Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Studies on a passive electromagnetic damper*

ZHENG Shui-ying[†1], PAN Xiao-hong[†‡2], MA Zhen-fei[1]
([1]Institute of Chemical Machinery, Zhejiang University, Hangzhou 310027, China)
([2]Institute of Manufacture Engineering, Zhejiang University, Hangzhou 310027, China)
[†]E-mail: zhengshuiying@zju.edu.cn; pan_xh@zju.edu.cn

Received Oct. 20, 2005; revision accepted May 1, 2006

Abstract: The passive electromagnetic damper has the same configuration as that of the electromagnetic bearing, but no sensors and no closed loop control are needed. Its robustness and no-contact structure are its great advantages. When the rotor vibrates, the electromagnetic field intensity in the air gap is altered, then fluctuating currents in the damper coils and eddy currents inside the surface layer of rotor are created. Damping force is caused by the fluctuating currents, while retardation torque is generated by eddy currents. The characteristics of a damper may be improved by adding an additional electrical circuit. Numerical studies showed that damping coefficient increases with increasing static current, but decreases with increasing frequency. And the damping coefficient of the improved damper at higher frequency is more evident than that of the original damper. Experimental results showed that the resonant vibration around the first critical speed was obviously suppressed by both types of passive electromagnetic damper.

Key words: Passive electromagnetic damper, Rotor, Vibration control
doi:10.1631/jzus.2006.AS0271 **Document code:** A **CLC number:** TH113

INTRODUCTION

Dampers are widely used in high speed rotary machines to improve the system stability and to suppress the resonant vibration around the first critical speed. Several types of damper for rotor systems have been proposed and studied, such as the squeeze film damper (Hahn, 1984; EL-Shafe and Hathout, 1993), the magnetorheological damper (Jolly *et al*., 1998; Noresson *et al*., 2002) and the active electromagnetic damper (Kasarda *et al*., 2004), etc.

Long-time research and practice found that the damping force will be created if only static current is supplied to electromagnetic bearing. This kind of damper needs no sensor and no closed loop control, so it is named as "the passive electromagnetic damper". Compared with the existing dampers it has the following advantages: a simple no-contact structure, low cost, and higher reliability. In this paper, the fluctuating current, damping coefficient, stiffness coefficient, and the additive power losses caused by the use of the electromagnetic damper are analyzed. Numerical and experimental studies are also carried out to show the characteristics of the damper.

WORKING PRINCIPLE OF THE PASSIVE ELECTROMAGNETIC DAMPER

The configuration of a passive electromagnetic damper is similar to that of a radial electromagnetic bearing, as shown in Fig.1. While constant voltage is supplied to each damper coil, the static current in the coils and static magnetic field in the air gaps between the rotor and the stator are formed. The magnetic circuits are shown by broken lines in Fig.1. As the rotor whirls, the thickness of the air gaps is changed, which leads to the change of the magnetic field. As a result the inductive currents in the coils are formed, though these inductive currents are much weaker than the static currents. Because the inductive current

---

[‡] Corresponding author

[*] Project (No. 50375140) supported by the National Natural Science Foundation of China

varies with time, it is called "the fluctuating current" in order to distinguish it from the static current. The fluctuating current and the rotor displacement have the same frequency, but different phases. This phase difference is the primary reason why the damping force is generated.

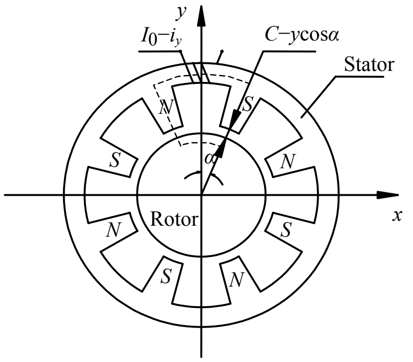

Fig.1 Structure of a passive damper

Analysis of the damping force

To simplify, the displacement in vertical direction may be supposed to be $y=y_0\mathrm{e}^{\mathrm{j}\omega t}$ (j is the unit of imaginary parts) while the rotor whirls, then the fluctuating current can be supposed to be $i_y=i_0\mathrm{e}^{\mathrm{j}(\omega t+\varphi_i)}$. Assuming that the eddy current effects, edge effects and material path reluctance are neglected, the magnetic flux can be calculated by applying Ampere's Law:

$$\phi=\frac{\mu_0 SN(I_0-i_y)}{2(C-y\cos\alpha)}, \tag{1}$$

where μ_0 is the vacuum magnetic inductivity, I_0 is the static current, S is the cross section area of a magnetic pole, N is the number of coils, C is the static thickness of the air gap, and α is the angle between the radial magnetic circuit and the coordinate which intersects the magnetic circuit, as shown in Fig.1.

The electrical loop of the damper is shown in Fig.2 (without additional circuit in the dashed-frame). Substituting Eq.(1) into the loop's voltage equation, $N\frac{\mathrm{d}\phi}{\mathrm{d}t}+R_1 I=U$, a new differential equation can be obtained:

$$-\frac{\mu_0 SN^2}{2C}\frac{\mathrm{d}i_y}{\mathrm{d}t}+\frac{\mu_0 SN^2 I_0\cos\alpha}{2C^2}\frac{\mathrm{d}y}{\mathrm{d}t}+R_1(I_0-i_y)=U, \tag{2}$$

where R is the coil's resistance, U is the voltage of constant voltage source.

Eq.(2) can be divided into two parts, time independent and time dependent. With the previous suppositions, y and i_y, the following equations are formed:

$$U-I_0R_1=0, \tag{3}$$

$$\mathrm{j}K_1 i_0\mathrm{e}^{\mathrm{j}(\omega t+\varphi_i)}-\mathrm{j}K_2 y_0\mathrm{e}^{\mathrm{j}\omega t}+R_1 i_0\mathrm{e}^{\mathrm{j}(\omega t+\varphi_i)}=0, \tag{4}$$

where $K_1=\frac{\mu_0 SN^2\omega}{2C}$, $K_2=\frac{\mu_0 SN^2 I_0\omega\cos\alpha}{2C^2}$.

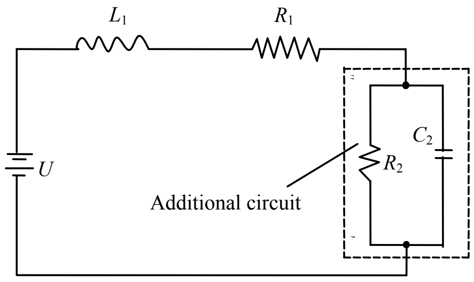

Fig.2 Equivalent circuit electromagnetic damper

Solving Eq.(3) and Eq.(4) yields the static and the fluctuating currents:

$$I_0=U/R_1, \tag{5}$$

$$i_y=K_i\mathrm{e}^{\mathrm{j}\varphi_i}y, \tag{6}$$

where K_i is magnifying coefficient, φ_i is the phase difference,

$$K_i=\frac{\mu_0 SN^2 I_0\omega\cos\alpha}{C\sqrt{(\mu_0 SN^2\omega)^2+(2R_1C)^2}},$$

$$\varphi_i=\mathrm{arctg}\frac{2CR_1}{\mu_0 SN^2\omega}.$$

Usually the damper's structure is symmetrical, so every magnetic pole's parameter, the number of coils, the coil's resistance, the air gaps' static thickness are the same, and while it is working, the damper coils in the same direction usually are connected to the same constant voltage source, so the static currents are equal. As the rotor is whirling, the phase of the rotor displacement for the up and down electromagnet poles has a difference of π, so it can be obtained from Eq.(6) that the fluctuating currents in the two electromagnet coils have a phase difference of π too. Then, the radial electromagnetic attraction forces between the vertical electromagnet poles and the rotor can be calculated by Eq.(7) with Maxwell's stress tensor:

$$F_y = \frac{\mu_0 S N^2 \cos\alpha}{4}\left[\frac{(I_0 - i_y)^2}{(C - y\cos\alpha)^2} - \frac{(I_0 + i_y)^2}{(C + y\cos\alpha)^2}\right]. \tag{7}$$

