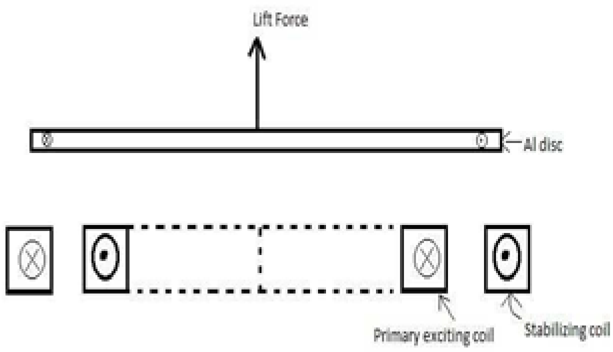

Fig. 1: MagneticLevitationbyrepulsionprinciple.

To stabilize the disc laterally, another coil known as stabilizing coil with about 50% to 60% of the primary turns is placed concentrically outside the primary coil and is connected in series opposition with the primary coil. Since the current in stabilizing coil is in phase with that of the disc, it attracts the disc thus pulling it down and at the same time stabilizing it. Another requirement to achieve the above objective is to keep the disc diameter a little more than the outer diameter of the primary coil and less than the outer diameter of the stabilizing coil. The final lift of the disc depends on the ampere-turns of the lift and the stabilizing coil, the frequency of the current, conductivity, diameter and the thickness of the disc. Since the last two factors increase the weight of the disc, aluminum is the obvious choice for the disc as it is being lightin weight and possessing good conductivity.

First, the magnetic fields on the disc have been calculated by mathematical formulation,and then a 3D-model is designed and

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simulated in both ANSYS-Electronics and COMSOL to compare the magnetic field values obtained by mathematical programming.

2. Magnetic fields on the disc

The magnetic fields produced around the vicinity of the disc are due to i) coil currents and ii) induced currents on the disc.

2.1. Field calculation due to coil currents

The magnetic fields produced due to the currents in both primary and secondary coils can be calculated as explained in [3, 4].
Suppose, the disc is moved away from the coaxial axis by a small distance, 'ε' as shown in Fig.2.

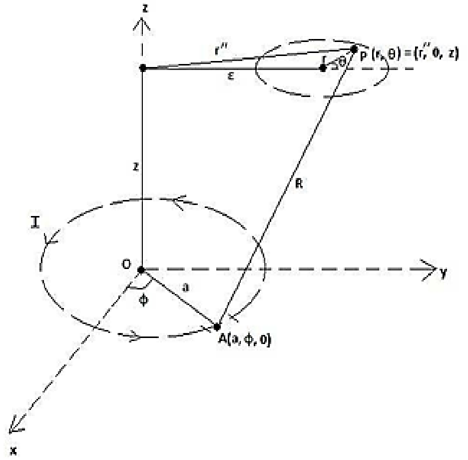

Fig. 2: Magnetic Field due to coil currents.

A point P(r, θ) on the disc (with the center of the disc as origin) will have a radial distance r″ from the axis of the coils, given by

$$r'' = \sqrt{r^2 + \varepsilon^2 + 2r\varepsilon\cos(\theta)} \tag{1}$$

Let, the radius of the primary coil is 'a' and that of the secondary coil is 'b' and both carrying a current of magnitude I but in the opposite direction. The axial component, B_Z and the radial component, $B_r$of $B_{Z1}$are calculated at a point (r″, z), where 'z' is the height from the plane of the coils and r″ is the distance from the axis of the coils. From the classical field theory as explained in [5]these components of $B_{Z1}$are presented here.
The axial component of B_{Z1} is,

$$B_z = \frac{\mu_0 I}{2\pi}\left[\frac{1}{\sqrt{(r''+a)^2+z^2}}\right]\left\{\frac{a^2-(r'')^2-z^2}{(a-r'')^2+z^2}\ E(k) + K(k)\right\} \tag{2}$$

