3-D ANALYSIS OF RADIAL TYPE ELECTROMAGNETIC BEARING USING THE FINITE ELEMENT METHOD

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ABSTRACT
In recent years, the subject of electromagnetic levitation has attracted considerable attention as a means of eliminating friction. Several studies concerning the feasibility of electromagnetic levitation in various applications like magnetic bearings, high speed ground transportation, electromagnetic dampers for vibration control, etc. have been reported. In the present work, the characteristics of a commonly used configuration of a radial type electromagnetic bearing are studied. To obtain magnetic vector potential field, the three dimensional Maxwell equation along with the appropriate boundary conditions is solved by using the powerful numerical technique “Finite Element Method”. The field is discretized into 4 noded tetrahedral elements. The effects of the control current, bias current, air gap and the different materials on the performance of electromagnetic bearings are studied, taking into account the non linearity of the B-H curve and the leakage flux.

1. INTRODUCTION

Magnetic bearings have great advantages over other types of bearings inasmuch as they involve no mechanical contact, and, consequently, do not need a lub-oil system. Wear and energy dissipation through friction are almost entirely eliminated. Because of this, the subject of electromagnetic levitation has attracted considerable attention in recent years.

It is estimated that about 30% of the energy produced in the world is dissipated in friction. Thus, considerable savings can be achieved if conventional bearings can be replaced by magnetic ones. For these reasons electromagnetic bearings (EMB’s) have found increasingly wide application in engineering industry. Such a possibility is particularly attractive for high speed rotating machinery, machine tools, transportation and heavy industrial applications. Their use is promising in aerospace industry too. The work reported here is part of a study undertaken to explore the possibility of replacing conventional hydrodynamical bearings by magnetic ones.

The load capacity of electromagnetic bearings is usually small in comparison with that of traditional hydrodynamic bearings. One possible way to overcome this limitation is to increase the field strength of electromagnetic bearings. This, however, introduces severe nonlinearities into the analysis because of saturation of the B-H curve. In this work, the effects of i) the control current, ii) the bias current, iii) the air gap and iv) different materials on the performance of magnetic bearings are studied, taking into account the nonlinearity of the B-H curve and the leakage flux. Being a three dimensional analysis, this is expected to lead to more realistic results.

Even though there is considerable literature [1 – 9] on electromagnetic bearings (See, for example, Schweitzer [1], Silvester & Chari [2], Habermann [3] and Form-Zone Hsia and An-Chen Lee [4]), a complete 3-dimensional analysis taking into account the nonlinearities and the leakage flux is not yet available. This study is such an attempt. As a sequel to the analysis, it is proposed to study the dynamics, particularly the instability, and to implement practical control strategies to improve the dynamic characteristics of such bearings. This latter part will be reported in due course.

2. ANALYSIS

2.1 Governing Equations

The heart of the problem is the calculation of the magnetic attractive force which is dependent on the flux density. This magnetic flux density is obtained by solving the full 3-dimensional equation for the desired magnetic vector potential, which is obtained from the Maxwell's equations Ñ ´ *H* = *J* and Ñ . *B* = 0, where the field strength *H* is related to the flux density by the relation *H* = g*B*. *J* is the current density in the coil of the bearing, and g the reluctivity of the material. Expressing the flux density *B* as Ñ ´ *A*, the governing 3-dimensional equation is obtained as

$$\frac{\partial}{\partial x}\left(\Delta\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\gamma\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial z}\left(\gamma\frac{\partial A}{\partial z}\right)=-J \quad \text{................(1)}$$

The boundary conditions are:

The flux density *B* ® 0 at far away locations in the radial and axial directions.

This equation, together with the boundary conditions, is solved for the given geometry by the finite element method.

2.2. Finite Element Formulation

The field is discretised into 4 noded tetrahedral elements, 34 in the radial direction, 28 elements in the circumferential direction and 4 in the axial direction (Two dimensional view is shown in Figure 1).

