Displacement-Sensorless Control Using Electromagnets*

(Vibration Control by Current and Magnetic Flux Feedback)

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This paper describes vibration control using electromagnets without displacement sensors. An electromagnet for vibration control has two natural feedback loops. One feedback loop is from the gap length to the magnetic flux; the amount of the magnetic flux depends on the gap length. The other is from the magnetic flux to the coil voltage; the back electromotive force is derived from the time derivative of the magnetic flux. Through these two feedback loops, information on the gap length pours into the magnetic flux and the coil current; therefore, the gap length can be detected from these two state variables of the electromagnet without a displacement sensor (self-sensing). The displacement, being the fluctuation of this gap length, can be estimated by subtraction of the coil current from the magnetic flux. The vibration control using this estimated displacement consists of the negative feedback of the magnetic flux and the positive feedback of the coil current. The PD feedback of the estimated displacement can produce a damping effect and positive stiffness.

Key Words: Vibration Control, Sensor, Damping, Electromagnet, Current, Magnetic Flux

1. Introduction

A displacement sensor has been used for vibration control, magnetic bearings and magnetic levitation. By constituting velocity feedback and displacement feedback from the output of the displacement sensor, the damping of vibration has been increased and stable levitation has been realized. However, since the displacement sensor is limited in terms of size, it is frequent that the sensor cannot detect the displacement at the position of the electromagnet which is an actuator (noncolocation). At times like this, vibration is sometimes caused in the mode such that the node exists between the position of detection and the position of the electromagnet.

Even if displacement sensors are not used, the fluctuation of the gap length between the electromagnet and the vibration body can be estimated simply by detecting the state variables of the electromagnet.

For example, the velocity can be estimated from the relationship between the voltage and the current applied to the coil of the electromagnet^{(1),(2)}. Moreover, if the magnetic flux in magnetic poles of the electromagnet is detected, estimation of the fluctuation of the gap length, namely estimation of the displacement, is feasible⁽³⁾. When the electromagnet is driven by the pulse-width modulation (PWM) technique, information on the fluctuation of the gap length can be obtained from the relationship between the voltage and the current of carrier wave components⁽⁴⁾.

If the estimated displacement and the estimated velocity obtained in this way are fed back, vibration can be controlled. With this method, the position of detection coincides with the position of the electromagnet. Moreover, since this method does not require any displacement sensors, vibration control can be realized at low cost.

This paper describes the method of controlling vibration by using the feedback of the current and the magnetic flux of the electromagnet. First, it is elucidated that there is self-sensing action in the electromagnet, and the fluctuation of the gap length can be estimated from the current and the magnetic

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flux. Next, it is shown that vibration can be controlled with the PD feedback of the estimated displacement even though displacement sensors are not used. Moreover, an experiment on controlling the vibration of a thin steel plate by using electromagnets is carried out, and these phenomena are confirmed.

2. Theory

2.1 Basic equations

The relationship between coil voltage e and coil current i in an electromagnet becomes as follows if the back electromotive force is taken into account.

$$e - N \frac{d\Phi_t}{dt} = Ri \quad (1)$$

where N is the number of turns of coil and R is coil resistance. The magnetic flux Φ_t that flows in the iron core is expressed as the sum of the effective magnetic flux Φ_g in the gap part and the leakage magnetic flux Φ_l .

$$\Phi_t = \Phi_g + \Phi_l \quad (2)$$

$$\Phi_g = P_g Ni = \frac{\mu_0 A_g}{2\delta} Ni \quad (3)$$

$$\Phi_l = P_l Ni \quad (4)$$

where μ_0 is the permeability in vacuum, A_g is the magnetic pole area and δ is the gap length. It was assumed that the gap permeance P_g is inversely proportional to the gap length δ and the leakage permeance P_l does not depend on the gap length δ . The magnetic force f is proportional to the square of the effective magnetic flux Φ_g in the gap part.

