8th International Symposium on Magnetic Bearing
August 26-28, 2002, Mito, Japan

ELECTROMAGNETIC PASSIVE DAMPERS

Satoru Fukata

Department of Industrial Design, Kyushu Institute of Design, Fukuoka 815-8540, Japan

fukata@kyushu-id.ac.jp

ABSTRACT

Magnetic passive dampers are considered using electromagnets, which have similar damping effect to magnetic seesaw dampers originally proposed by Murakami and Satoh using permanent magnets. A linear model is presented in the frequency domain with the application of a model of electromagnets composed of solid iron cores. Equivalent spring stiffness and damping factor are formulated to define the natural frequency and damping ratio of the dampers. The analysis is checked in part with experimental results.

INTRODUCTION

Murakami and Satoh [1] proposed an innovative magnetic damper of passive type using permanent magnets. In this damping system, a moving iron core, which is supported by a beam or springs, is placed in a magnetic field generated by permanent magnets that are set between two stator cores. For the movement of the moving core, eddy currents are induced in the iron cores to preserve the initial magnetic flux against the variation of the magnetic field. This effect delays the variation of the magnetic force acting on the moving core and gives a phase-lag to the incremental magnetic force. This phase lag results in the phase lead to produce damping.

About the modeling of this damping system the inventors presented several forms [2, 3]. The author [4] applied a model of electromagnetic actuators composed of solid iron cores [5] based on Feeley's result [6]. In this application the author had an idea that magnetic damping is also realized using electromagnets with constant coil current.

The permanent magnetic dampers have a simpler composition and have a merit in cost. The electromagnetic dampers, however, are simpler in the construction of associated magnetic flux paths, and may have flexibility and some possibilities in practice.

In this paper, an electromagnetic damper is constructed to check the damping effect. A numerical analysis follows using some measurements.

A CONSTRUCTION OF ELECTROMAGNETIC DAMPERS

Figure 1 shows a schematic configuration of electromagnetic dampers in the two-dimensional application.

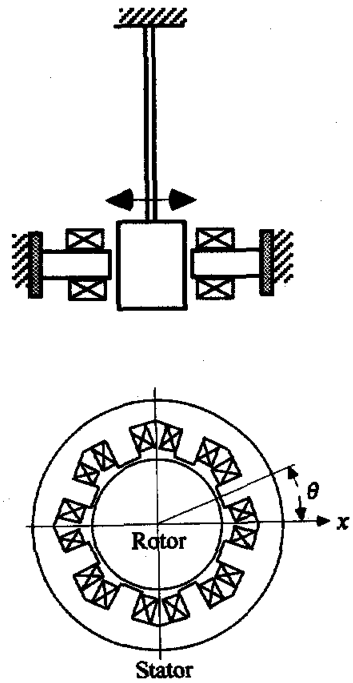

FIGURE 1: A configuration of electromagnetic passive dampers

A moving part (moving core, rotor in rotational machines) in the shape of a cylinder is placed with airgap on the inner side of a fixed part (stator). The stator has eight pole legs (more, in general, and not necessarily an even number) to set magnet coils and to be pole faces to the moving core. A pair of two adjoining coils is wound in the opposite direction each other, so that the magnetic flux path closes by itself through the stator core and a part of the moving core. The stator may be divided into four parts. All the electromagnet coils may be connected in series and driven with one power supply. The moving core is supposed to have sufficiently large recovery from its deviation close to the stator.

When the moving core moves, magnetic flux will increase on the side approaching to the stator, and decrease on the opposite, leaving side. For this motion, eddy currents are generated in the iron cores against the variation of magnetic flux. These eddy currents delay the variation of the magnetic flux, i. e., magnetic force. This delay produce a phase lead in the resulting recovery force.

The form of the electromagnetic damper may be quite similar to that of active magnetic bearings; but there is no need to control coil current, so that the electromagnet system becomes very simple.