And, the radial component of B_{Z1} is,

$$B_r = \frac{\mu_0 I}{2\pi}\left[\frac{z}{r''}\right]\left[\frac{1}{\sqrt{(r''+a)^2+z^2}}\right]\left\{\frac{(r'')^2+a^2+z^2}{(a-r'')^2+z^2}E(k) - K(k)\right\} \tag{3}$$

where, the Elliptic integral of the first kind is,

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{d\alpha}{\sqrt{1-k^2\sin^2\alpha}} \tag{4}$$

andthe Elliptic integral of the second kind is,

$$E(k) = \int_0^{\frac{\pi}{2}}(\sqrt{1-k^2\sin^2\alpha})d\alpha \tag{5}$$

$$\text{and, } k = \sqrt{\frac{4ar''}{(r''+a)^2+z^2}} \tag{6}$$

$$\vec{B}_{z_1} = \vec{B}_z + \vec{B}_r$$

The coil consists of several turns in a given layer,and there isa number of such layers in the coil. Adding contributions due to several turns of the lift and the stabilizing coils, the magnetic field on the disc is determined. The radius of the coils and the height of the point, where the field is to be determined, from the plane of the coils are varied to cover different turns of any one layer and different turns in various layers respectively. The sign of the current in the stabilizing coil is changed as compared to the exciting coil.

2.2. Field calculation due to eddy currents on the disc

The alternating current flowing through the two coils produce an axis-symmetric time-varying flux which links with the disc placed above the coils inducing a current in it. The field produced by these induced currents discussed in [3] has been presented here.

$$\vec{B}_{z_2} = \left(\frac{\mu_0\tau}{4\pi}\right)\int_0^a\int_0^{2\pi}\left\{\frac{[J_{r'}\, r\sin(\theta-\theta')] - [J_{\theta'}(r\cos(\theta-\theta')-r')]}{|\vec{r}-\vec{r}'|^3}\right\} r'dr'd\theta' \tag{7}$$

Combining equations (6) and (7) and using Maxwell's equations we get,

$$\nabla^2 U_Z = j\omega\sigma(B_{Z1} + B_{Z2}) \tag{8}$$

The above equation is difficult to solve since B_{Z2} depends on U_Z in a complex way (through Biot-Savart's law). By expanding the equation (8), we have

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial U_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 U_z}{\partial\theta^2} + j\omega\sigma\left(\frac{\mu_0\tau}{4\pi}\right)\int_0^a\int_0^{2\pi}\left\{\frac{[J_{r'}\, r\sin(\theta-\theta')]}{|\vec{r}-\vec{r}'|^3}\right\} - \left\{\frac{[J_{\theta'}(r\cos(\theta-\theta')-r')]}{|\vec{r}-\vec{r}'|^3}\right\} r'dr'd\theta' = j\omega\sigma B_{z_1} \tag{9}$$

3. Numerical Analysis

The solution of the equation (9) is difficult to obtain as it is a non-linear equation and contains both integral and differential terms. Hence, a numerical technique based on FDM is used to solve the equation by discretizing the disc into several elements as shown in Fig.3.

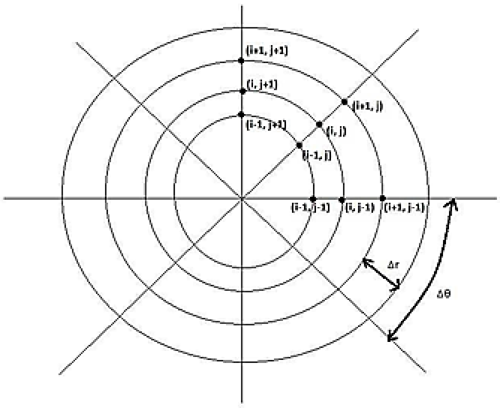

Fig. 3: DiscretizationofDiscfornumericalanalysis.

