Sensorless Magnetic Levitation Control by Measuring the PWM Carrier Frequency Component

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ABSTRACT

Active magnetic levitation control has been gradually used for clean room carrier or highspeed magnetic bearings. Usually it requires a displacement sensor causing some trouble of noncollocated sensor and actuator arrangement, and a good sensor is expensive. A sensorless active magnetic control has been reported, but not so successful.

This paper introduces a simple sensorless active levitation control. The magnet is driven by a constant voltage pulse width modulated (PWM) signal. The PWM carrier frequency component of the measured current is the function of the magnetic inductance, which is the function of the gap displacement. This signal is put into a detecting circuit to produce the control signal. A simple test apparatus is made to clarify its capability. The results are showing high possibility of this sensorless levitation control.

INTRODUCTION

Active magnetic levitation control has miraculous advantage of noncontact supporting capability, hence it has been gradually used. Usually it requires a displacement sensor. Eddy current type sensor has been widely used to produce the control signal. Magnetic actuator produces the magnetic flux which interacts adversely to the eddy current sensor. Hence the sensor is located with some distance from the actuator. This noncollocated arrangement affects adversely to the feedback stability.

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To overcome this difficulty, a sensorless active magnetic bearing has been reported by D. Vischer and H. Bleuler 1990[1], but not so successful. J. Jin, et. al. 1991 reported a sensorless AC magnetic levitation control, but not tested[2]. In our previous paper[3], the velocity is estimated from the driving voltage and current which is successfully used to reduce the resonant vibration.

This paper introduces a practical method of using the electromagnet as a levitation actuator and a gap sensor. Power magnetic actuator is driven by a pulse width modulated (PWM) signal to control the attractive force efficiently. The inductance of the magnet is a function of the gap displacement to the levitated object. Hence the gap distance can be calculated from the PWM carrier component of the driving voltage and current. Hence the electromagnet can be used as an attractive actuator and gap displacement sensor. The similar method was introduced by D. Visher, but not so successful[4]. In this paper, a simple experimental setup is constructed to confirm the capability of the proposed sensorless magnetic levitation.

MODELING OF ACTIVE LEVITATION SYSTEM

Figure 1 shows the proposed sensorless active levitation system. For simplicity, the levitated object is assumed to move only in vertical direction. The hysteresis and saturation can be neglected. The magnet is also assumed to produce the attractive force $f(t)$ proportional to the

