The dissipation models of AMB and its computational methods*

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Abstract **–**Active magnetic bearing (AMB) is a kind of advanced high speed bearing, it is used to suspend rotor without contact between stator and rotor by magnetic power. At present researches on active magnetic bearing mainly focus on power amplifier and control system, but the researches on its power losses are very few. Because active magnetic bearing is turning at high speed, its power losses can not be neglected. Power losses can increase the temperature of AMB, make stator and rotor thermal deformation, have an effect on bearing's orientation, even make stator and rotor produce distortion, and influence active magnetic bearing normal operation. At the same time, it can reduce insulation capability of windings; shorten its life-span. So it is important to estimate the power losses to insure AMB normal operation. There are three kinds of power losses in AMB, including copper losses, iron losses and windage losses. It is necessary to research and compute the three kind of power losses. This paper investigated present researches on power dissipation of AMB, summarized three dissipation models, gave their computational methods and their application range. Copper losses can be computed by ohm law. Iron losses consist of eddy losses and hysteresis losses. Eddy losses are generally proportional to the square of frequency. Hysteresis losses are generally proportional to frequency. So hysteresis losses are very low in iron losses at high frequency and can be ignored, but it will account for the large proportion of iron losses at low frequency. And iron losses depend on the arrangement of magnetic pole, such as alternating pole (NSSN) and paired pole (NNSS). At present the analysis of iron losses are based on such assumptions as material linearity and neglect of magnetic saturation, but material nonlinearity must be token into account when AMB rotates at high speed, so actual iron losses are larger than computational results. Windage losses can be described by fluid state in air gap and corresponding empirical formula, and in high-speed motors the surface speed of the rotor is typically between 150 and 400 m/s. At this range the windage losses are proportional to the cube of the surface speed.

Index Terms **– active magnetic bearing; copper losses; iron losses; windage losses.**

I. INTRODUCTION

Active magnetic bearing (AMB) is a kind of advanced high speed bearing which is used to suspend rotor without contact between stator and rotor by magnetic power. Because of non-contact, rotor speed can run at very high, so that AMB has many advantages, e.g. long life-span, no pollution etc. It has been applied in many areas, such as aviation and energy source and so on[1].

At present researches on AMBs mainly focus on power amplifier and control system, but the researches on its power losses are very few. Because rotor is turning at high speed, its power losses can not be neglected in some situations. Power losses can increase the temperature of AMB, make stator and rotor thermal deformation, have an effect on bearing's orientation, even make stator and rotor distortion, and influence AMB normal operation[2]. At the same time, it can reduce insulation capability of windings; shorten their life-span and cause the malfunction. So it is necessary to estimate the power losses and take some measurements to insure AMB normal operation. This paper investigated present research of dissipation of AMB, summarized dissipation models, gave their computational methods and their application range.

II. INTRODUCTION TO AMB AND ANALYSLS OF POWER DISSIPATION

Active magnetic bearing usually includes journal and axial (thrust bearing) bearings as shown in Fig.1 and 2.

Fig.1 shows that journal bearing with rotor suspended 8 poles magnetic bearing and stator, journal freedom of rotor can be controlled by magnetic force produced by current of windings. Fig.2 shows axial bearing is made up of stator and thrust disk, controlling axial freedom degree.

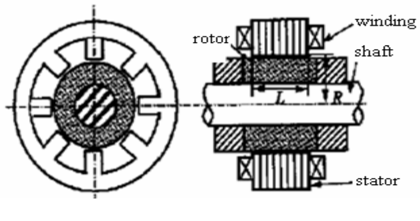

Fig. 1 sketch map of journal bearing [3]

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* This work is supported by State Hi-Tech Research and Development Program of China. (No. 2003AA511010)

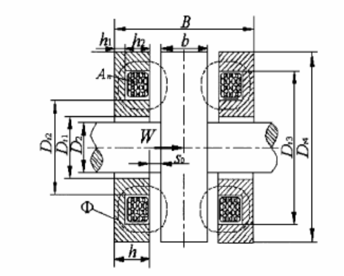

Fig. 2 sketch map of axial bearing [4]

Active magnetic bearing produces three kinds of power dissipation at high speed, including copper losses, iron losses and windage losses. Copper losses are caused by resistance of windings. Iron losses include eddy and hysteresis losses. Magnetic field of surface of rotor and stator will be changed periodically due to rotor turning, then electrical field are produced by the changeable magnetic field, so it will produce eddy losses. Stator and rotor in magnetic field produced power losses because of hysteresis effect when magnet was time and again magnetized; the losses are defined as hysteresis losses. Between rotor surface and the gas in gap can produces power losses due to friction when rotor turning, named windage losses. Because the three kinds of power losses need to be estimated for insuring AMB normal operation. The analysis of the power losses of journal and axial bearings are introduced respectively as follows.

