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MODELING OF EDDY CURRENT LOSS FOR MAGNETIC THRUST BEARINGS

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ABSTRACT

In this paper, an analytical model for calculating eddy current loss in magnetic thrust bearings (MTBs) is presented. The surface magnetic field intensity, considering the skin effect of eddy current, is varying with the frequency and can be calculated by effective reluctance method. The magnetic field distribution and eddy current loss can be obtained from it. Finally, the validity of the model is verified by the finite element method (FEM) simulation and experimental results.

INTRODUCTION

With contact-free rotors, active magnetic bearings (AMBs) usually have much lower losses than rolling bearings or oil bearings [1]. However, winding loss and iron losses which include hysteresis loss and eddy current loss are still inevitable in the operation of AMBs. For MTBs, because of the non-laminated structure and high frequency time-dependent field, the iron losses will be great in the stator and thrust disk, and the eddy current loss will be dominant[2]. Therefore, an accurate analytical model of eddy current loss for non-laminated structures would be useful during the design process.

MODELING

Figure 1 shows the cross section of a MTB. Except for the coil, the stator, air-gap and thrust disk are divided into 6 elementary parts according to the flux path. When one dimensional hypothesis is proposed, part 2 and 5 just have radial flux component and part 1, 3, 4 and 6 only have axial flux component. Therefore, 1-D Maxwell equations can be easily used to these elementary geometries [2].

In order to simplify the analysis, material nonlinear, hysteresis and leakage are ignored and the flux distribution in the air gap is assumed to be uniform.

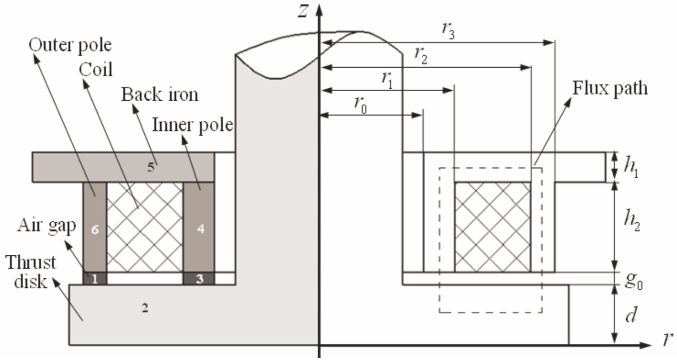

Figure 1 Cross section of a MTB

Models of rotational symmetric plate (such as part 2 and 5) and semi-infinite cylinder (such as part 4 and 6) had been presented by Kucera to analyze the magnetic field in MTBs [2]. The magnetic field in part 2, 4, 5 and 6 shown in Fig.1 can be written as

$$H_{(2)r}(r,z)=\frac{e^{\alpha d}}{1+e^{2\alpha d}}(e^{\alpha z}+e^{-\alpha z})H_{(2)sf} \tag{1}$$

$$H_{(4)z}(r)=\frac{I_0(\alpha r)}{I_0(\alpha r_1)}H_{(4)sf} \tag{2}$$

$$H_{(5)r}(r,z)=(\frac{e^{-\alpha(d+g_0+h_2)}}{1+e^{2\alpha h1}}e^{\alpha z}+\frac{e^{\alpha(d+g_0+h_2)}}{1+e^{-2\alpha h1}}e^{-\alpha z})H_{(5)sf} \tag{3}$$

$$H_{(6)z}(r)=\frac{K_1(\alpha r_3)I_0(\alpha r)+I_1(\alpha r_3)K_0(\alpha r)}{K_0(\alpha r_2)I_1(\alpha r_3)+I_0(\alpha r_2)K_1(\alpha r_3)}H_{(6)sf} \tag{4}$$

where: $\alpha = (1+j)/\delta$ and $\delta = \sqrt{2/\omega\mu\sigma}$ is the skin depth, ω is the angular frequency of the coil current, μ and σ are permeability and conductivity of the iron material, $I_n(\alpha r)$ and $K_n(\alpha r)$ are modified Bessel function of first and second type and n order, $H_{(k)sf}$ is the surface magnetic field intensity for part k , which will be discussed later.