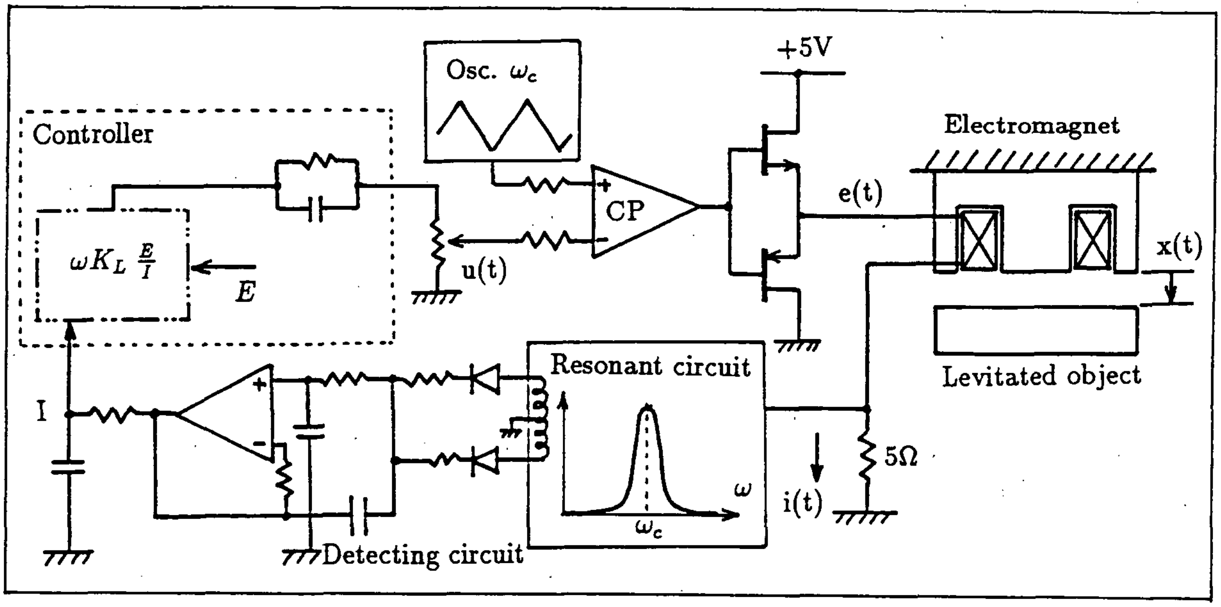


Fig.1 Scheme of the proposed sensorless levitation control

command signal $u(t)$.

$$f(t) = K_f u(t) \tag{1}$$

Then the equation of motion of the levitated object is written by

$$m\frac{d^2x(t)}{dt^2} = mg - f(t) \tag{2}$$

GAP ESTIMATION CIRCUIT

The driving circuit of magnet is considered to have the resistance $R[\Omega]$ and inductance $L[H]$. The inductance L is a function of the gap displacement x. Then the equation of driving circuit is written by

$$\frac{dL(x)i(t)}{dt} + Ri(t) = e(t) \tag{3}$$