Ⅲ. COPPER LOSSES

Copper losses can be exactly computed by Joule law. As follows:

$$p_{cu} = \frac{\rho_{cu} l_m}{A_n K_n} (ni)^2 \qquad (1)$$

where ρ_{cu} is resistance of power windings, $\Omega \cdot m$; l_m is the average length of each circle coils, m; A_n is the cross-sectional areas of winding, m^2; K_n is the cross-sectional coefficient, n is number of turns in the coil; i is current, A, the above equation is applied in both journal and axial bearings.

Ⅳ. IRON LOSSES

Generally speaking, iron losses occupy the largest proportion among the three kinds of power losses. Braking momentum by iron losses includes eddy losses and hysteresis losses. And the eddy losses are direct proportional to the square of frequency, the hysteresis losses are direct proportional to frequency.

A. Eddy losses

Eddy losses are produced both in stator and high speed rotor. Since rotor losses are not the same between journal and axial bearing, so described by separately.

There are some basic assumptions that all the bearings parameter and configures are the same; ignoring the effect of magnet of two sides in poles; electrical conductivity and magnetic permeability are const. ignoring magnetic saturation and magnetic hysteresis effect.

Eddy losses of journal bearing with laminated stator

Eddy losses will be produced when magnetic flux changed. Eddy current losses can be decreased by laminated iron core. Eddy losses of laminated mgnetic can be expressed as following formula[5]:

$$p_e = k_w f_u^2 B_{\max}^2 V_{fe} \qquad (2)$$

If magnetic field density distribution of laminated magnetic is sine wave and symmetrical, then can be expressed as

$$p_e = \frac{1}{6\rho} \pi^2 e^2 f_u^2 B_{\max}^2 V_{fe} \qquad (3)$$

where k_e is the coefficient of eddy losses, e is journal sheet thickness, f_u is dominant frequency of magnetic field density B(t), V_{fe} is the total volume, B_m is the max value of B(t), equations (2), (3) are not applied in solid magnet.

Eddy losess of journal bearing with laminated rotor

Rotors usually are laminated to decrease their eddy losses in some situations. And eddy losses of differential volume can be computed by following formula[6].:

$$dP_e = C_1 B_m^2 f_e^2 dV \qquad (4)$$

where C_1 lied on materia property is const; B_m is the max magnetic field density value; f_e is dominated frequency of B(t); and $f_e = r f_o$, r is edge pass and flux density shape constant, f_o is rotating frequency. So the eddy losses of the total volume can be expressed as

$$P_e = \int_V C_1 \gamma 2 B_m^2 f_0^2 dV \qquad (5)$$

Eddy losses of journal bearing with solid rotor

Eddy losses of rotor are very low when rotor is laminated. But because non-laminated (solid) rotor has many advantages such as the low cost, high intensity and so on, solid rotor has been successfully applied in most AMBs. Eddy losses are very large when rotor is solid, it will produce tangential force by magnetic field, and the tangential force will produce losses. Eddy losses can be expressed as

$$P_e = F_x \cdot V_x \qquad (6)$$

where F_x is tangential forec, V_x is surface speed of rotor.

Yu Lie[3] and Ha-Yong Kim[7] developed different models of computing different tangential forces separately based on the above method (the computational methods are the same in both NSNS and NNSS arrangement, only results are different)

Yu Lie presented a magnetic field analytical model of magnetic bearing-solid rotor system, giving tangetial force formula, and calculation results are in good agreement with those of experiment. Since skin depth of magnetic field is very small , compared with rotor radius, so rotor will be “unrolled” into a periodic sheet, utilized right-angle instead of cylinder coordinate, and the differences also is very few. Controlling currents function are folded by Fourier, we can compute the tangential force acted on rotor by Maxwell stress tensor[8], then the eddy losses are easily computed.

Saturation and nonlinearity of rotor's magnetic curve can't be ignored when high speed, so it isn't applied when high speed.