Let, 'Δr' be the differential radial distance between any two consecutive circles (r_i= iΔrand 'Δθ' be the differential length between any two consecutive radial lines ($\theta_j = j\Delta\theta$)
The differential elements are obtained by drawing 'n' concentric circles and 'm' radial lines.
Suppose P(i, j) is the point of interest where the magnetic field is to be calculated on the disc and P'(i', j') is the source point. Now, discretize the above integro-differential equation around the point P(i, j) by using central difference method and B_{Z2}can be represented in discretized form as

$$B_{z_2} = \left(\frac{\mu_0\tau}{4\pi}\right)\sum_{i'}\sum_{j'}\frac{r_{ij}r_{i'j'}J1}{R} - \left(\frac{\mu_0\tau}{4\pi}\right)\sum_{i'}\sum_{j'}\frac{r_{i'j'}J2}{R} \quad (10)$$

except for (i', j') = (i, j)
where,

$$J_1 = J_r(i',j')\sin(\theta_{ij} - \theta_{i'j'}) \triangle\theta \triangle r \quad (11)$$

$$J_2 = J_\theta(i',j')[r_{ij}\cos(\theta_{ij} - \theta_{i'j'}) - r_{i'j'}] \triangle\theta \triangle r \quad (12)$$

$$R = [(r_{ij})^2 + (r_{i'j'})^2 - 2r_{ij}r_{i'j'}\cos(\theta_{ij} - \theta_{i'j'})]^{\frac{3}{2}} \quad (13)$$

The equation (10) can be written in compact form as

$$B_{z_2} = C_1\sum_{i'}\sum_{j'}[K_rJ_r + K_\theta J_\theta] \quad (14)$$

$$\text{where, } C_1 = \frac{\mu_0\tau}{4\pi}, \quad (15)$$

$$K_r = \text{kernel-r}, K_r(ij;i'j') = \frac{r_{ij}r_{i'j'}J_1}{R} \quad (16)$$

$$K_\theta = \text{kernel-}\theta, \text{and } K_\theta(ij;i'j') = \frac{r_{i'j'}J_\theta(i',j')J_2}{R} \quad (17)$$

$$\therefore B_{z_2} = C_1\sum_{i'}\sum_{j'}[(\text{kernel} - r)(J_r) + (\text{kernel} - \theta)(J_\theta)] \quad (18)$$

$$J_r = \frac{1}{r}\frac{\partial U_z}{\partial\theta} = \frac{1}{r_i}\frac{[U_i^{j+1} - U_i^j]}{\Delta\theta} \quad (19)$$

$$J_\theta = -\frac{\partial U_z}{\partial r} = -\frac{[U_{i+1}^j - U_i^j]}{\Delta r} \quad (20)$$

In matrix form,B_{Z2} can be represented as,

$$[B_{z_2}] = C_1([K_r][J_r] + [K_\theta][J_\theta]) \quad (21)$$

whereK_r, $K_\theta$is the unknown values of U_Z (including the center),and their order is (mn+1).
All the elements of K_r, K_θ are full except for (i', j') = (i, j) which is zero. J_r, J_θ are the column matrices of the same order,and their elements can be obtained from the difference values of U_Z at different nodes.

$$\therefore \{\nabla^2 - j\omega\sigma C_1([K_r][D_r] + [K_\theta][D_\theta])\}[U_z] = j\omega\sigma[B_{z_1}] \quad (22)$$

By solving the equation (22), (mn+1) values of $U_Z$are obtained. With these values of U_Z, B_{Z2} can be calculated by using the equation,

$$[B_{z_2}] = C_1\{[K_r][D_r][U_z] + [K_\theta][D_\theta][U_z]\} \quad (23)$$

4. Results

4.1. Numerical Technique

The net magnetic field due to coil currents and the induced disc currents is shown in Fig.4. These magnetic fields obtained from the numerical technique are calculated and plotted using MATLAB programming.Also,thenetmagneticfieldobtainediscomparedby modelingthelevitation setupinANSYSandCOMSOL.

4.2. Models developed using ANSYS-Electronics and COMSOL Multi-physics

The actual setup shown in Fig.1 is modeled using ANSYS-Electronics as well as COMSOL. The models developed using ANSYS - Electronics and COMSOL Multi-physics are shown in Fig.5 and Fig.6.

