EFFICIENT METHOD OF FORCE CALCULATION FOR BIASED MAGNETIC BEARINGS

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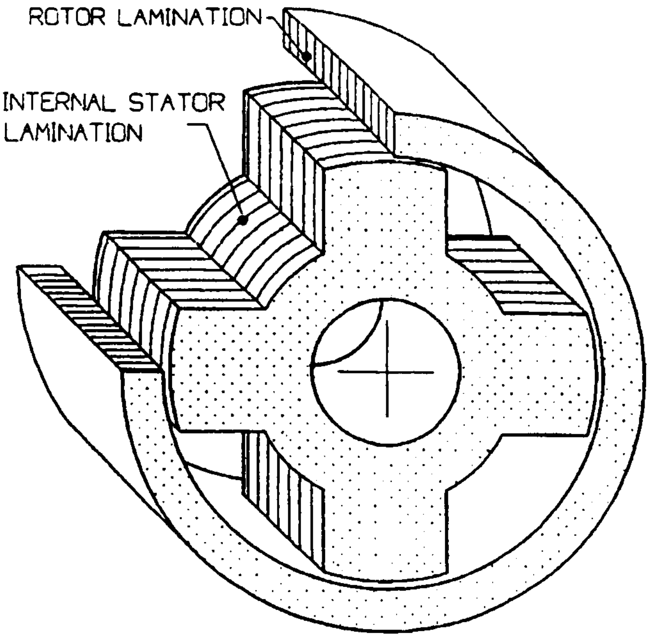
SUMMARY

Magnetic field in biased radial magnetic bearings is of a three dimensional nature. This means that if a high accuracy is required, design, analysis, and performance calculations of such a bearing would call for a three dimensional (3-D) finite element analysis. Unfortunately 3-D finite element analysis is both time consuming and requires significant computer resources. For force (load) calculation purposes, this 3-D problem can be reduced to a two dimensional one. Such a move significantly reduces both time required to design a finite element model as well as the solution time. It also opens new opportunities e.g. makes parametric analysis and optimisation of the bearing much more viable. The proposed method was verified on a prototype high speed (35,000 rpm, 125 lb) homopolar radial magnetic bearing with a permanent magnet bias. Force acting on the rotor of the bearing was calculated using both 3-D and 2-D finite element models of the magnetic bearing. The values obtained from the FE analysis were compared with the force measured on the prototype bearing. The agreement between the calculated and measured values was very good.

INTRODUCTION

A magnetic bearing system can be advantageous for rotating machinery due to the absence of mechanical wear, elimination of lubricating oil, and ability to operate at higher speeds than mechanical bearings. The forces required to support the rotating shaft are developed by an electromagnetic actuator, typically a part of a feedback control system. The electromagnetic actuator of a magnetic bearing has a rotating member (rotor) and a stationary member (stator) concentrically located with respect to each other. The rotor may be located concentrically internal or external to the stator. A magnetic bearing uses adjustable electromagnetic force generated by a current flowing through coils wrapped around the stator poles and controlled by a control circuit, to adjust the distance between the stator and rotor. Also, proximity sensors are typically used to measure the length of the gap and to provide input signals to the control circuit. In addition to the variable electromagnetic control flux, a magnetic bearing may also have a constant DC bias flux, which premagnetizes the working air gaps to a specified level of the magnetic flux density. The bias linearizes the control laws of the bearing. In some configurations, with a homopolar bias, a permanent magnet can be used to provide the bias flux, eliminating the ohmic losses associated with the bias coils.

Magnetic drag and iron losses are created whenever the rotor rotates within a spatially varying magnetic bias.