Ha-Yong Kim founded that analysis of eddy losses based on the change of magnetic flux change and number of poles is not very efficient , so they proposed a new eddy current brake model for the eddy loss in AMBs, as shown in Fig. 3. This paper computed eddy losses by the change of movable charge, not the magnetic flux , derived the surface charge density and the electric field intensity by using Coulomb's law, then the tangential force acted on rotor can be get, the particular computational methods are presented in paper[7].

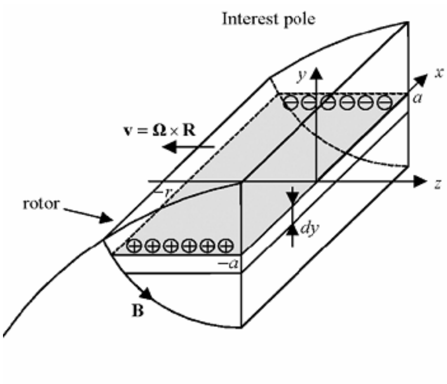

Fig.3 analysis model[8]

Eddy losses of journal bearing

Because equations (2), (3) are based on laminated iron, but experiment shows eddy losses of axial disk are more than that of laminated iron due to radial and axial vibrancy of thrust disk and so on, not be ignored[9].

Computational methods of eddy losses of axial bearing include three kinds of methods, experimental method, analytical and the finite element method.

Computational formula of eddy losses of axial bearing[9]

According to experimental results, eddy losses of axial disk P_{de} and soild magnet P_{me} can be computed by equation (7), and verified by equation (8).

$$P_{le} = K_{le}\frac{\delta_l^2 f_l^2 B_{l\max}^2 V_l}{\rho_l}\ (l = d, m) \qquad (7)$$

$$P_{le} \le 5 v_l V_l p_{5le}\ (l = d, m) \qquad (8)$$

where K_{le}, δ_l, f_l, B_{lmax} and V_l are the correct coefficient of eddy losses, sheet thickness, dominant frequency of magnetic field density B(t), the max value of B(t) and volume separately. v, V and p_{5e} are mass density, volume and ratio losses of the same standard accessory made by $5\times10^{-4}\text{m}^3$ sheet.

Analytical solutions of eddy losses of axial bearing

Sun Shou qun utilized analysis methods on both magnetic circuit and magnetic field, and gave analytical solutions and finite element of eddy current losses in steady state[4].

Two-dimension magnetic field computational model of axial magnetic bearing is shown in Fig. 2. Eddy losses of axial bearing can be computed by both Maxwell and Ohm laws.

Finite element solutions of eddy losses of axial bearing

Physical model Figure.4 shows finite element computational field of magnetic bearing. A1 is the air gap of magnet/winding and rotor/axial disk, A2 is magnet, A3 is rotor/axial disk, A4 is windings.

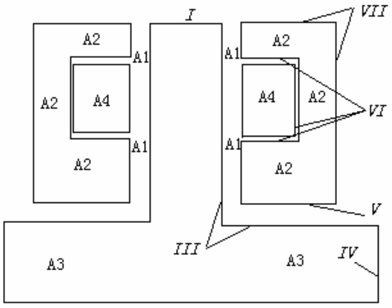

Fig. 4. computational field of temperature
of axial magnetic bearing

The inside and outside boundarys of the total area are shown in Fig. 4, the basic equations and boundary conditions are shown in table 1.

Table 1 basic equations and boundary conditions

Baisc equations	$\frac{\partial}{\partial z}(\nu\frac{\partial A}{\partial z})+\frac{\partial}{\partial r}(\nu\frac{\partial A}{\partial r})+J_s=\gamma\frac{\partial A}{\partial t}$
Boundary conditions	（1）without magnetic leak, boundary conditions of *I*、*IV* and *VII* which are parallel to magnetic circuit $\left.\frac{\partial A(i)}{\partial n}\right\|_I=\left.\frac{\partial A(i)}{\partial n}\right\|_{IV}=\left.\frac{\partial A(i)}{\partial n}\right\|_{VII}=0$ （2）insulation thickness in *VI* is zero $\left.\frac{\partial A(i)}{\partial n}\right\|_{VI}=0,\left.\frac{\partial J(i)}{\partial n}\right\|_{VI}=0$ （3）all inner boundary $A_1(i)=A_2(i)$ $n\times\left\{\frac{1}{\mu_1}[\nabla\times A_1(i)]-\frac{1}{\mu_2}[\nabla\times A_2(i)]\right\}=J(i)$

Cell griding Axial magnetic field is axisymmetric, number of nodes can be followed by anticlockwise sequence. And some assumptions are that there is only one materia in every element; and each boundary of magnetic field with only one condition.