The driving voltage $e(t)$ is modulated by a PWM signal. The carrier frequency ω_c is high enough (30 kHz in this case) so that the carrier frequency component of eq.(3) can be written as the following.

$$j\omega_c L(x)Ie^{j\omega_c t} + RIe^{j\omega_c t} = Ee^{j\omega_c t} \tag{4}$$

where ω_c is the carrier frequency, E and I are the fundamental carrier components of $e(t)$ and $i(t)$. Since ω_c is high, the second part of the left side of eq.(4) can be neglected.

$$\frac{I}{E} = \frac{1}{\omega_c L(x)} \tag{5}$$

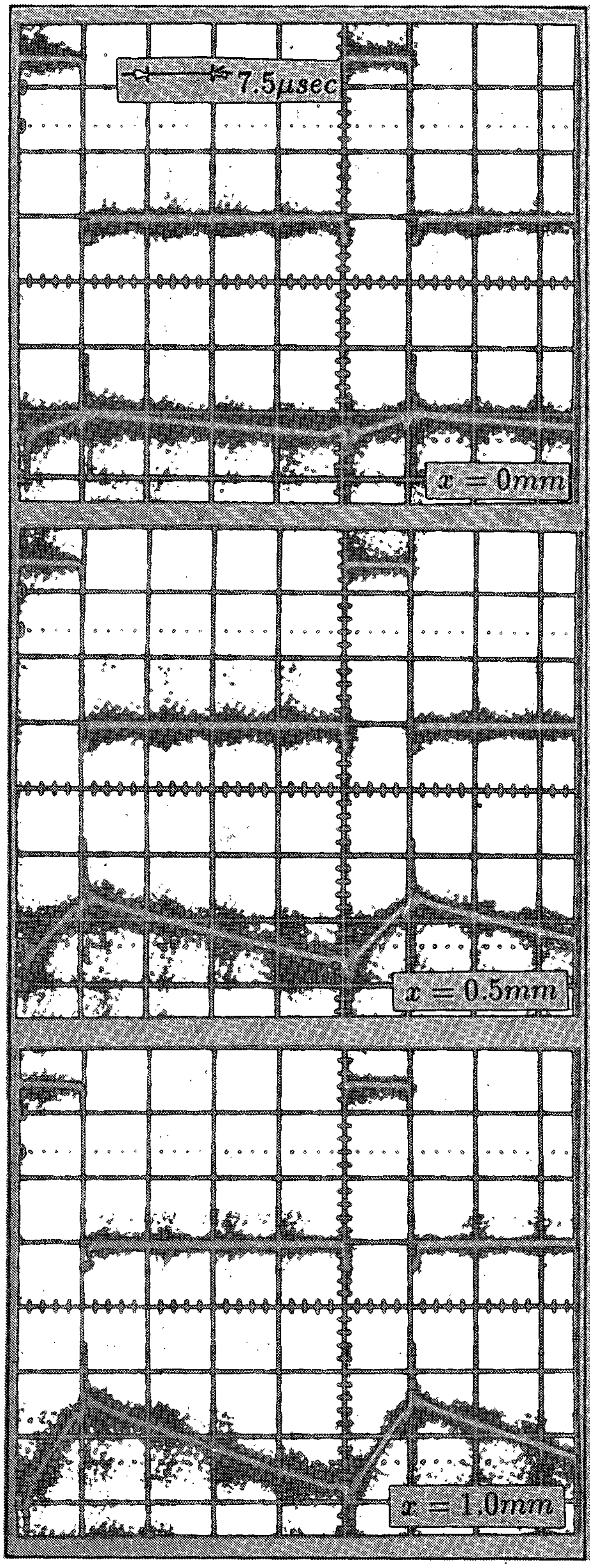
If we neglect the magnetic resistance of the core material, the inductance is inversely proportional to the gap displacement; $L(x) = \frac{K_L}{x}$. Then we have