$$f = \frac{\Phi_g^2}{\mu_0 A_g} \quad (5)$$

These relationships are shown by a block diagram in Fig. 1. The diagram expresses the action of the electromagnet in a lumped parameter model and it shows the relationships among the coil voltage e , the coil current i , the gap length δ and the magnetic force f . As shown in Fig. 1, there are two natural feedback loops in the electromagnet. One feedback loop is gap dependence of the effective magnetic flux Φ_g and the other is the back electromotive force derived from the time derivative of the total magnetic flux Φ_t . By

Fig. 1 Nonlinear model of an electromagnet

these two feedback loops, even if the coil voltage e does not change, when the gap length δ fluctuates, the coil current i and the effective magnetic flux Φ_g fluctuate.

In order to investigate the transfer property of the electromagnet, equations for relationships among infinitesimal quantities are derived from Eqs. (1)–(5).

$$\Delta e - Ns\Delta\Phi_t = R\Delta i \quad (6)$$

$$\Delta\Phi_t = \Delta\Phi_g + \Delta\Phi_l \quad (7)$$

$$\Delta\Phi_g = P_{g0}N\Delta i + P_{g0}N\frac{I}{X}\Delta x \quad (8)$$

$$\Delta\Phi_l = P_l N\Delta i \quad (9)$$

$$\Delta f = \frac{I}{X}N\Delta\Phi_g \quad (10)$$

where Δ represents an infinitesimal quantity and s is the Laplace operator. P_{g0} , I and X represent the steady components of the gap permeance, the coil current and the gap length. The positive direction of the displacement x was defined as the direction in which the gap length decreases.

$$\Delta x = -\Delta\delta \quad (11)$$

The relationships of Eqs. (6)–(10) are shown by a block diagram in Fig. 2. Figure 2 is the linearized version of Fig. 1.

2.2 Self-sensing action and natural velocity feedback

Even if displacement sensors are not used, the fluctuation of the gap length can be estimated simply by detecting the state variables of the electromagnet. It is seen in the upper diagram of Fig. 2 that the fluctuation of the gap length Δx exerts an influence on the magnetic flux $\Delta\Phi_g$ and the coil current Δi . In

Fig. 2 Linear model of an electromagnet

order to clarify what that influence is, this diagram is rearranged in the lower figure. In this new form, the dot ($\dot{}$) indicates the derivative regarding time and a is the time constant of the coil. As shown there, information on the velocity $\Delta\dot{x}$ is included in the coil current Δi and information on the velocity $\Delta\dot{x}$ and the displacement Δx is included in the magnetic flux $\Delta\Phi_g$ (self-sensing action).

With this self-sensing action, the effect of velocity feedback is obtained even simply by applying a constant voltage to the electromagnet. Even when the coil voltage does not fluctuate and $\Delta e = 0$, namely when only a constant voltage is applied, the coil current Δi fluctuates due to the velocity $\Delta\dot{x}$, and a damping force Δf in proportion to the velocity occurs (natural velocity feedback).

Furthermore, it is shown that the feedback loop on the right side in the lower diagram of Fig. 2 is positive feedback and an unstable magnetic force exists. The electromagnet to which only a constant voltage is applied possesses negative spring characteristics. In the coil current Δi , information on the velocity $\Delta\dot{x}$ is included, but that on the displacement Δx is not. Accordingly, by using the coil current Δi , velocity feedback can be constituted, but displacement feedback cannot. This fact indicates that simply detecting the coil current Δi and constituting its feedback will not make it possible to compensate for the negative spring characteristics that the electromagnet possesses.