Computation of eddy losses of axial bearing Eddy losses of every element can be computed at high frequency, according to eddy current density J_i , expressed as

$$p_i(t)\big|_{r_i,\phi_i,z_i} = \rho J_i^2 = \rho(J_{iz}^{\ 2} + J_{ir}^{\ 2})(W/m^3) \qquad (9)$$

where ρ is function of temperature:

$$\rho = \rho_0(1 + aT)(O \cdot m) \qquad (10)$$

Thus the total eddy losses are

$$P_e = \sum_{i=1}^{N_z} P_i(t)(W/m^3) \qquad (11)$$

B. Hysteresis losses

The analysis of hysteresis losses mainly bases on hysteresis loop and experimental methods.

Hysteresis losses of laminated magnet

Magnetic field density changes with *B-H* curve when magnetization, hysteresis losses $W_h = V_{fe}A_{BH}$, where A_{BH} is the area of hysteresis loop, V_{fe} is the volume of magnet. So hysteresis losses are direct proporational to frequency f_u. A_{BH} depends on the max value of magnetic field density. The equation is right to magnet material when the range of magnetic flux density is 0.2~1.5T. As follows:

$$P_h = k_h f_u B_m^{1.6} V_{fe} \qquad (12)$$

where material property constant k_h can be get according to experimential measurement and the area of hysteresis loop A_{BH}. The above equation and data in electric engineering only can be applied to one dimension changeable magnetic field. Hysteresis losses can be twice as many as the former because of rotating magnetic field, and the detailed losses can be get according to the area of hysteresis loop based on experiment.

Hysteresis losses of axial disk with solid magnet

When material and configuration of beaing is certain, hysteresis losses of solid magnet and axial disk are porprotional to eddy losses at steady state, as follows[10]:

$$P_{lh} \cong K_{lt} P_{lw} \qquad (13)$$

where P_{lh}, K_{lt} and P_{lw} are hysteresis losses of axial disk and solid magnet, hysteresis-eddy equivalent coefficient and eddy losses separately, they are functions of steady state.

Hysteresis model

David C. Meekerde developed the hysteresis model according to the phase difference between sinusoidal *B* and *H*[11]: *B* lags *H* by an angle φ_u denoted the "hysteresis angle" as shown in Fig. 5. The harmonics caused by saturation are ignored, and the hysteresis loop becomes an ellipse with the major axis making an angle of $\tan^{-1}\mu$ with the *H* axis. A complex permeability due to hysteresis can be defined through

$$B = \mu_h H: \ \mu_h = \mu e^{-j\varphi_u} \qquad (14)$$

So the average power per unit volume due to hysteresis losses is

$$\overline{p}_{n,hyst} = -\frac{nw}{2}\mathrm{Im}(\mu_h)\frac{\mathrm{Re}(\mu_n)}{\mathrm{Re}(\mu_h)}\left|h_{n,o}\right|^2 \qquad (15)$$

where $\mu_n = \mu_h \tanh(\sqrt{jn\omega\sigma\mu_h}\frac{d}{2})/(\sqrt{jn\omega\sigma\mu_h}\frac{d}{2})$, boundary conditions of two sides of laminated stator is $h_n = h_{n,0}$. Equation (15) only is applied in laminated magnet.

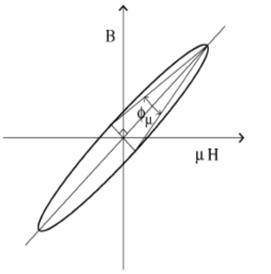

Fig. 5 Approximation of a hysteresis loop

The average total losses for the *n*th harmonic per unit volume(including both hysteresis and eddy effects)

$$\overline{p}_n = -\frac{nw}{2}\mathrm{Im}(\mu_n)\left|h_{n,o}\right|^2 \qquad (16)$$

The ratio of total losses to hysteresis losses for the *n*th harmonic can then be obtained by taking the ratio of (15) to (16)

$$\frac{\overline{p}_{n,hyst}}{\overline{p}_n} = -\tan(\phi_\mu)\frac{\mathrm{Re}(\mu_n)}{\mathrm{Im}(\mu_n)} \qquad (17)$$

According to the comparsion of model results and experimental data, it is necessary to take the effects of hysteresis into account when low speed. So hysteresis losses usually are ignored in high speed, not in low speed.