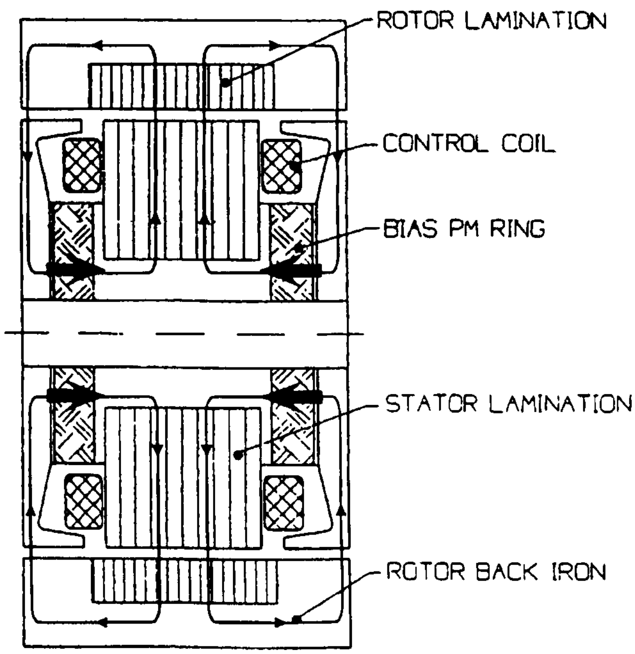
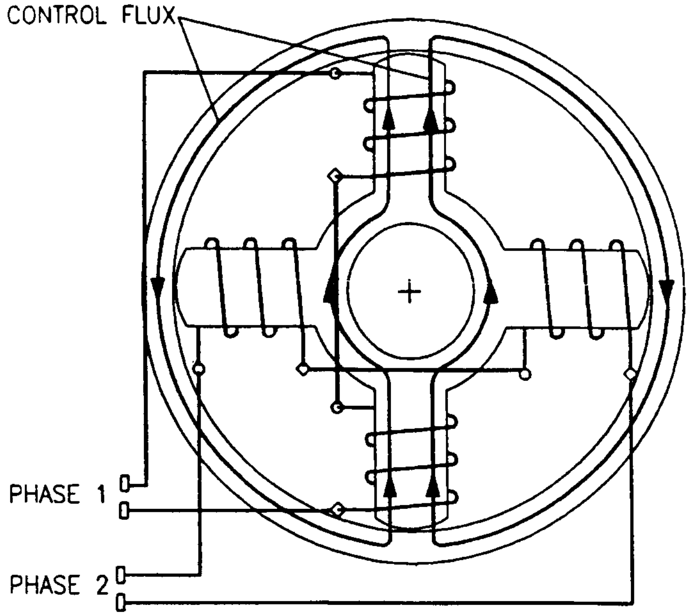


Fig. 1 (a) and (b)



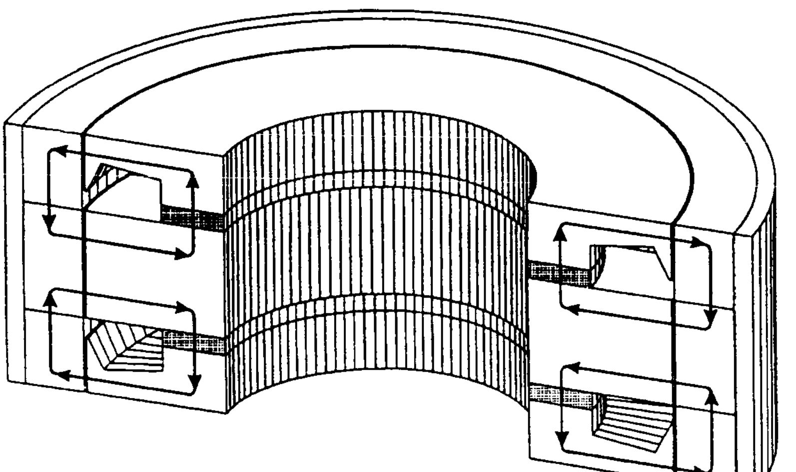


Fig. 1 (c) and (d)

Fig. 1. Permanent magnet biased radial magnetic bearing with external rotor: (a) simplified general layout, (b) longitudinal section showing bias flux path, (c) cross-section showing control flux path for the case when phase 1 carries control current, (d) 3-d view showing bias flux path

Novel homopolar magnetic bearing concepts were described and patented by Malsky [1] and Meeks [2]. These concepts employ a homopolar flux to bias the stator poles to the same polarity, e.g. all are 'north' poles. Control windings direct the flux at opposite poles to one side of the stator or the other to produce a control force in the axis of the poles. Fig. 1 shows the configuration of the homopolar bearing with four poles, described in the patent [1]. The rotor lamination is subjected to a time varying magnetic flux as it rotates through the spatially varying time-invariant bias flux. The perceived advantage of the homopolar bearing is that the bias flux is of one polarity, hence the variation in the rotor flux will be reduced, and the rotor losses should be reduced relative to a heteropolar magnetic bearing.

To design 3-D finite element (FE) model which fully reflects a complex 3-D distribution of both bias and control magnetic fluxes, as well as to perform magnetic field analysis is a very time consuming task. For the designer of a magnetic bearing the most interesting parameter is the magnetic force acting on the rotor. Since this force is created mostly in the air gap between the stator and rotor, the FE model can be reduced to two dimensions. To account for the bias magnetic flux, which is generated by permanent magnets located in the "third dimension", specific boundary conditions are required.

THE METHOD

The relationship between the magnetic flux density **B** and magnetic vector potential **A** is given by:

$$\mathbf{B} = curl\,\mathbf{A} \tag{1}$$

For polar coordinates eq. (1) translates into:

$$B_r = \frac{1}{r}\frac{\partial A}{\partial \theta}\,; \qquad B_\theta = -\frac{\partial A}{\partial r} \tag{2}$$

Magnetic flux lines generated by the permanent magnet (bias flux) enter the rotor of the magnetic bearing (arc AB) perpendicularly. This can be expressed by:

$$\frac{\partial A}{\partial r} = \frac{\partial A}{\partial n} = 0 \tag{3}$$

Therefore, the natural Neumann boundary condition applies on this boundary (arc AB). The same applies to the inner arc CD, through which the bias magnetic flux leaves the stator.