MAGNETIC FORCE

Symbols and Notations

- A_a Cross-sectional area in airgap
- B_0 : Initial magnetic flux density
- f_n : Undamped natural frequency
- f_d : Damped natural frequency
- f_0 : Original, undamped natural frequency
- I_0 : Coil current
- $j := \sqrt{-1}$
- $k_m(s)$: Magnetic stiffness with positive real part for $s = j\omega$
- k_0 : Stiffness of undamped system
- l_0 : Nominal airgap length
- m : Equivalent mass
- N : Turns of electromagnet coil
- $R_C(s)$: Magnetic reluctance in iron cores
- R_{a0} : Magnetic reluctance in nominal airgap
- s : Laplace transform's variable
- x : Displacement at measuring point
- $x(s)$: Laplace transform of x (the same for all variables)
- x_c : Displacement of moving core
- z : Incremental airgap length
- γ : Phase of static magnetic hysteresis
- ς : Damping ratio
- θ : A half angle between two pole legs
- μ_o : Permeability of air
- ϕ : Incremental magnetic flux
- φ : Phase lag at damped natural frequency
- ω : Angular frequency
- $\omega_d := 2\pi f_d$

Incremental Magnetic Flux

We set two axes perpendicular to each other passing through the center of a pair of pole legs. We assume that the characteristics of the electromagnet systems are independent of each other. Then the dynamic model in each is similar to that of Up-shaped electromagnets.

Figure 2 shows an equivalent magnetic circuit of an electromagnet system, where

- F_{m1}, F_{m2} : Magnetomotive forces due to the variation of airgap length
- R_{a1}, R_{a2} : Magnetic reluctances in airgap
- R_1 : Magnetic reluctances of moving iron core
- R_{S1}, R_{S2} : Magnetic reluctances in pole legs
- R_{S3} : Magnetic reluctance of stator iron core

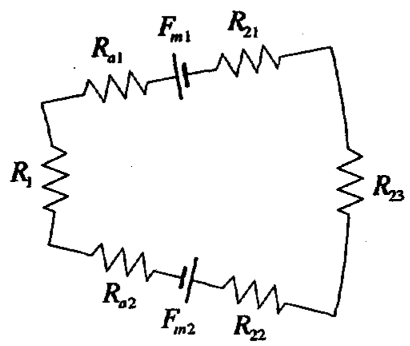

FIGURE 2: Equivalent magnetic circuit

We consider the dynamic characteristics of incremental magnetic flux due to the variation of the working airgap length. An analysis in [5] suggests that the model may be described in the frequency domain as follows:

$$\frac{\phi(s)}{z(s)} = \frac{NI_0}{(1+\bar{r}_0)\, l_0 R_{a0}} \frac{e^{-j\gamma}}{1+\bar{r}(s)}$$

$$= \frac{A_a B_0}{l_0} \frac{e^{-j\gamma}}{1+\bar{r}(s)} \tag{1}$$

where

$$\bar{r}(s) = \frac{R_C(s)}{R_{a0}}, \qquad \bar{r}_0 = \frac{R_C(0)}{R_{a0}}$$

$$R_{a0} = \frac{2l_0}{\mu_o A_a}, \qquad B_0 = \frac{\mu_0 N I_0}{2l_0(1+\bar{r}_0)} \tag{2}$$

and where the displacement z is taken positive when the working airgap becomes narrow.

We write the displacement of the moving core along an axis as x_c. If the displacement is sufficiently small, then we may write as

$$z \cong \cos\theta \cdot x_c \qquad (3)$$

where θ is the angle of the pole leg from the axis of the motion. Then, we have the relation

$$\frac{\phi(s)}{x_c(s)} = \frac{A_a B_0}{l_0}\cos\theta \cdot \frac{e^{-j\gamma}}{1+\bar{r}(s)} \qquad (4)$$

Incidentally, an analysis in [5] gives the relation between the incremental magnetic flux and the incremental coil current as follows:

$$\frac{\phi(s)}{i(s)} = \frac{N}{R_{a0}}\frac{e^{-j\gamma}}{1+\bar{r}(s)}$$

$$= \frac{(1+\bar{r}_0)A_a B_0}{I_0}\frac{e^{-j\gamma}}{1+\bar{r}(s)} \qquad (5)$$

Equations (4) and (5) gives the relation between the two transfer functions as

$$\frac{\phi(s)/x_c(s)}{\phi(s)/i(s)} = \frac{I_0\cos\theta}{(1+\bar{r}_0)l_0} \cong \frac{I_0}{l_0}\cos\theta \qquad (6)$$