Since the displacement y is only a tiny amount compared with air gaps' static thickness C, and the fluctuating current i_y is also a tiny amount compared with static current I_0, the force F_y can be expanded with Taylor series at the point (y=0, i_y=0). When higher order elements are ignored, the linear expression of F_y is:

$$F_y = -\,\mathrm{j}\omega K_\mathrm{c} y - K_\mathrm{d} y - K_\mathrm{n} y, \tag{8}$$

where

$$K_\mathrm{c} = \frac{2{\mu_0}^2 S^2 N^4 {I_0}^2 R_1 \cos^2\alpha}{C^2[(\mu_0 S N^2 \omega)^2 + (2R_1 C)^2]},$$

$$K_\mathrm{d} = \frac{{\mu_0}^3 S^3 N^6 {I_0}^2 \omega^2 \cos^2\alpha}{C^3[(\mu_0 S N^2 \omega)^2 + (2R_1 C)^2]},$$

$$K_\mathrm{n} = -\frac{\mu_0 S N^2 {I_0}^2 \cos^2\alpha}{C^3}.$$

It is easy to understand by Eq.(8) that K_c and K_d are the damping coefficient and the stiffness coefficient respectively caused by the fluctuating current, while K_n is a negative stiffness coefficient similar to that of the electromagnetic bearing, which is independent from the fluctuating current.

Improvement

According to the calculation formula of K_c it can be seen that the damping coefficient is directly proportional to the square of static current. Unfortunately, the static current cannot be increased infinitely because the magnetic flux density in the magnetic medium will be saturated. On the other hand, the problems of retardation torque, additional power loss, heat generation will become more serious and the reduction of system stiffness will deteriorate sharply.

To improve the damping characteristic of the passive electromagnetic damper at the fixed static current, the new method of adding an additional circuit is put forward, shown by dashed-frame in Fig.2. L_1 and R_1 are respectively the equivalent inductance and resistance of the damper coil. R_2 and C_2 are the additional capacitance and resistance. Analyzing this electrical circuit by the same method as shown above, formulas for calculating damping and stiffness coefficients are deduced as follows:

$$\begin{aligned} K_\mathrm{c} = {} & 2(\mu_0 S N^2 I_0 \cos\alpha)^2 (R_1 + R_2 + R_1 R_2^2 C_2^2 \omega^2) \\ & /\{C^2[(\mu_0 S N^2 \omega + 2CR_1 R_2 C_2 \omega)^2 \\ & + (2R_1 C + 2R_2 C - \mu_0 S N^2 R_2 C_2 \omega^2)^2]\}, \end{aligned} \tag{9}$$

$$\begin{aligned} K_\mathrm{d} = {} & (\mu_0 S N^2 I_0 \omega \cos\alpha)^2 (\mu_0 S N^2 + \mu_0 S N^2 \omega^2 R_2^2 C_2^2 \\ & - 2CR_2^2 C_2)/\{C^3[(\mu_0 S N^2 \omega + 2CR_1 R_2 C_2 \omega)^2 \\ & + (2R_1 C + 2R_2 C - \mu_0 S N^2 R_2 C_2 \omega^2)^2]\}, \end{aligned} \tag{10}$$

$$K_\mathrm{n} = -\,\mu_0 S N^2 {I_0}^2 \cos^2\alpha / C^3. \tag{11}$$

Analysis of additive power loss

When an unlaminated rotor rotates in a passive electromagnetic damper, eddy currents are caused to flow inside the conducting material of the rotor. These eddy currents change the magnetic field of the passive damper and, therefore, the forces on the rotor depend on the eddy currents. In addition to the radial force, a tangential force acts on the rotor. It needs to be clarified that the effect of the eddy currents on the radial force is smaller, so it is ignored when analyzing the damping effect in the foregoing part.

The tangential force causes a retardation torque that has already been measured in many magnetic bearing systems. The existence of the retardation torque results in the changing of the rotating speed, the additive power loss, the heating of the rotor and other problems. For proper designing of a passive electromagnetic damper the tangential force must be considered.