According to Ampere's law ($\nabla \times H = J$), the eddy current density for every iron part can be obtained. Then the power density can be obtained and used to calculate the eddy current loss in each iron part. After some simplifications for Bessel functions, the eddy current loss in every iron part can be derived as

$$P_{(2)} = \frac{\pi \left| H_{(2)sf} \right|^2}{\sigma\delta}(1-e^{-4d/\delta} - 2e^{-2d/\delta}\sin(\frac{2d}{\delta}))(r_3^2 - r_0^2) \tag{5}$$

$$P_{(4)} = \frac{2\pi \left| H_{(4)sf} \right|^2 r_1}{\sigma\delta}(1-e^{-\frac{2(r_1-r_0)}{\delta}})h_2 \tag{6}$$

$$P_{(5)} = \frac{\pi \left| H_{(5)sf} \right|^2}{\sigma\delta}(1-e^{-4h1/\delta} - 2e^{-2h1/\delta}\sin(\frac{2h1}{\delta}))(r_2^2 - r_1^2) \tag{7}$$

$$P_{(6)} = \frac{2\pi \left| H_{(2)sf} \right|^2 r_2}{\sigma\delta}(1-e^{-4(r_3-r_2)/\delta} - 2e^{-2(r_3-r_2)/\delta}\sin(\frac{2(r_3-r_2)}{\delta}))h_2 \tag{8}$$

After the Ampere circuital theorem is used to the surface (near to the coil) of the stator and thrust disk， it can be expressed as

$$\oint H(s)\cdot dl = H_{sf}(s)\cdot l_{iron} + H_{air}(s)\cdot 2g_0 = NI(s) \tag{9}$$

where l_{iron} is the length of the iron surface, $H_{air}(s)$ is the air-gap magnetic field intensity, g_0 is the nominal length of the air-gap, N is the number of the coil turns, $I(s)$ is the current of the coil and s is the complex frequency variable ($s = 2j\pi f$ for a harmonic field with frequency of f Hertz).

The surface magnetic field intensity, which has been considered to be invariable in the literature [2], will be changed because of the eddy currents induced. The magnetic flux will decrease and cause to the reduction of the air-gap magnetic field intensity. At the same time, the surface magnetic field intensities of the stator and the thrust disk, as the boundary condition of magnetic field problem in equation (5) to (8), will increase with the reduction of air-gap magnetic field intensity according to Equation (9). So, the air-gap magnetic field intensity must be confirmed firstly.

The effective reluctance [3] could be introduced to solve this problem. The effective reluctance, which considering the effects of skin effect of eddy current, can be written as

$$\Re = \Re_r + \Re_i\sqrt{j\omega} \tag{10}$$

where $\Re$ is the total effective reluctance, $\Re_r$ is the static reluctance and $\Re_i$ is the coefficient of dynamic reluctance.

When we combine the Faraday's and Ohm's law, the fractional transfer function of the MTB with input $I(s)$ and output $H_{air}(s)$ can be described as

$$H_{air}(s)/I(s) = N/(A_{eff}\mu_0(\Re_r + \Re_i\sqrt{s})) \tag{11}$$

After the frequency response of this fractional transfer function is carried out, the air-gap magnetic field intensity at different frequency can be easily obtained. Finally, the surface magnetic field intensity can also be calculated with $H_{air}(s)$:

$$H_{sf}(s) = (NI(s) - H_{air}(s)\cdot 2g_0)/l_{iron} \tag{12}$$

Now, all of the parameters needed to calculate the eddy current loss with equations (5) to (8) are known. The total eddy current loss of the MTB can be obtained as

$$P_e = P_{(2)} + P_{(4)} + P_{(5)} + P_{(6)} \tag{13}$$

VERIFICATION

In order to verify the validity of the analytical model derived, the harmonic finite element method (FEM) analysis and experimental measurements of the eddy current loss are performed.

In the FEM analysis, material nonlinear, leakage and fringing flux are considered, and a 2-D axisymmetric electromagnetic coupling model was constructed. Finally, the air-gap magnetic field intensity, surface magnetic field intensity and eddy current loss at different frequency were obtained by harmonic analysis.

In experiments, a MTB and a rotor as shown in Figure 1 were used to measure the eddy current loss. The thrust disk was supported by a horizontal stand and the rotor was kept in vertical position. At the same time, the air-gap length between the stator and thrust disk was kept constantly by sheets of paper. The coil of the MTB was driven by a linear power amplifier, and the current was regulated by a signal generator. Then, the power losses, containing winding loss, hysteresis loss and eddy current loss, were analyzed using a power analyzer by measuring the coil current and voltage between the two ends of the coil. Finally, the wingding loss was subtracted by ohm's law and the hysteresis loss was ignored because it was smaller and difficult to separate.

