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AN INTEGRATED MAGNETIC CIRCUIT MODEL AND FINITE ELEMENT MODEL APPROACH TO MAGNETIC BEARING DESIGN

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ABSTRACT

A code for designing magnetic bearings is described. The code generates curves from magnetic circuit equations relating important bearing performance parameters. Bearing parameters selected from the curves by a designer to meet the requirements of a particular application are input directly by the code into a three dimensional finite element analysis preprocessor. This means that a three dimensional computer model of the bearing being developed is immediately available for viewing. The finite element model solution can be used to show areas of magnetic saturation and make more accurate predictions of the bearing load capacity, current stiffness, position stiffness, and inductance than the magnetic circuit equations did at the start of the design process. In summary the code combines one dimensional and three dimensional modeling methods for designing magnetic bearings.

INTRODUCTION

Magnetic bearings must meet certain specifications such as size, load capacity, frequency response bandwidth, and other parameters. This paper describes a design code used to automate the calculation of these parameters. Advances toward more accurate prediction of the bearing parameters have been made by others such as Schweitzer (1994), Hawkins (1997), and Palazzolo et. al. (2001). Usually these advances focused on improvements to one dimensional magnetic circuit calculations or to multidimensional finite element analysis. The method described herein takes advantage of these advances by combining one dimensional magnetic circuit calculations with three dimensional finite element calculations in an integrated manner.

In this approach the one dimensional magnetic circuit equations are arranged to generate plots showing the relationships between all the parameters. The designer uses these plots to pick the best combination of performance parameters that meet the requirements of the particular application. This choice of parameters necessarily fixes the dmensions of the bearing which are sent to a finite element analysis preprocessor, and a three dimensional model is created, analyzed, and the results are available for comparison to the one dimensional circuit model predictions.

MAGNETIC CIRCUIT APPROACH

Linear algebraic equations using the bearing parameters as variables are developed using the magnetic circuit approach. These equations can be arranged to calculate the values of the unknown parameters from the known ones. The four basic elements in a magnetic model of a magnetic bearing are permanent magnets, air gaps, magnetic metal paths, and electric coils. An elementary circuit is shown in Figure 1.

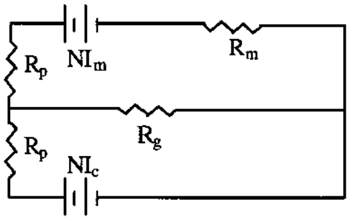

Figure 1. Elementary Magnetic Circuit.

The permanent magnet has the highest reluctance of any element in this circuit. Therefore flux driven by the electric coil cannot flow through the branch with the permanent magnet. This fact is often used to simplify the magnetic circuit models of magnetic bearings by breaking the multi-loop circuits into simpler single loop circuits for the permanent magnet flux and the electric coil flux as by Lee, Hsiao, and Ko, (1994).

The air gap has the next highest reluctance after the permanent magnet in Figure 1. Although the permanent magnet and the air gap have nearly the same permeability, the permanent magnet is much longer than the air gap which must be very thin to allow flux driven through it by the electric coils with out excessive current.

The metal paths have a very low reluctance. The important exception is in the direction perpendicular to laminates in a stack.

Equations 1 to 2 are the equations for the magnetomotive force produced by the electric coil, NI_c, and permanent magnet, NI_m. In these equations l_m is the magnet length, H_c is the magnet coercivity, I_c is the current in the coil, and N is the number of turns in the coil.

$$NI_m = H_c \cdot l_m \qquad \text{Eq. 1}$$

$$NI_c = N_c \cdot I_c \qquad \text{Eq. 2}$$

The circuit path reluctances depend on their cross section areas, lengths, and material permeabilities and are given by Equations 3 to 5. Here R_m is the reluctance of the magnet, R_g is the reluctance of the air gap, and R_p is the reluctance of the metal path. The cross section area and length are given by, A and l, and the permeability is indicated by μ.

$$R_m = \frac{l_m}{\mu_m A_m} \qquad \text{Eq. 3}$$

$$R_g = \frac{l_g}{\mu_o A_g} \qquad \text{Eq. 4}$$

$$R_p = \frac{l_p}{\mu_o A_p} \qquad \text{Eq. 5}$$

Kirchoff's laws are used to calculate the magnetic flux flowing through the loops. The two loop equations for Figure 1 are given by Equations 6 and 7. The flux through the permanent magnet loop is a constant bias flux, Φ_b, and the flux through the control loop is ϕ_c. These equations can be rearranged to solve for any of the geometric and magnetic variables. This illustrates the key advantage of the circuit model approach.

$$\Phi_b = \frac{NI_m}{R_m + R_g + R_p} \qquad \text{Eq. 6}$$

$$\phi_c = \frac{NI_c}{R_m + R_g + R_p} \qquad \text{Eq. 7}$$

The circuit model approach's main limitation is the inaccuracy of the simple circuits used to model. In fact, nearly fifty percent of the flux produced by the permanent magnet does not circulate through the magnet circuit, but bypasses the circuit through the air adjacent to the magnet. This effect has to be estimated and used to reduce the value of bias flux used in subsequent calculations after it is calculated from Equation 6. Another effect that must be estimated is called air gap fringing. It is dilution of the flux density in the air gap by flux escaping out the air gap sides. This effect must also be estimated which is typically done by multiplying a fringe factor times the bias and control flux densities calculated from Equations 6 and 7.

The error from these estimates is amplified in calculations of the position stiffness and current stiffness which are proportional to the square of the bias flux and the product of the bias and control flux respectively.