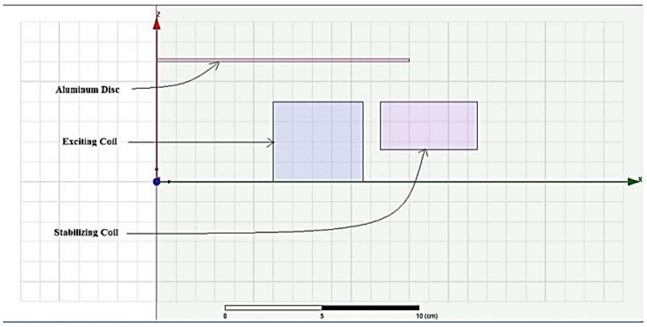

Fig.5: Model simulated using ANSYS

ANSYS Electronics is engineering analysis software used for electromagnetic, circuit and system simulation. It uses Finite Element analysis tool for simulating Electromagnetic fields. The 2D-electromagnetics is used for modeling,and the solution type used is 'eddy current' type.
COMSOL Multi-physics software is an interactive environment for modeling and simulating various engineering and scientific problems. Out of various modules available in this software, AC/DC module is used here to calculate the force on the aluminum disc. The magnetic fields interface is used for modeling the setup. This interface is used to compute magnetic field and induced current distributions in and around coils, conductors, and magnets. The physics interface solves Maxwell's equations formulated using the magnetic vector potential as the dependent variables. The type of the study used is 'frequency domain' and the setup is modeled in 2D-axisymmetric.

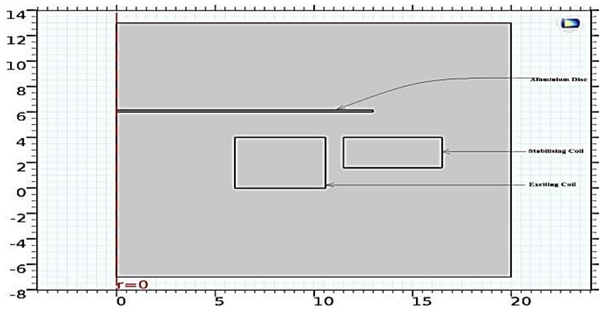

Fig.5: Model simulated using ANSYS

The net magnetic field due to coil currents and induced currents on the disc obtained by using ANSYS and COMSOL models are shown in Fig.6 and Fig.7 respectively.

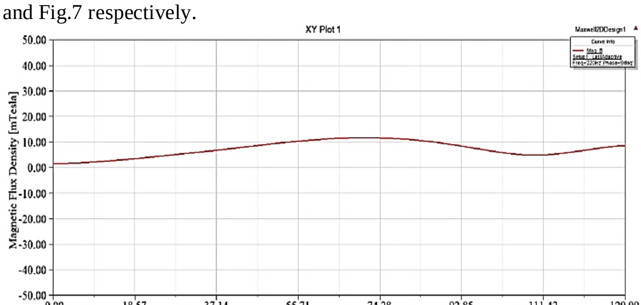

Fig. 6: Net Magnetic Field obtained from ANSYS model

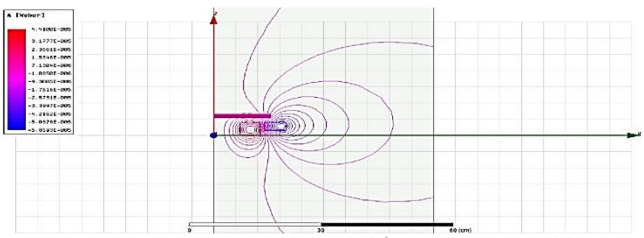

Fig. 7: Net Magnetic Field obtained from COMSOL model

The magnetic flux lines obtained by using both models ANSYS and COMSOL are shown in Fig.8 and Fig.9 respectively.