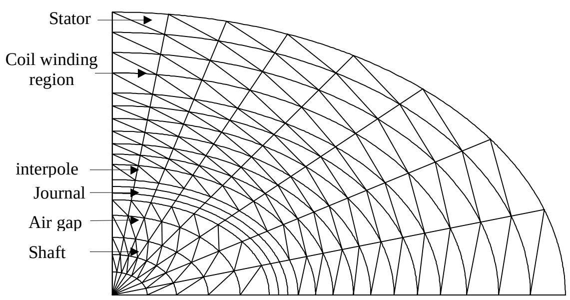

FIGURE 1: Discretisation of Shaft, Air gap and Poles

By applying the Galerkin technique and choosing appropriate shape functions [5], the following equations are obtained.

$$\frac{\partial}{\partial x}\sum_{e=1}^{n_e}\left\{[k_{ij}]^e[A_j]^e-T_{ij}^e[J_j]^e\right\}=0-J \quad \text{.................. (2)}$$

where the summation is carried out over all the elements n_e to obtain the global equation. The element stiffness matrix k_{ij}^e is expressed in terms of the shape functions N_i as:

$$k_{ij}^e=\int_{\Omega^e}\nu\,|B|K_{ij}\,dx\,dy \quad \text{................(3)}$$

$$T_{ij}=\int_{\Omega^e}t_{ij}\,dx\,dy\ ;\ t_{ij}=N_iN_j$$

$$K_{ij}=\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x}+\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}+\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}$$

The equation (2) is nonlinear, as the material property g depends on the field variable A. The numerical solution of the non-linear problems is usually accomplished by the some kind of linearisation of the equation and by iteratively improving upon an initial guess of the solution. The linearisation involves some inherent approximation as a result of which the exact answer is never obtained at the first iteration. The Newton method solving non linear equation is the most powerful method available. Thus Eq (2) has to be linearised by using the Newton-Raphson linearisation method [4], we linearise Eq (2) to the following form:

$$\left[K_{ij}^{i}\right]^e\left[\Delta A_j\right]^e=-\left[K_{ij}^{i}\right]^e\left[A_j\right]^e+\left[T_{ij}\right]\left[J_j\right]=\{R\} \quad \text{...(4)}$$

where $K'_{ij}=K_{ij}+\int_{\Omega^e}2\frac{\partial\gamma}{\partial B^2}\sum_{r=1}^{m}k_{ij}A_r\sum_{s=1}^{m}k_{js}A_s\,d\Omega^e$

The relation between n and B is obtained from the B-H curve and is approximated by cubic spline fitting.

Force is calculated by Maxwell stress tensor method. The total force acting on a volume distribution of charge is given as:

$$F=\int_v F_v\,dv \quad \text{..............(5)}$$

where $F_v = J$ ´ *B N mm*

According to the above method, the total force can be calculated by integrating over an arbitrary surface a stress function that depends at each point only on the field at that point and the direction of the surface area. Mathematically.

$$F=\int_v F_v\,dv=\int_s T\cdot ds$$

Where *T* is called the Maxwell stress tensor given as

T = m(*n* . *H*)*H* - m/2(*H*.*H*)*n*

Where *n* is the unit outword normal to the surface

3. SOLUTION PROCEDURE

The geometric data of the electromagnetic bearing, material property, rotor displacement and current density through the coils are the inputs. Initially the magnetic vector potential is assumed and corresponding reluctivity are obtained. Then the change in magnetic potential is calculated and the new reluctivities are obtained from the B-H curve. This iterative process is repeated until convergence is obtained

4. RESULTS AND DISCUSSIONS

Using the analysis and the solution algorithm mentioned

above, the magnetic attractive forces are computed for different (i) control current (ii) bias current (iii) air gap length and (iv) pole face angle.
(1) Neglecting leakage flux
(2) Considering leakage flux

Fig. 2 shows the relation between force and control current for different air gap lengths under the above cases. From the graph it is seen that when the air gap length decreases, the attractive force increases, and that for any value of the air gap length, the force increases up to a certain value of control current and after that it decreases. Also the magnetic attractive force obtained.