$$x = \omega_c K_L \frac{I}{E} \tag{6}$$

The driving voltage $e(t)$ is a pulse width modulated by the command signal u. The E can be calculated by the Fourier Transformation.

$$E = A\sin \pi u \tag{7}$$

where u is the duty ratio.



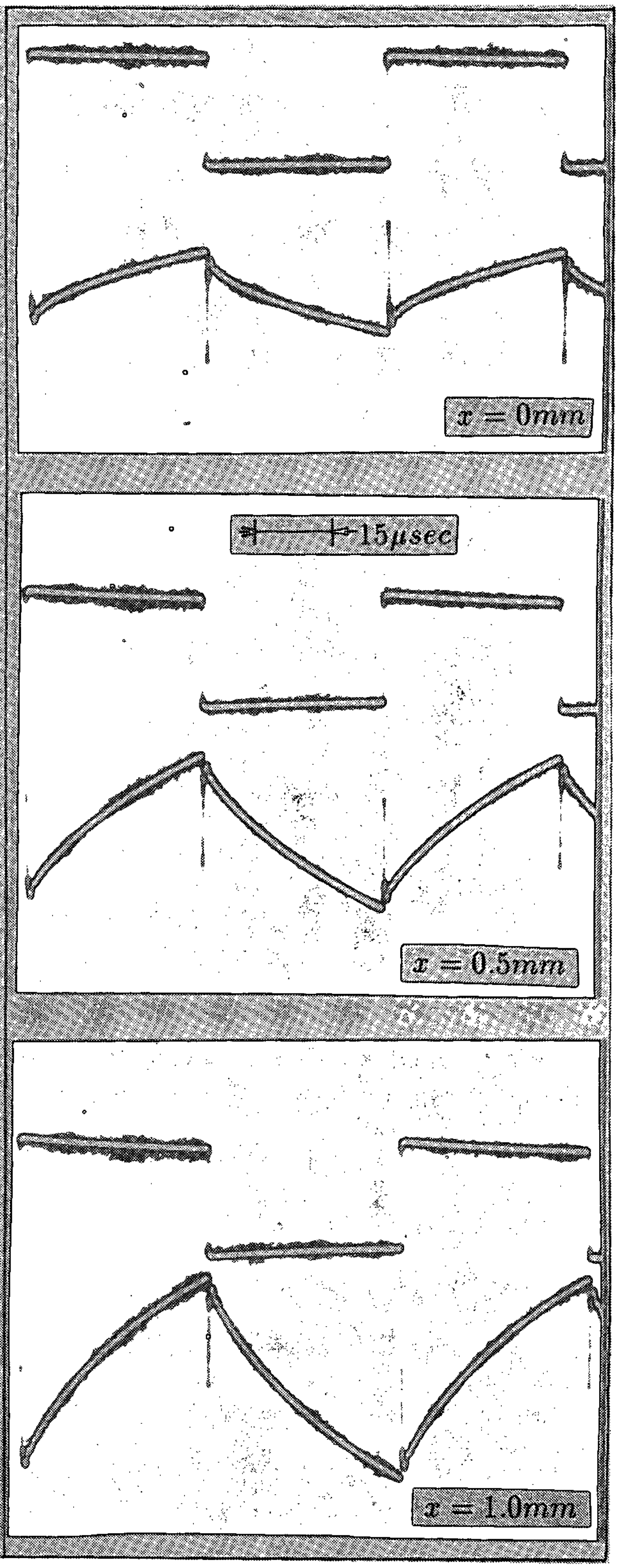


Fig.2 The driving voltage (upper) and the current response (lower) of ferrite core with the duty ratio of 20% and the PWM carrier at 30 kHz

Fig.3 The driving voltage (upper) and the current response (lower) of laminated steel with the duty ratio of 50% and the PWM carrier at 15 kHz

EXPERIMENTAL RESULTS AND CONSIDERATIONS

To confirm the capability of sensorless levitation control, a simple analog circuit is made as shown in Fig. 1. First, the sensing capability is tested for two types of core material; high frequency ferrite core and standard laminated steel sheet. Some examples of current responses are shown in Figs. 2 and 3. Increasing the gap displacement, the carrier component of current increases. Which means that both magnets indicate high gap sensing capability. Figure 4 shows the relation of the ferrite core magnet between the output voltage of I of the detecting circuit versus gap displacement x. The relation between the output voltage versus duty ratio is shown in Fig. 5. If the duty ratio is smaller than 20 % or larger than 80 %, the detecting capability is poor. This can be improved by improving the detecting circuit.

Then a simple levitation setup is made by using the ferrite core. To obtain the accurate gap displacement, a nonlinear compensation is necessary which is indicated in the dash-dot-dot block in Fig. 1. Digital control is highly requested to calculate this nonlinear relation. In this paper, however, the nonlinear compensation is neglected and the fundamental carrier component I is fed back directly to the demand signal.