The analytical model deduced by Ahrens and Kucera (1996) may be used to calculate the magnetic fields and tangential force F_t. This analytical solution has some advantages compared with numerical results achieved by finite element analysis because it gives a better insight into the problem. Furthermore, numerical calculations often do not succeed.

Then the additive power loss may be obtained:

$$P=F_t r\omega, \tag{12}$$

where r is the rotor radius.

NUMERICAL STUDIES

The rotor system with passive electromagnetic damper used in numerical and experimental studies is shown in Fig.3. The shaft is supported by two roller bearings, and the disc surrounded by the damper is mounted in the middle of the shaft. The rotor is driven by direct current gearshift electromotor through a flexible coupling. The shaft diameter is 11 mm, and the distance between the two bearings is 410 mm. The damper is designed with 8 magnet poles and 4 independent coils (up, down, left and right), as shown in Fig.1. The parameters of the damper are listed in Table 1.

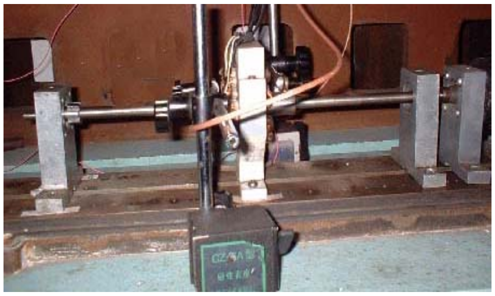

Fig.3 Jeffcott rotor system

Table 1 Parameters of the damper

Parameters	Value
Rotor radius (r)	43.3 mm
Coil turns (N)	720
Air gap (C)	0.65 mm
Pole area (S)	100 mm^2
Coil resistance (R)	29 Ω
Additional resistance (R_2)	50 Ω
Additional capacitance (C_2)	120 μF

The characteristics of the passive electromagnetic damper are first studied by numerical calculation. The calculated damping and stiffness coefficients depending on the static currents are shown in Figs.4 and 5, respectively, by which the whirl frequency is 95 Hz. It can be seen that the curve for the damping coefficient K_c is a parabola with increasing static current and that the damping coefficient of the improved passive damper is more evident than that of the passive damper without additional circuit. The stiffness coefficient, $K_z=K_d+K_n$, is always negative and the absolute value of K_z increases with increasing static current. The critical speed of a rotor system will be reduced because of this negative stiffness.