The magnetic flux per unit length in z-direction Φ_{AB} is given by:

$$\Phi_{AB} = \int_A^B B_{AB}(\theta)\; r_{AB}\; d\theta \tag{4}$$

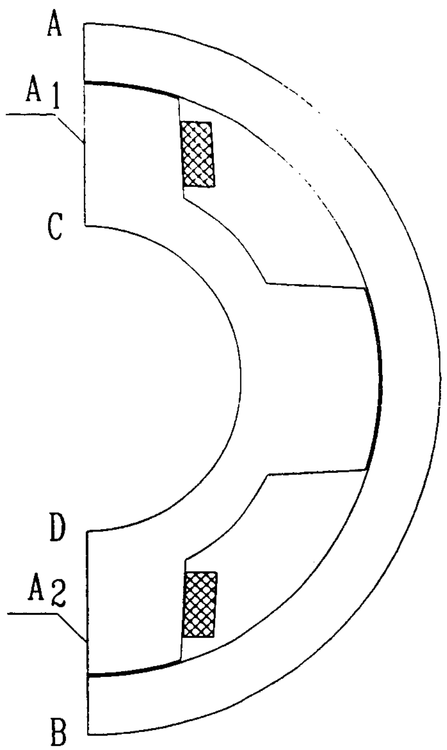


Fig. 2. Finite element 2 D model of biased radial magnetic bearing

Since, according to eq. (2) and eq.(3), the azimuthal component of the magnetic flux density $B_\theta = 0$,

$$\Phi_{AB} = \int_A^B \left(\frac{1}{r_{AB}}\frac{\partial A}{\partial \theta}\right) r_{AB}\, d\theta = A_B - A_A \tag{5}$$

The magnetic flux density along the arc AB (per unit length in z-direction):

$$B = B_r = \frac{\Phi_{AB}}{\pi\, r_{AB}} = \frac{A_B - A_A}{\pi\, r_{AB}} \tag{6}$$

Since the magnetic bearing is symmetrical with respect to the lines AC and DB (or with respect to the planes associated with these two lines, if the depth of the bearing (z-dimension) is taken into account) the magnetic vector potential A is constant along both line AC and DB and equals A_1 and A_2 respectively. This means the Dirichlet boundary conditions apply to these two boundaries.

Concluding, the magnetic flux and magnetic flux density are proportional to the difference between A_1 and A_2 and are given by:

$$\Phi_{AB} = A_2 - A_1 \tag{7}$$

$$B_r = \frac{1}{\pi\, r_{AB}} (A_2 - A_1) \tag{8}$$

Assuming: $A_1 = -A_2 = A$

$$A = 0.5\, \Phi_{AB} \tag{9}$$

or

$$A = 0.5\, \pi\, r_{AB}\, B \tag{10}$$

Eq. (9) and eq. (10) do not take into account nonlinearity of ferromagnetic materials and usually complex geometry of a magnetic bearing. For those reasons values calculated using the above equations should be further adjusted until the required value, e.g. of flux density in the air gap, is reached.

In other words the 2-D FE modelling procedure appears as follows. A 2-D FE model of the bearing, as shown in Fig. 2, is built. The bias flux, produced by two ring permanent magnets which lay beyond the plane of the FE model, is enforced by setting the difference between A_2 and A_1 to the value obtained from eq. (10), using the required value of the flux density B in the air gap between the stator and rotor. The solution process is then started. The value of the magnetic flux density in the air gap, obtained from this solution, is compared with the value required. Any discrepancy is reduced by correcting the difference between A_2 and A_1 and solving the FE problem again. This cycle is repeated until the required value of the magnetic flux density is reached. Usually a couple of such iterations suffices. The 2-D FE model is now ready for force calculations.

RESULTS

The method introduced in the paper was applied to force calculation of a high speed (35,000 rpm) radial, homopolar magnetic bearing with a permanent magnet bias, designed for a flywheel energy storage system [3]. Both 2-D and 3-D FE models of the bearing were built and the results of force calculations with the help of these models were verified experimentally.

Calculated Results and Experimental Verification

Force acting on the rotor was calculated using both 3-D and 2-D finite element models of the magnetic bearing. In both cases the virtual work method of force calculation, based on the magnetic field solution, was used [4, 5]. The values obtained from the FE analysis were compared with the force measured on the prototype bearing. As can seen from Table 1, the agreement between calculated and measured values is very good (4 %).

Table 1. Comparison of calculated and measured force acting on the rotor; control winding current 10 A.

Force [N]		
Calculated		Measured
2-D FE model	3-D FE model	-
512	523	534

CONCLUSIONS

The method of magnetic bearing force calculation, presented in the paper, replaces time and resources consuming 3-D finite element modelling with a much faster and cheaper 2-D FE modelling. Despite its simplicity, the method offers very good accuracy.

The method was also successfully applied to the calculation of magnetic bearing stiffness and other constants.

REFERENCES

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