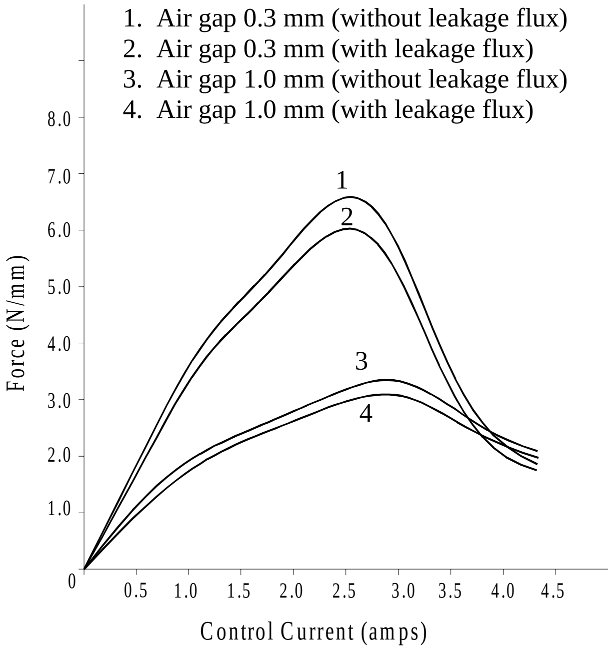

FIGURE 2: Force vs Control Current

when the leakage flux is considered is less than that obtained in the case of neglecting leakage and this reduction is appreciable at smaller values of air gap length. The magnetic attractive force obtained is higher when the leakage flux is taken into account than when it is neglected and these reductions appreciable for small values of air gap length.

Fig.3 shows the variation of force when control current changes at different values of bias currents. It is seen that for any value of bias current, the force increases when control current increases upto a certain value and after that it decreases. At large value of bias current the effects produced is more significant than that at smaller bias current.

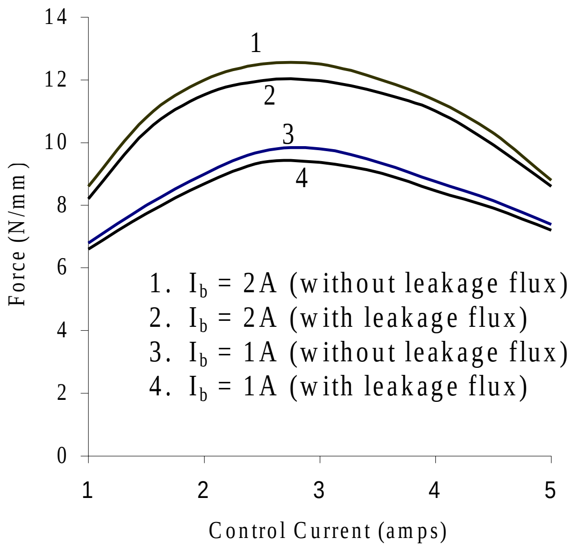

FIGURE 3: Force vs Control Current for different Bias Currents

The relation between bearing force and control current for different gap sizes are shown in Fig. 4. From the graph it is seen that at smaller gap size the bearing force becomes larger when saturation does not occur and the linear range of force versus control current becomes narrower as the gap length is reduced.

The span angle of the pole face is an important factor affecting the load capacity of an EMB. Figure 5 shows the relation between bearing force and control current density for 3 different pole face half angles. Increasing the pole face angle widens the width of the pole ribs, so that a larger air gap flux is induced for a specified coil current and consequently a larger force is generated.

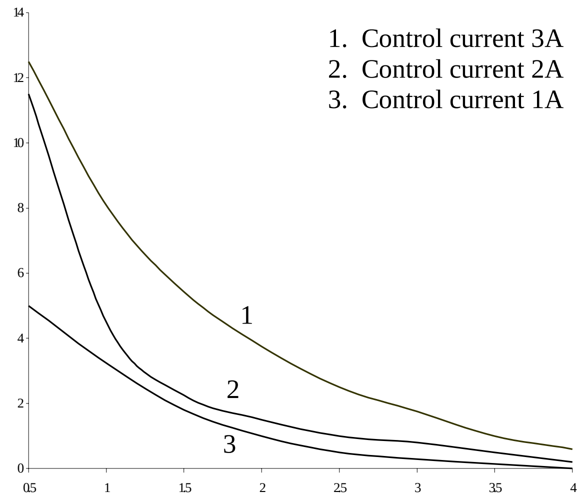

FIGURE 4 : Force vs Air gap for different Control Currents

It is seen that for any value of face angle, when control current increases force increases upto a certain value of control current and after that it decreases. When the face angle increases the magnetic force obtained increases at any value of control current.