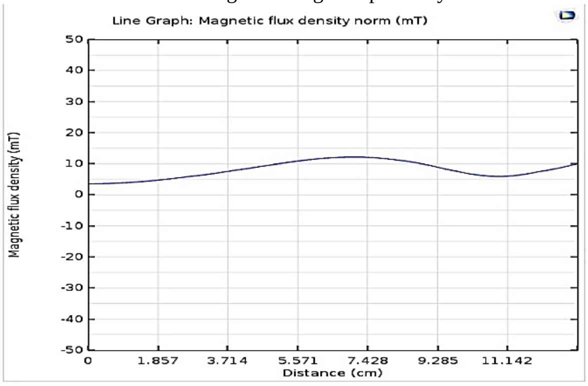

Fig. 8: Magnetic Flux lines obtained from ANSYS model

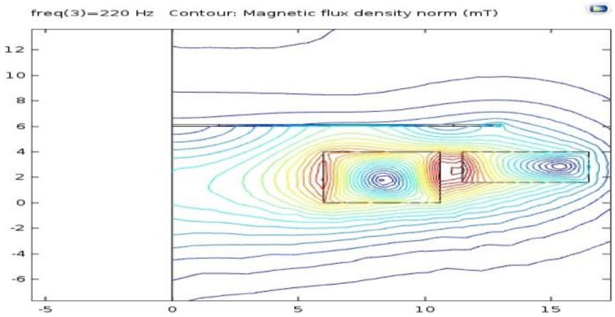

Fig. 9: Magnetic Flux lines obtained from the COMSOL model

The net magnetic flux density values at a different radius of the disc are obtained as shown in Table 1 using ANSYS, COMSOL,and mathematical modeling. These values are plotted,and the graph is shown in Fig.10.

Table. 1: Net Magnetic Fllux density at diffrent Disc radii.

S.No.	The radiusofthe-disc(cm)	NetMagneticFluxdensity(T)		
		dueto ANSYS-Model	dueto COM-SOLModel	duetoMATLAB-Progmming
1	0	0.003522726	0.00349066	0.004520466
2	1.857	0.004722637	0.004714346	0.005591272
3	3.7143	0.00755238	0.007537577	0.008022383
4	5.5714	0.010826675	0.010833352	0.011617298
5	7.4286	0.011843195	0.012021035	0.0123022383
6	9.2857	0.008841288	0.008915342	0.009729782
7	11.143	0.006050761	0.005982907	0.006527455
8	13	0.008535962	0.010096984	0.009093699

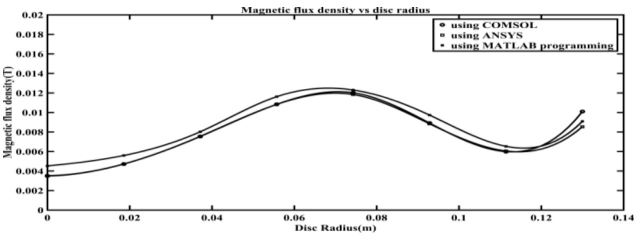

Fig. 10: Comparison of net magnetic field intensity obtained by using the numerical technique, ANSYS,and COMSOL models.

The parameters and specifications used for modeling are given in Table 2.

Table.2: ParametersandSpecification.

S.No.	Parameter	Value
1	InnerRadiusofExcitingCoil	6(cm)
2	OuterRadiusofExcitingCoil	10.6(cm)
3	InnerRadiusofStabilizingCoil	11.5(cm)
4	OuterRadiusofStabilizingCoil	16.5(cm)
5	The heightoftheExcitingCoil	4(cm)
6	The heightoftheStabilizingCoil	2.4(cm)
7	No.ofturnsoftheExcitingCoil	238
8	No.ofturnsoftheStabilizingCoil	136
9	The radiusoftheDisc	13(cm)
10	The thicknessoftheDisc	0.15(cm)
11	The positionoftheDisc	6(cm)
12	CurrentthroughtheExcitingCoil	10(A)
13	CurrentthroughtheStabilizingCoil	-10(A)
14	Frequency	220(Hz)

5. Conclusion

Themagneticfieldsduetoeddycurrentsontheconductingdiscaremathematicallyformulatedbyusingthe numericaltechnique,andthenetmagneticfluxdensityofafloatingaluminumdischasbeencalculated,andtheresultsarecompared.Thefieldofthefloatingdiscbasedon repulsionprincipleisdue tocoilcurrent andinduceddisc current.Thediscisdiscretizedintoalargenumberofcurvilinearmeshes bydrawingconcentriccirclesandradial-lines.Ateachofthenodesthusformed,theoff-axisfieldduetocoilcurrentsiscalculated.Thefieldduetotheinduceddisccurrentatthesamenodesiscalculatedmakinguseofthenumericaltechnique.ThecalculatedvaluesofthefieldateachofthenodesonthediscbasedontheprogramwrittenarecomparedwiththesimulationmodelresultsobtainedbyANSYSandCOMSOL.

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