2.3 Current PD positive feedback control⁽⁵⁾

First, the meaning of the feedback of the coil current Δi is considered. As seen in the lower diagram of Fig. 2, the velocity $\Delta\dot{x}$ can be estimated from the coil voltage Δe and the coil current Δi .

$$\Delta\dot{x} = \frac{\{\Delta e - R(1+as)\Delta i\}}{N^2 P_{g0} \frac{I}{X}} \quad (12)$$

Constituting velocity feedback by using this estimated value of velocity becomes equivalent to providing PD positive feedback of the coil current to the coil voltage. As known from Eq. (12), the feedback of the estimated velocity is the feedback of the coil voltage Δe and the coil current Δi . The feedback of the coil voltage Δe can be canceled by changing the feedback gain, and only the term of the positive feedback of the coil current Δi remains.

Next, the function of this current positive feedback control is investigated. The block diagram of current PD positive feedback control is shown in Fig. 3, where K_P represents the proportional gain, K_D represents the differential gain, K_0 represents the power amplifier gain, and, R_s is the value of the shunt resistance. When the current PD positive feedback

Fig. 3 Current feedback

loop shown in the upper diagram of Fig. 3 is put together as the forward-facing transfer function, it becomes the lower diagram of Fig. 3. It is known in that diagram that the current PD positive feedback control amplifies the effect of natural velocity feedback. The proportional gain K_P increases the effect of velocity feedback in the lower frequency region, and the differential gain K_D increases it in the high-frequency region.

In this way, when the coil current is detected and used for control, the effect of natural velocity feedback can be enlarged. However, since information on the displacement is not included in the coil current, displacement feedback cannot be constituted. Therefore, by current feedback only, the negative spring characteristics that the electromagnet possesses can not be compensated.

2.4 Estimation of displacement using current and magnetic flux

Next, we attempt to detect not only the coil current but also the magnetic flux and to use them for control. In the magnetic flux, information on the displacement is included; therefore, displacement feedback can be constituted. As seen in the lower diagram of Fig. 2, by using the coil current Δi and the effective magnetic flux $\Delta\Phi_g$ in the gap part, the fluctuation of the gap length Δx can be estimated.

$$\Delta x = \frac{(N\Delta\Phi_g - N^2 P_{g0} \Delta i)}{N^2 P_{g0} \frac{I}{X}} \quad (13)$$

By applying PD operation to this estimated value of the fluctuation of the gap length and feeding it back to the coil voltage, feedback of the displacement and the velocity is realized. The block diagram of the feedback control of the coil current and the magnetic

flux is shown in Fig. 4, where K_ϕ is the magnetic flux detection gain and $K_{i\phi}$ is the current-magnetic flux conversion gain. The mark (*) attached to the shoulder indicates the voltage signals of respective physical quantities. As shown in Fig. 4, the feedback of the estimated displacement consists of the negative feedback of the magnetic flux $\Delta\phi_g$ and the positive feedback of the coil current Δi . Namely, the PD feedback control system of the estimated displacement has become the control system in which the magnetic flux PD negative feedback loop is added to the current PD positive feedback loop mentioned in section 2.3.

3. Experimental

3.1 Experimental apparatus

An experiment to control the vibration of a thin steel plate by using electromagnets was carried out. Even though displacement sensors were not used, the vibration was controlled by the feedback of only the coil current and the magnetic flux. The outline of the apparatus used for the experiment is shown in Fig. 5⁽⁶⁾. A thin steel plate 1470 mm in length, 200 mm in width and 0.6 mm in thickness was fixed to the experimental apparatus, and a specified tension was applied.

Four electromagnets were used to control the vibration of this plate. The electromagnets were installed under the plate and were each controlled

Fig. 4 Current and magnetic flux feedback

Fig. 5 Experimental apparatus

independently. In order to control as many vibration modes as possible, the electromagnets for vibration control were arranged not only in twos in the width direction but also in two rows in the longitudinal direction of the plate. Moreover, the current flowing in the electromagnets was detected with shunt resistances, and the magnetic flux in the gap parts was detected with Hall elements affixed to the middle of the magnetic poles of the electromagnets.