Geometric constraint equations can be combined with the electromagnetic circuit equations to calculate dimensions for various types of bearing configurations such as heteropolar, homopolar, and bias pole. The magnetic path dimensions are sized to allow room for all the coil turns required to drive sufficient flux. The path cross section areas must be balanced to prevent magnetic saturation in all path branches. Other bearing dimensions can be limited by the size of the machine in which the bearing is placed. The rotor outer diameter can be limited by the stresses due to high speed rotation.

For example Equation 8 shows a typical geometric constraint equation which requires the number coil layers, nl, times the coil diameter, dw, to be equal to the space of the coil slot, h.

$$nl \cdot dw = h \qquad \text{Eq. 8}$$

This is illustrated by Figure 2. Sets of the parameters for all the geometric configurations which will fit into the geometric envelope are calculated by the design code by simply iterating through all the possibilities of the dimensions with the computer.

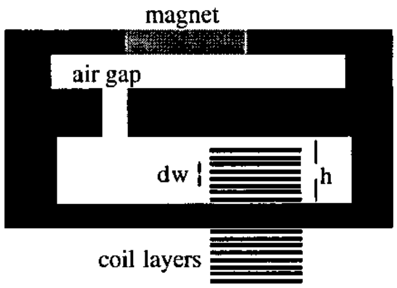

Figure 2. Geometric Constraint of Coil Wire Slots.

THREE DIMENSIONAL FINITE ELEMENT METHOD APPROACH

Three dimensional finite element methods are well established for electromagnetic analysis. Texts have been written for example by Salon (1995) and Ida and Bastos (1997). Several commercial codes complete with preprocessors for modeling geometry, magnetostatic and time varying solvers, and post processors are available. In this work the code by Vector Fields Opera (1999) was used.

Traditionally the drawback of finite element analysis has been the time required to build a model. The advent of solid model preprocessors in the early nineties helped somewhat, as did automatic mesh generators. However a slow manual input was required every time a new magnetic bearing design needed to be analyzed. This reduced the finite element analysis to mainly a check of designs determined from the equations derived by one dimensional circuit analysis.

Recently solid model preprocessors have been introduced with parametric capability. Dimensions, material properties, electric current levels, and other parameters of the magnetic bearing can be specified as variable parameters. Essentially each type of magnetic bearing, (heteropolar, homopolar, or bias pole), only needs to be manually input into the preprocessor once. After that new configurations of the same type of bearing can be analyzed simply by changing the values of the parameterized dimensions. This significantly enhances the utility of the finite element model since the effect of different parameters on a design can be determined nearly as rapidly with the finite element analysis solver as they can with the circuit model equations which also use parametric variables.

The one dimensional circuit equations predict bearing dimensions that will be required to meet certain performance objectives and constraints. These bearing dimensions are input directly to the finite element analysis preprocessor as values for the parameters for the model. Specifically for the Vector Fields Modeller, the values are written in the model log file, where all the bearing dimensions and material properties have been strategically placed at the beginning. The log file is a text file read by the preprocessor. The parameters are clearly visible in the log file text.

This new solid model with the new dimensions is displayed in three dimensions. A visual check is thereby obtained of a fairly complex machine based on many different dimensions.

Figure 3 shows for example a solid model of a heteropolar bearing built with parametric dimensions. These dimensions include the rotor laminate stack inner and outer diameter, the stator inner diameter of the poles, the slot radius, the width of the poles, the angle between adjacent pole tips, the number of coil turns, the height and thickness of the coils, and the bearing outer diameter, as well as the material properties of the laminates. Effects like fringing and flux recirculation are accounted for in the model by the air which completely surrounds the actuator but is not shown in Figure 3 since it would hide the internal parts.

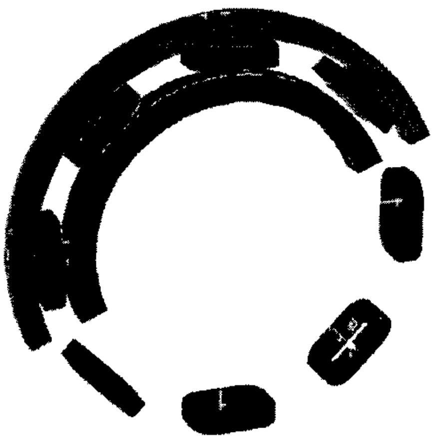

Figure 3. Heteropolar Bearing Solid Model Generated from Parametric Dimensions.

The finite element analysis follows automatically after the finite element model is generated from new parameters. The flux patterns are displayed as contours on the solid model. These show the effect of magnetic saturation since the material B-H curve is part of the finite element analysis. Certain things which are difficult to ascertain with the one dimensional circuit model equations, such as choking with certain coils on, are clearly seen from the finite element analysis.

Verification of the performance predictions made by the one dimensional code is done by comparison to the predictions of the finite element analysis. Since the finite element analysis is three dimensional and accounts for gap fringing and permanent magnet flux recirculation the finite element analysis predictions are more accurate. Better knowledge of load capacity, current and position stiffness, and inductance are thereby obtained.

SUMMARY

An integrated one and three dimensional design approach for magnetic bearings has been described. The traditional method of using magnetic circuit equations to predict determine bearing performance and dimensions is followed by inputting the dimensions automatically into to parametric solid model file. The bearing performance predicted by the one dimensional circuit equations is immediately compared to the performance predicted by the three dimensional finite element analysis. This results in more reliable predictions of bearing performance in less time.

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