Magnetic Force

We calculate the magnetic force by

$$F_m = \frac{1}{2\mu_0 A_a}\Phi^2 \qquad (7)$$

where Φ is the flux. When the initial flux is Φ_0($= A_a B_0$), the net force acting on the moving core on the both sides is written as

$$f_m = \frac{2}{2\mu_0 A_a}\left[(\Phi_0+\phi)^2 - (\Phi_0-\phi)^2\right]\cos\theta$$

$$= 4\frac{B_0}{\mu_0}\cos\theta\cdot\phi \qquad (8)$$

A MODEL OF DAMPING SYSTEM

Damping effect

Neglecting the damping effect of the original system, we describe the vibration system with the differential equation

$$m\ddot{x} + k_0 x = f_m(t) + f(t) \qquad (9)$$

where

m : Equivalent mass

k_0 : Stiffness of supporting system

$f(t)$: External force

$f_m(t)$: Magnetic net force

The variable x is the displacement of the measuring point. Assuming that this displacement is directly proportional to the displacement of the moving core, x_c, we write eq. (8) with the Laplace transforms as

$$f_m(s) = k_m(s)x(s) \qquad (10)$$

$$k_m(s) = 4\frac{B_0}{\mu_0}\cos\theta\cdot k_{\phi x}(s) \qquad (11)$$

where

$$k_{\phi x}(s) = \frac{\phi(s)}{x(s)} \qquad (12)$$

The above relation may be written in an explicit form as

$$k_m(s) = k_{m0}\frac{e^{-j\gamma}}{1+\bar{r}(s)} \qquad (13)$$

where

$$k_{m0} = 4k_x\frac{A_a B_0^2}{\mu_0 l_0}\cos^2\theta \qquad (14)$$

where k_x is the ratio of two displacements x_c/x . Then, the Laplace transform of eq. (9) with the initial conditions of zero reduces to

$$\frac{x(s)}{f(s)} = \frac{1}{ms^2 + k_0 - k_m(s)} \qquad (15)$$

We consider the frequency characteristics of eq. (15). The term $k_m(j\omega)$, whose inversion may be called magnetic stiffness, has frequency characteristics whose real part is positive and imaginary part is negative, as is seen from the form in eq. (13). In this way, a phase lead is produced in the resulting complex stiffness $k_0 - k_m(j\omega)$ whereas the resulting real stiffness decreases by the real part of $k_m(j\omega)$.

Equivalent Parameters of Damped System

We write the negative magnetic stiffness $k_m(j\omega)$ by the real part $k_{mR}(\omega)$ and the imaginary part $k_{mI}(\omega)$ as

$$k_m(j\omega) = k_{mR}(\omega) + jk_{mI}(\omega) \qquad (16)$$

We consider the equivalent stiffness $k(\omega)$ and damping coefficient $c(\omega)$ as

$$k(\omega) = k_0 - k_{mR}(\omega) \qquad (17)$$

$$c(\omega) = -\frac{k_{mI}(\omega)}{\omega} \tag{18}$$

Then, we define the undamped natural frequency ω_n and the damping ratio ς by

$$\omega_n = \sqrt{\frac{k(\omega_n)}{m}} \tag{19}$$

$$\varsigma = \frac{c(\omega_n)}{2m\omega_n} \tag{20}$$

If it is possible to estimate $k_m(j\omega)$ qualitatively, we can predict the undamped natural frequency as a solution of

$$m\omega_n^2 - k(\omega_n) = m\omega_n^2 + k_{mR}(\omega_n) - k_0 = 0 \tag{21}$$

It seems difficult to obtain the concrete expression of $k_m(s)$, in general; hence we will not discuss it here.

EXPERIMENTAL RESULTS

Experimental Setup

Figure 3 shows the experimental setup of one dimensional damper. A moving core is attached to the free end of a cantilever. The core is made of soft iron and 30.8mm in diameter; the lever is made of steel, 5.6mm in thickness and 30mm in width but 20mm near the fixed end. The beam has a target for displacement sensing and a bar for hammering. The primary data are as follows:

Pole legs: 6mm wide and 10mm high
Magnet coil: 45 turns per leg (0.65mm in diameter)
Mass of moving core: 0.24 kg
Nominal Airgap length: 0.6mm
Angle between two pole legs: $2\theta = 45$ deg

Damping Effects

The electromagnet coil current was given to set about 0.15T and 0.2T for the nominal magnetic flux density. The transient responses of free vibration are shown in Fig. 3 to check the damping effect. From the spectrum analysis, the damped natural frequencies were obtained as in Table 1.