Electromagnets for excitation and a displacement sensor for measurement were used for examining the vibration characteristics of the plate which is controlled in this way. The electromagnets installed above and under the plate excited the vibration of the plate without touching it, based on an excitation signal. Two sets of electromagnets for excitation were arranged in the direction of plate width. Moreover, in order to measure the vibration of the plate, a displacement sensor of the eddy current type was installed near the fixed end of the plate.

3.2 Self-sensing action

As shown in section 2.2, the coil current Δi and the magnetic flux $\Delta\phi_g$ are subjected to the effect of the fluctuation of the gap length Δx . When vibration is generated on the plate and the gap length fluctuates, the coil current and the magnetic flux also fluctuate. This self-sensing action was examined.

A constant voltage was applied to only one of the electromagnets for vibration control. A step voltage was input into the electromagnets for excitation, and the displacement of the plate, the coil current and the magnetic flux were measured. The eddy-current-type sensor was arranged just above the electromagnet for vibration control so that the fluctuation of the gap length between the electromagnet and the plate was detected. The measured waveforms are shown in Fig. 6.

It can be seen in Fig. 6 that when the vibration displacement is large, the fluctuations of the coil current and the magnetic flux are also large. Even if

Fig. 6 Self-sensing action of an electromagnet

only a constant voltage is applied to the electromagnet for vibration control, the current flowing in the coil and the magnetic flux at the middle of the magnetic pole fluctuate corresponding to the vibration displacement of the plate. Namely, the electromagnet itself senses the vibration of the plate. This means that even if an external displacement sensor is not used, the vibration of the plate can be estimated simply by detecting the state variables of the electromagnet.

3.3 Estimation of displacement using current and magnetic flux

Using the detected signals of the coil current and the magnetic flux, the fluctuation of the gap length can be estimated. According to Eq. (3), the magnetic flux Φ_g is proportional to the coil current i and inversely proportional to the gap length δ ; thereupon, the gap length δ should be proportional to the ratio of the coil current signal i^* to the magnetic flux signal Φ_g^* .

$$\delta \propto \frac{i^*}{\Phi_g^*} \quad (14)$$

An experiment to confirm the relationship of Eq. (14) was carried out. The gap length and the coil current were varied in a number of steps, and the magnetic flux was measured. The relationship of the ratio i^*/Φ_g^* with the gap length δ is shown in Fig. 7. As seen in Fig. 7, the gap length can be estimated by using the ratio i^*/Φ_g^* .

In order to estimate the displacement Δx , the relationship among the infinitesimal quantities is derived from Eq. (14). When the relationship of Eq. (11) is taken into consideration, the vibration displacement Δx can be estimated using the coil current signal Δi^* and the magnetic flux signal $\Delta \Phi_g^*$.

$$\Delta x \propto \Delta \Phi_g^* - K_{i\phi} \Delta i^* \quad (15)$$

$$K_{i\phi} = \frac{\Phi_{g0}^*}{I^*} \quad (16)$$

Fig. 7 Estimation of gap length using current and magnetic flux

where $K_{i\phi}$ depends on the magnitude of the steady components.

The output of the displacement estimator which was constituted on the basis of the relationship of Eq. (15) was compared with the output of the displacement sensor for measurement. A constant voltage was applied beforehand to only one of the four electromagnets for vibration control, and the displacement estimator was constituted. By inputting random noise into the electromagnets for excitation, the plate was vibrated. The vibration was measured with the displacement estimator and the displacement sensor. The displacement estimator estimates the displacement in the gap part, using the current flowing in the coil and the magnetic flux in the magnetic pole part. This displacement in the gap part was detected with the displacement sensor for measurement arranged just above the electromagnet for vibration control. The transfer functions from the random noise to the output of the displacement sensor and the displacement estimator are shown in Fig. 8. As compared with the displacement sensor, the sensitivity of the displacement estimator was lower by about 25 dB throughout the entire frequency region, but it has estimated the amplitude and the phase of vibration with good accuracy.