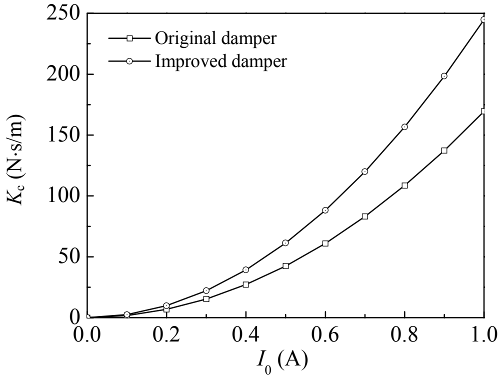

Fig.4 Damping coefficient vs static current

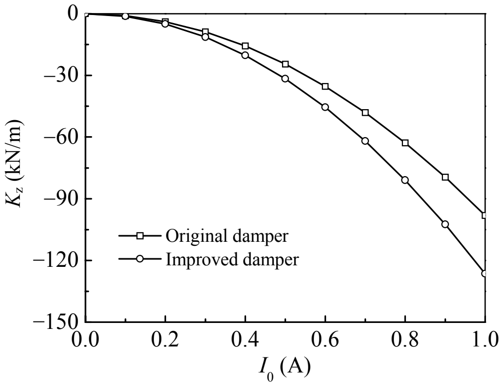

Fig.5 Stiffness coefficient vs static current

Fig.6 presents the relationship between the damping coefficient and the whirl frequency, and the effect of varying capacitance on the damping coefficient. It can be seen that the damping coefficient decreases rapidly with increasing whirl frequency if there is no additional circuit. So the passive electromagnetic damper is suitable only for rotor systems with lower rotating speeds. But for relatively higher rotating speeds, the damping coefficient can be increased by adding an additional circuit. For example, the damping coefficient at 90 Hz may be increased by about 43% with both a capacitance of 120 μF and 80 μF. At 150 Hz it may be increased by 33% with a capacitance of 120 μF, 52% with a capacitance of 80 μF and 84% with 40 μF, respectively. The calculation results also showed that the damping effect may be further enhanced by increasing additional resistance R_2. For different application the damping coefficient can be optimized for a special rotating speed by selecting suitable R_2 and C_2.

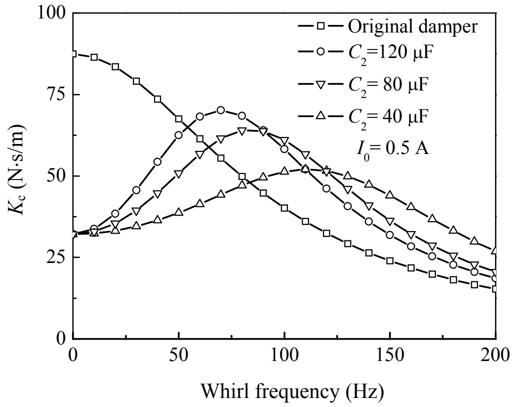

Fig.6 Damping coefficient vs whirl frequency

Fig.7 shows the curves of the additive power loss caused by retardation torque. It could be inferred that the additive power loss increases rapidly with increasing static current, particularly in unlaminated rotors working at high rotating speeds whose power loss is very big and cannot be ignored.

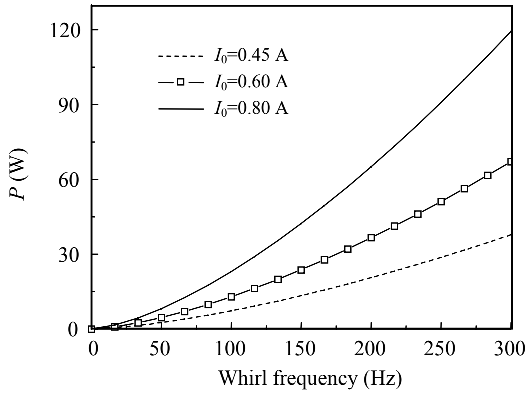

Fig.7 Additive power loss vs whirl frequency

EXPERIMENTS

In order to demonstrate the effect of the passive electromagnetic damper, experiments are also carried out on the rotor system shown in Fig.3.

The electrical currents flowing through the coils and the displacement of the disc are first measured and analyzed by FFT in order to testify the existence of the fluctuating current when the rotor is rotating. The results are shown in Figs.8 and 9. During the measurement, the rotating speed was 4248 r/min and only the lower coil is working. The static current in the lower coil is 0.51 A. One can find that there really exists a fluctuating current and that both fluctuating current and disc displacement have the same frequency. This result proves that the fluctuating current is caused by rotor vibration and that its previous assumption is correct.