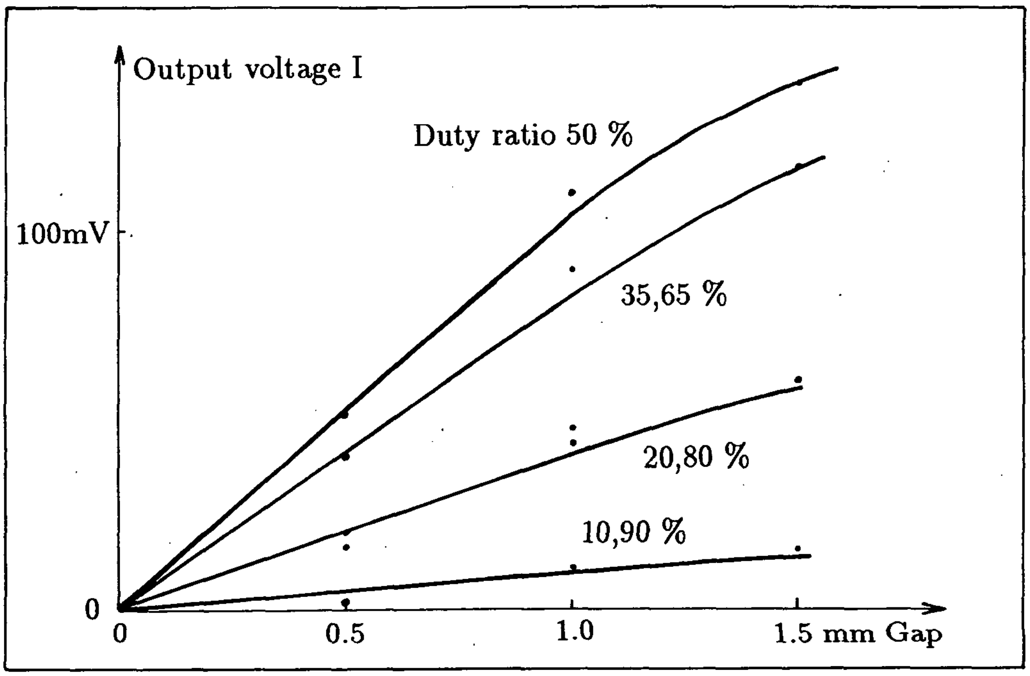


Fig. 4 The relation between the output voltage and the gap displacement

The lower response of Fig. 6 indicates the unstable response of the displacement x without phase-lead compensation. The duty ratio of the modulated driving voltage $e(t)$ is changing between 13 % and 60 % as shown in Fig. 7. This unstable vibration is compensated by a phase lead compensation $(0.02s+1)/(0.002s+1)$. The levitated step response is shown in Fig. 8. However, the stable region is restricted within a narrow range, because of nonlinear sensing capability. Also the supporting force is small, because PWM duty ratio is limited within 10 to 90 % and the magnetic flux is limited in the linear range.

CONCLUSIONS

A sensorless magnetic levitation scheme is proposed. The levitation displacement is calculated from the PWM carrier components of driving voltage and current. A simple experimental setup is made and the capability of sensorless active levitation control is confirmed. However the attractive magnetic force should be limited within the linear range of the magnetic flux. The duty ratio of PWM signal is also limited between