(a) Result of measurement with a displacement sensor

(b) Result of measurement with a displacement estimator

Fig. 8 Comparison of the result of measurement with a displacement sensor and a displacement estimator

3.4 Vibration control characteristics

The vibration control characteristics were investigated. Comparisons were made among the cases when current did not flow at all in the electromagnets for vibration control, when a constant voltage was applied, when control with current PD positive feedback was carried out, and when control with the PD feedback of the displacement estimated using the coil current and the magnetic flux was carried out. By inputting random noise into the electromagnets for excitation, the plate was vibrated. The vibration was detected with the displacement sensor arranged near the fixed end of the plate. The transfer function from the input signal of the electromagnets for excitation to the output signal of the sensor for measurement represents the vibration characteristics of the plate. The vibration characteristics of the plate measured in this way are shown in Fig. 9 - Fig. 11.

The vibration characteristics of the plate when current did not flow in the electromagnets are shown with the dotted lines in Fig. 9 - Fig. 11. The natural frequencies of the plate exist near 20 Hz, 40 Hz, 60 Hz and 80 Hz. The fact that the natural frequencies existed at equal intervals shows that the vibration of this system resembles that of a chord. It can be said that the factor determining the natural frequencies is the tension of the plate, and the flexural rigidity of the plate did not exert much effect. Moreover, the natural frequencies existed in pairs of two, and this fact corresponds to the parallel mode in which two separate points in the direction of plate width vibrated in the same phase, and to the torsional mode in which they vibrated in opposite phase.

Even by applying simply a constant voltage to the electromagnets for vibration control, the vibration of the plate was damped (natural velocity feedback). The vibration characteristics at this time are shown with the solid line in Fig. 9. As can be seen in Fig. 9, the vibration near 20 Hz was lowered by about 20 dB. Moreover, the vibration near 40 Hz was lowered by about 10 dB, but those near 60 Hz and 80 Hz were hardly damped.

Furthermore, in the vicinity of the DC component, the transfer function has increased by about 4 dB. As mentioned in section 2. 2, when a constant voltage was applied to the electromagnets, the negative spring characteristics arose. The magnitude of the negative spring is subtracted from that of the positive spring arising due to the tension of the plate, and the static rigidity against external forces is lowered. Therefore, the transfer function from external forces to the vibration displacement of the plate increases near the DC component.

Current PD positive feedback control amplifies

Fig. 9 Damping effect by natural velocity feedback

Fig. 10 Damping effect by current feedback

Fig. 11 Damping effect by current and magnetic flux feedback

the damping effect by natural velocity feedback. The vibration characteristics of the plate when this control was applied are shown with the solid line in Fig. 10. Also, the vibrations near 60 Hz and 80 Hz, which were not damped when only a constant voltage was applied, were reduced by about 10 dB by this control. Moreover, the vibrations near 20 Hz and 40 Hz, in which the damping effect was observed, were lowered further.

When control with the PD feedback of the displacement estimated using the coil current and the magnetic flux was carried out, the damping characteristics were improved. The vibration characteristics of the plate when this control was applied are shown with the solid line in Fig. 11. Not only was the damping increased compared with the case of current

PD positive feedback control, but also the negative spring characteristics of the electromagnets were compensated.

4. Conclusions

In this paper, it was clarified that vibration can be controlled using electromagnets without displacement sensors. The obtained results are summarized as follows.

(1) There is self-sensing action in the electromagnet. The coil current includes information on the vibration velocity, and the magnetic flux in the gap part includes that on the vibration displacement.

(2) Even by simply applying a constant voltage to the electromagnet, the same effect as that of velocity feedback arose, and damping force proportional to velocity occurred.

(3) Current PD positive feedback control amplified the damping effect of natural velocity feedback. However, the negative spring characteristics that the electromagnet possesses cannot be compensated simply by feedback of the coil current.

(4) Displacement can be estimated using the coil current and the magnetic flux. The control with the PD feedback of this estimated displacement improved the damping characteristics and also compensated the

negative spring characteristics of the electromagnet.

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