V. WINDAGE LOSSES

In many situations gap of bearing exist fluid or bearing needed be cooled by fluid (gas in general) , then it will produce windage losses when magnetic bearing turning. We need to divide bearing into cylinder and disk parts having the same frictional condition to compute windage losses.

Based on the flow model of gas in gap, we can compute friction coefficient according to Reynolds number, then get windage losses. Experiment shows the windage losses are proportional to the cube of the surface speed at the range between 150 and 400 m/s.

Table 2 and table 3 present both friction coefficient and windage losses formula of cylinder and disk parts separately.

Equations (1), (3) of table 2, and equation (1) of table 3 are applied in finite space, equation (2) of table 2 and table 3 in definite space, but when rotor speed are less than 20000rpm at laminar flow or are less than 60000rpm at turbulence, the equation (2) is applied in finite space. In comparison computational results to experimental data, they are agreement with each other.

And we compute viscous resistance by hydrodynamics, then get friction torque M[16]. Windage losses are easily computed according to $P=\sum M\omega$ [5]. Where ω is the mechanical angular frequency, rad/s.

Ⅵ. CONCLUSIONs

This paper summarized computational model and formula of copper losses, iron losses and windage losses of active magnetic bearing. Copper losses can be computed by Joule laws. Iron losses include eddy losses and hysteresis losses. Eddy losses approximately are proportional to square of frequency, and relative to arrangement of poles; hysteresis losses are proportional to frequency, so the proportion of hysteresis losses is very small at high frequency, it can be ignored in many occasions. But it is dominated at low frequency. At present computational methods of eddy losses are based on linearity of materia and ignoring of magnetic saturation. It makes that really eddy losses are more than computational results based on above assumptions because of nonlinearity of material property, skin effects of materia at high speed. So accurate results of eddy losses should take non-linear model into account. Windage losses can be computed by experiential formula according to gas state in gap, they usually are proportional to the cube of the surface speed at the range of between 150 and 400m/s.

Table 2 windage losses of cylinder part①

	Reynolds number	the friction coefficient	windage losses
1	$\mathrm{Re}=\frac{\rho\omega \mathrm{D}\delta}{2\mu}$	$c_f=\frac{0.0152}{\mathrm{Re}^{0.24}}$ [13]	$P=c_f\pi\rho\varpi^3(\mathrm{D}/2)^4 l$ [12]
2	$\mathrm{Re}=\rho\pi\omega(\mathrm{D}/2)^2/2\mu$	$c_f=1.728\times\mathrm{Re}^{-0.5}$（laminar flow） $=0.072\times\mathrm{Re}^{-0.2}$（turbulent flow）	$P=1.027\pi\rho\omega^2(D/2)^4 l c_f N/g$ [15]
3	$\mathrm{Re}=\rho \mathrm{r_m}\delta\omega/\mu$	$c_f=0.00759(r_m\cdot\delta\cdot\omega/\upsilon)^{-0.24}$	$P=1.2893\times10^{-9}\sum D^{3.76} l N^{2.76}$ [15]*

①: ρ- the density of the fluid, kg/m^3; *w*-the mechanical angular frequency, rad/s; D-diameter of rotor, m; δ-the radial air-gap length, m; μ-the dynamic viscosity of the fluid, kg/(m·s); l-the length of the rotor, m; N-rotor speed, rpm; r_m-radius of air-gap ; * N-rotor speed（$\times10^4$rpm）

Table 3 windage losses of disk part②

	Reynolds number	the friction coefficient	windage losses
1	$\mathrm{Re}=\frac{\rho\varpi r^2}{\mu}$ [11]	$c_f=\frac{0.15}{\mathrm{Re}^{0.2}}$ [14]	$P=\frac{1}{2}c_f\rho\varpi(r^5-r_{sh}^5)$ [12]
2	$\mathrm{Re}=\rho r^2\omega/\mu$	$c_f=1.728\times\mathrm{Re}^{-0.5}$（laminar flow） $=0.072\times\mathrm{Re}^{-0.2}$（turbulent flow）	$P=1.027\rho\omega^2 r^5 c_f N/2g$ [15]

②: r-radius of disk, m; r_{sh}-radius of shaft, m; for laminar flows $\mathrm{Re}\leqslant10^5$, for turbulent flow $\mathrm{Re}\geqslant5\times10^5$

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