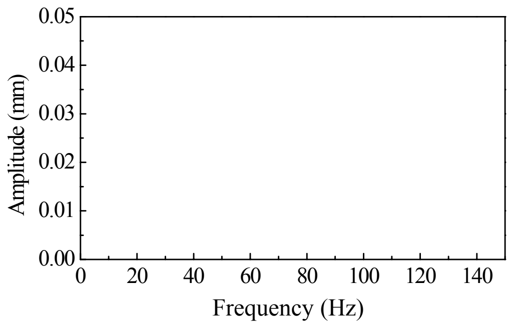

Fig.8 Vertical displacement's frequency amplitude diagram

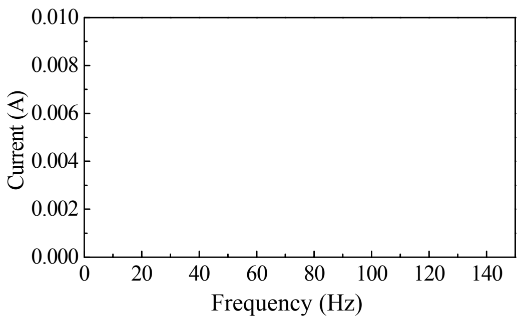

Fig.9 Fluctuating current's frequency amplitude diagram

Experiments for the unbalance responses of the rotor at different frequencies were carried out afterwards. Four coils work together and the static current in each coil is 0.45 A. Fig.10 shows the Bode plots of the rotor system, from which it can be seen that the resonance amplitude is suppressed by the passive damper to less than 25% of the original one. It can be clearly seen also that the improved damper has better damping effects. The peak of the system without damper appears at 101 Hz, while the peak of the system with damper appears at about 96 Hz. This phenomenon may be explained as follows: There is a negative stiffness introduced by the passive electromagnetic damper. This additional negative stiffness results in a reduction of the system stiffness. Therefore the natural frequency of the system with damper becomes lower.

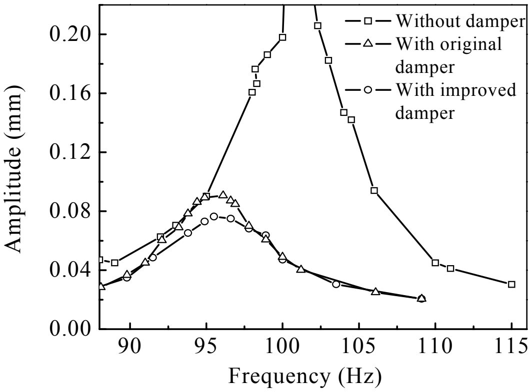

Fig.10 Unbalance responses of the rotor system

CONCLUSION

The change of the air gaps between the stator and the rotor leads to the change of the magnetic field of the damper. As a result fluctuating currents in the damper coils are generated and consequently damping forces on the rotor are formed. But the damping effects decrease rapidly with increasing frequency, so it is only suitable for the rotor working at lower frequencies. To improve the damping characteristic of the passive damper at relatively higher frequencies, a new method of adding an additional circuit is put forward. Experimental results showed that the use of both passive electromagnetic dampers can reduce vibration and allows passage through critical speed. The improved damper has better damping effects. For proper designing of a passive electromagnetic damper the parameters should be optimized for a special frequency range.

Passive electromagnetic damper has the advantages of a simple no-contact structure, low cost and higher reliability. If a rotor is unlaminated, the existence of the retardation torque will cause additive power loss, heat generation and other problems. Too large static currents will cause also undesired reduction of system stiffness and the change of the critical speed.

References

Ahrens, M., Kucera, L., 1996. Analytical Calculation of Fields, Forces and Losses of a Radial Magnetic Bearing with a Rotating Rotor Considering Eddy Currents. 5th International Symposium on Magnetic Bearing, Japan, p.253-258.

El-Shafei, A., Hathout, J., 1993. Experimental and analytical investigation of hybrid squeeze film dampers. *ASME Trans. on J. Eng. for Gas Turbine and Power*, **115**:353-359.

Hahn, E.J., 1984. Squeeze Film Dampers in General Multi-Mass Rotor Bearing Systems, Part 1: Theory. Report 1984/AM/1, UNSW, Sydney.

Jolly, M.R., Bender, J.W., Carlson, J.D., 1998. Properties and Applications of Magnetortheological Fluids. Proc. of SPIE-Int. Soc. Opt. Eng. SPIE, Washington, p.262-275.

Kasarda, M.E.F., Mendoza, H., Kirk, R.G., Wicks, A., 2004. Reduction of subsynchronous vibrations in a single-disk rotor using an active magnetic damper. *Mechanics Research Communications*, **31**(6):689-695. [doi:10.1016/j.mechrescom.2004.04.004]

Noresson, V., Ohlson, N.G., Nilsson, M., 2002. Design of electrorheological dampers by means of finite element analysis: theory and applications. *Materials and Design*, **23**(4):361-369. [doi:10.1016/S0261-3069(02)00006-7]