RESULTS AND DISCUSSION

The frequency responses of the air-gap magnetic field intensity derived from the results of FEM analysis and the fractional transfer function are shown in Figure 2. With the decreasing of the air-gap magnetic field intensity, the amplitude of the surface magnetic field intensity of the stator and the thrust disk will increase according to Ampere's circuital law, which can be seen in Figure 3.

It can be seen that the difference between results of the two methods are mainly in the high frequency region because of the material nonlinear and leakage effects. The maximum difference in magnitude and phase of the air-gap magnetic field intensity are only 1dB and 2 degrees at 10kHz. Thus the analytical model could well incorporate effects of the eddy current and give good result in eddy current loss calculation.

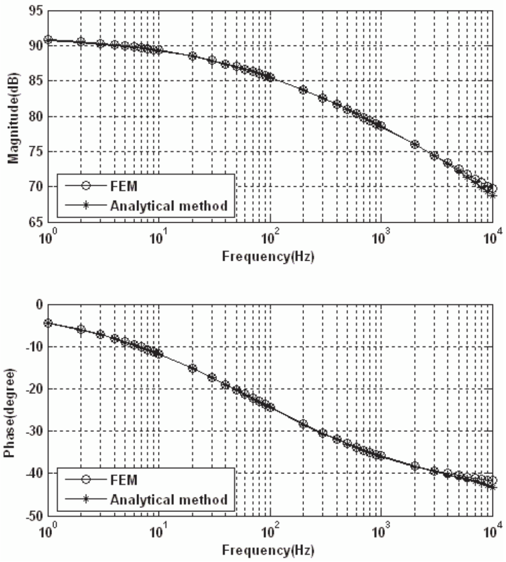

Figure 2 Frequency response of the air-gap magnetic field intensity

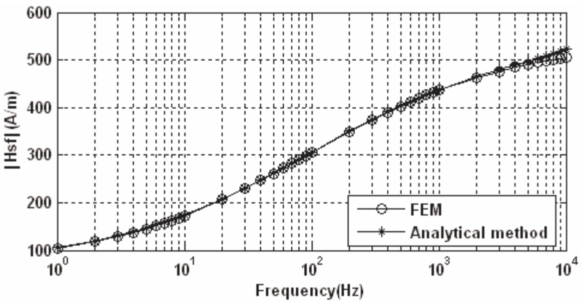

Figure 3 The amplitude of the surface magnetic field intensity at different frequency

The measured and calculated results of the eddy current loss at different frequency are shown in Figure 4. The winding loss has been subtracted from the measured and FEM analysis results. It can be shown that both of the analytical method and FEM analysis show good validity for eddy current loss calculation. Compared with the experimental results, the maximum differences of FEM result and analytical result are 7% and 1% as respectively. However, the FEM analysis result should be closer to the measured results than the analytical method because the material nonlinear and leakage are considered in the FEM analysis, but it is not reflected in Figure 4. It can be explained by the hysteresis loss, which is ignored by FEM analysis and analytical method. In addition, the analytical result is bigger than FEM result because of the material nonlinear and leakage effects has been ignored.

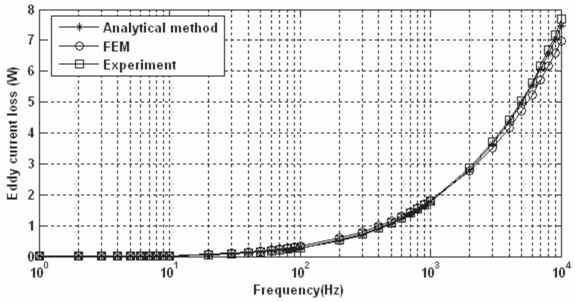

Figure 4 The eddy current loss at different frequency

CONCLUSION

This study presents an analytical model of eddy current loss for a MTB based on the Maxwell equations and effective reluctance. The surface magnetic field intensity, as the boundary condition of the magnetic field problem, is derived by effective reluctance method. It is used to calculate magnetic field distribution and eddy current loss after considering the skin effect of eddy current. At the same time, the results of FEM analysis and experiments verify the validity of the analytical model. However, other effects, such as hysteresis, material nonlinear and leakage, also need to be considered for a more accurate model in the future work.

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