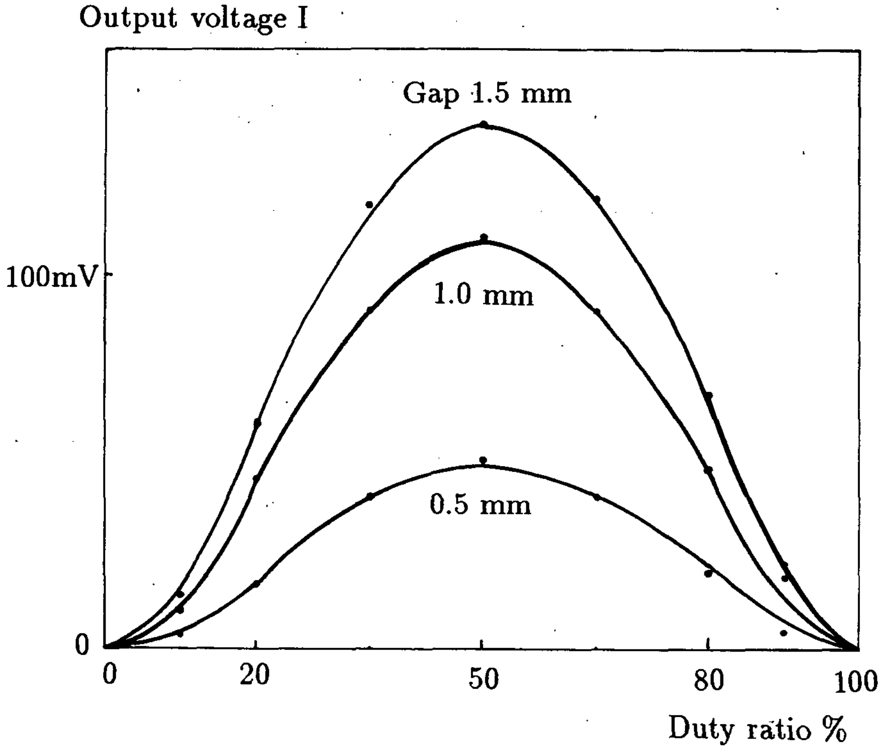


Fig. 5 The relation between the output voltage and the duty ratio

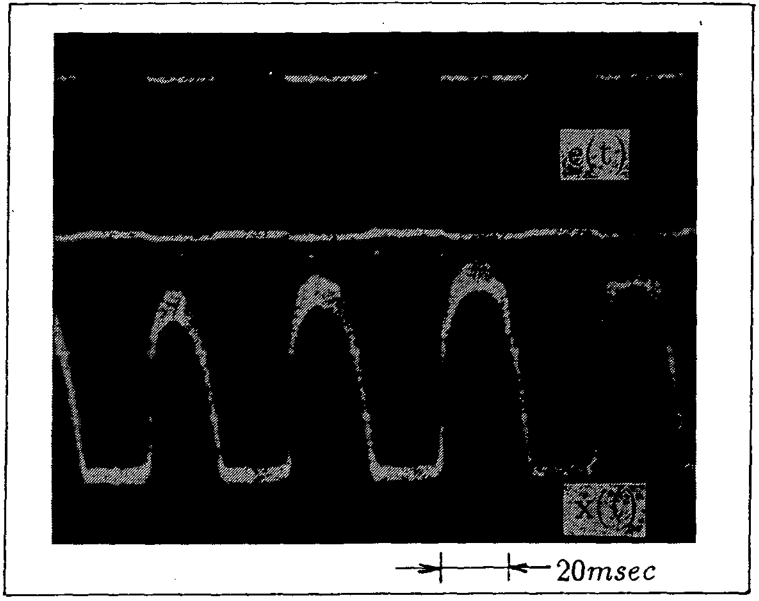


Fig. 6 The unstable response without phase-lead compensation

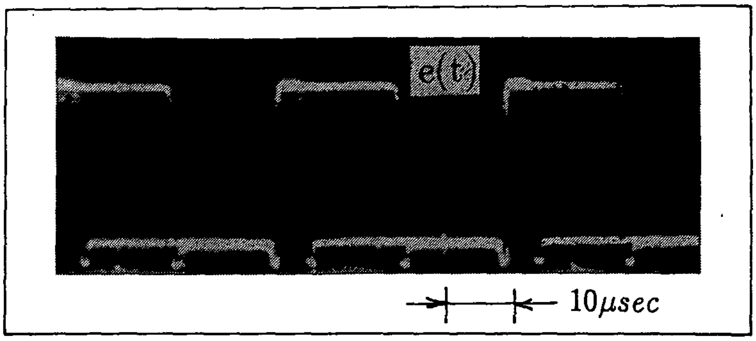


Fig. 7 The corresponding driving voltage

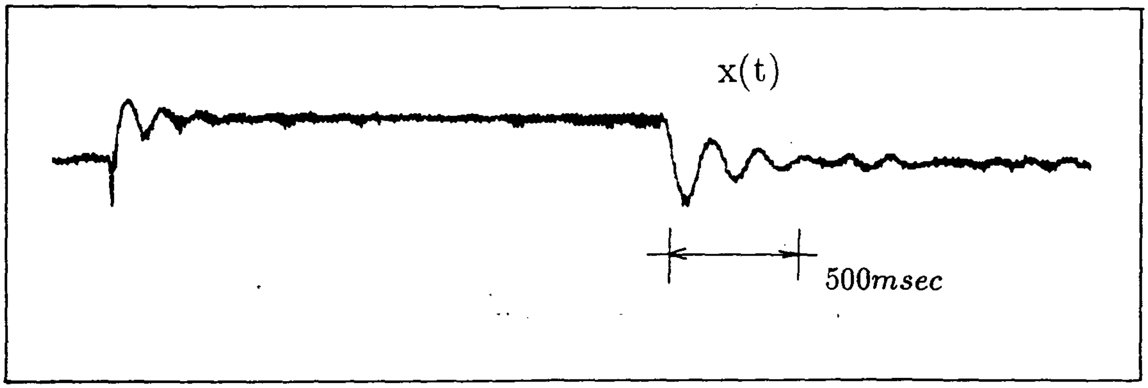


Fig.8 The step response of the levitated subject

10 and 90 %. Hence the sensorless levitation is adequate to very small equipment where any type of gap sensor is difficult to be installed.

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