Equivalent Parameters of One-Degree-of-Freedom

We consider the system an equivalent one-degree-of-freedom system with the output of displacement at the sensing point and the input of force at the hammering point. First, the undamped natural frequency was obtained from the free vibration. Next, the stiffness of the beam

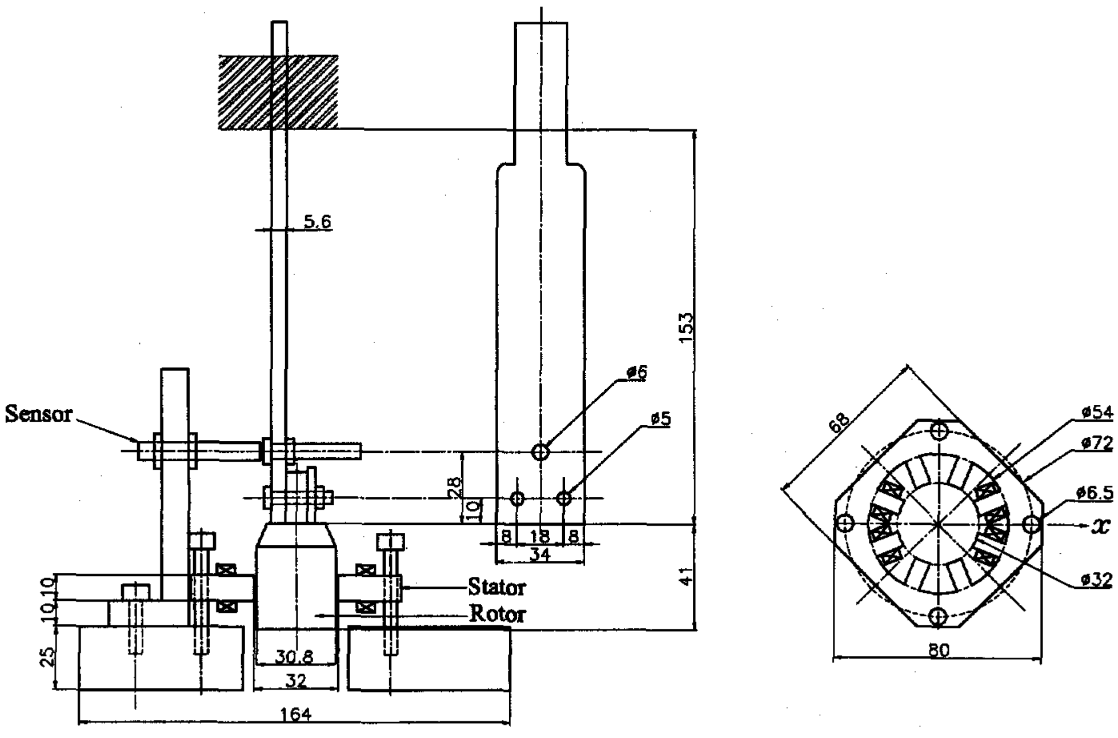

FIGURE 3: Experimental setup

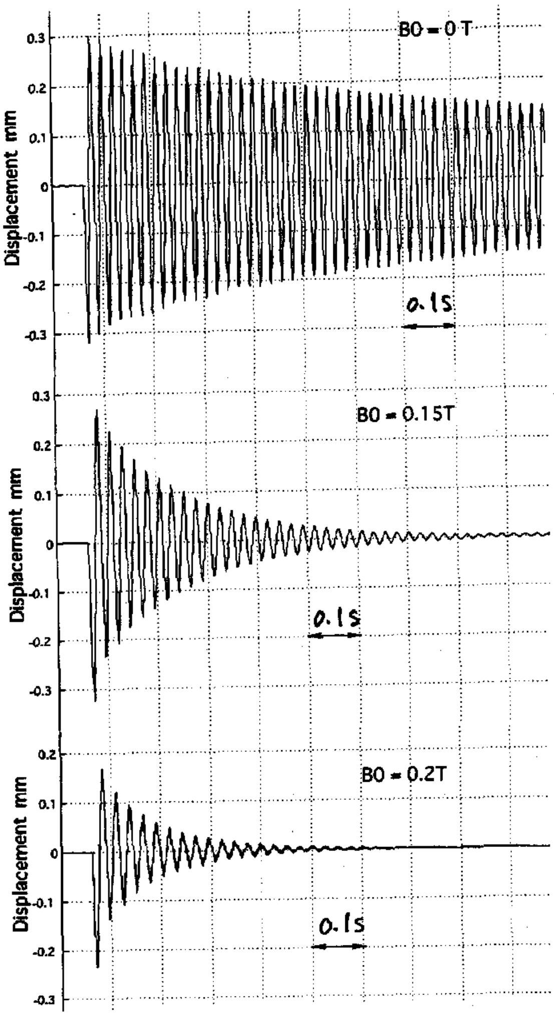

FIGURE 4: Damping effect in free vibration

was estimated from the static gain of the frequency transfer function between the displacement and the input force. With those results the equivalent mass was computed from the relation similar to eq. (19). The results were summarized as follows:

Original, undamped natural frequency

$f_0 = 46.5$ Hz

Equivalent stiffness of support $k_0 = 3.6\times 10^4$ N/m

Equivalent mass $m = 0.42$ kg

Incremental Magnetic Flux with Displacement

Search coils were wound around the pole legs close to pole face to detect the incremental magnetic flux. The frequency transfer characteristics to the displacement were measured in the free vibrations as follows.

Table 1: Experimental and numerical results

No.		①	②
Bias current	I_0 [A]	1.59	2.1
Theoretical values:			
Magnetic flux density	B_0 [T]	0.15	0.20
Static magnetic stiffness	$k_{m0}\times 10^4$ [N/m]	0.61	1.09
Measured values:			
Damped natural frequency	f_d [Hz]	41.5	38
Incremental magnetic flux by displacement $k_{\phi x}(j\omega_d)$			
Gain	[dB]	-36.1	-33.5
Absolute value	$\times 10^{-2}$ [T/m]	1.57	2.11
Phase lag	φ [deg]	10	8
Estimated values:			
Magnetic stiffness $k_m(j\omega_d)$ [N/m]			
Real part	$k_{mR}(\omega_d)\times 10^4$	0.68	1.23
Imaginary part	$k_{mI}(\omega_d)\times 10^4$	0.120	0.173
Undamped natural frequency	f_n [Hz]	42	38
Damping ratio	ς	0.021	0.036

$$k_{\phi x}(j\omega_d) = \left|k_{\phi x}(j\omega_d)\right| e^{-j\varphi} \qquad (22)$$

①: $\left|k_{\phi x}(j\omega_d)\right| = -36.1\text{dB}, \quad \varphi = 9.7\text{deg}$

②: $\left|k_{\phi x}(j\omega_d)\right| = -33.5\text{dB}, \quad \varphi = 7.5\text{deg}.$

Using these results, the magnetic stiffness $k_m(j\omega_d)$ is calculated with eq. (11) as shown in Table 1.

Natural Frequency and Damping Ratio

Provided that the damping ratio ς is so small that the damp natural frequency is close to the undamped one, eqs. (17) through (20) were applied with the above measured results to compute the parameters. The undamped natural frequency f_n and the damping ratio ς are shown in Table 1. These estimated parameters are in very good agreement with experimental results. This suggests that we can estimate those parameters with a good accuracy if we have a precise model for the incremental magnetic flux.

CONCLUSIONS

Electromagnetic passive dampers were considered and their damping effect was confirmed, associated with magnetic seesaw dampers using permanent magnets.

The primary subject remained in the modeling is the frequency characteristics of incremental flux for the variation of the airgap length. If we obtain a quantitatively useful model or data for them, we can estimate the damping parameters to design the dampers.

ACKNOWLEDGMENTS

I thank Ebara Corporation for presenting me a primary part of the experimental setup. I am also grateful to Drs. C. Murakami and I. Satoh for their kindness.

REFERENCES

1. Murakami, C. and Satoh, I., Study on New-type Passive Eddy Current Dampers, Proc. of the 9th Symposium on Electromagnetics and Dynamics, pp. 187-192, 1997 (in Japanese).
2. Murakami, C. and Satoh, I., Analysis of a Novel Magnetic Damper Using Bessel Function, Proc. of the 10th Symposium on Electromagnetics and Dynamics, pp. 29-34, 1998 (in Japanese).
3. Murakami, C. , Analysis of a Ring-Type-Two-DOF Magnetic Seesaw Damper, Proc. of the 11th Symposium on Electromagnetics and Dynamics, pp. 483-486, 1999 (in Japanese).
4. Fukata, S., A Model of Magnetic Seesaw Dampers, Proc. of the 13th Symposium on Electromagnetics and Dynamics, pp. 41-44, 2001 (in Japanese).
5. Fukata, S., A Frequency-Domain Model of Electromagnetic Actuators Composed of Solid Iron Cores, JSME Int. Journal, C-43-1, pp. 38-46, 2000.
6. Feeley, J. J., A Simple Dynamic Model for Eddy Currents in a Magnetic Actuators, IEEE Trans. on Magnetics, 32-2, pp. 453-459, 1996.