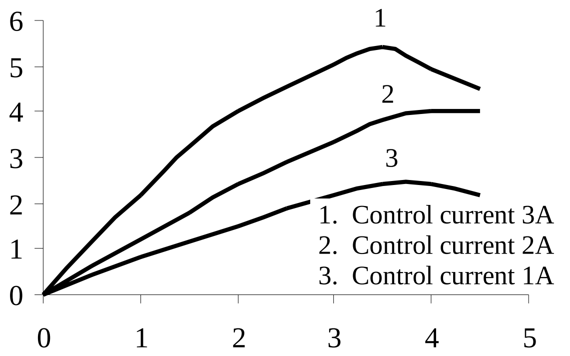

FIGURE 5 : Force vs Control Current for different Pole Face Angles

5. CONCLUSIONS

On the basis of results obtained the following conclusions are made.

1. For smaller values of bias current, the magnetic force increases with increase in control current density.
2. For larger values of bias current, the magnetic force increases with increase in control current density up to a certain value of control current density and after that decreases.
3. When the air gap length increases the magnetic force decreases exponentially.
4. When large magnetic force is experienced, for accurate production of performance of bearing leakage flux must be considered. Whenever the magnetic force is large, leakage flux must be taken into account to predict accurately the performance of the bearing.

6. FURTHER WORK

What is discussed above pertains only to static analysis. The most important dynamic characteristics, stability analysis, etc. will be carried out in due course and reported as Part II of this work. Control strategies to improve stability characteristics and their physical realization and implementation also will be taken up in Part II.

ACKNOWLEDGEMENT

The financial support in the form of a grant given by All India Council for Technical Education, New Delhi, India and the encouragement of Regional Engineering College, Calicut are gratefully acknowledged.

REFERENCES

1. G. Schweitzer, *Magnetic Bearings-Application, Concepts and Theory*, – JSME International Journal, 1990.
2. P. P. Silvester and M.V.K. Chari, *Finite Element Solutions for Saturable Magnetic Field Problems* – IEEE Transaction on Power Apparatus and Systems, 1970.
3. H. Habermann and G.L. Liard, *An Active Magnetic Bearing Systems*, – Tribology International, April 1980.
4. Form-Zone Hsia and An-Chen Lee, *An Investigation of Characteristics of Electromagnetic Bearings Using Finite Element Method*, – Transactions of ASME, Journal of Tribology, Vol. 116, October 1994.
5. P. P. Silvester and M.V.K. Chari, *Finite Elements in Electrical and Magnetic Field Problems*, – Wiley, New York, 1984.
6. Kenzon Noname and Manabu Tominaga, *Vibration and Control of a Flexible Rotor Supported by Magetic Bearings*, ISME International Journal, Series III, Vol. 33, No. 4, 1990.
7. Mulukut'a S, Sarma and Akira Yamamura, *Nonlinear Analysis of Magnetic Bearings for Space Technology*, IEEE Transactions on Aerospace and Electronic System, Vol. Aes-15, No.1, 1979.
8. Nonami K. and Yamaguchi H., *Robust Control of Magnetic Bearings by Means of Sliding Mode Control*, ISMB, International Journal Series III, Vol. 58, No. 545.
9. Yoshimoto T., *Eddy Current Effect in a Magnetic Bearings Model*, IEEE Trans. on Magnetics, No. 5, pp. 2097-2099.
10. John D. Kraus, *Electromagnetics*, McGraw-Hill International Edition, Newyork, 1991.
11. Moore A.D., *Fundamentals Electrical Design*, McGraw-Hill Book Company, Newyork, 1985.
12. J.N. Reddy, *Finite Element Method*, McGraw-Hill Book Company, Newyork, 1985.