Contactless Starting and Positioning of a Steel Ball in Single-Axis Magnetic Suspension Device by Variable Structure Control

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ABSTRACT

The application of variable structure control has been proposed for a single-axis magnetic suspension device. The system enables a suspended body to move from a starting position located beyond a stable suspension region into an equilibrium point and control the position around the equilibrium point. Two variable controllers have been successfully applied;switching control from PD to I-PD and sliding mode control.

INTRODUCTION

The first practical magnetic suspension for high speed rotating devices was developed by Jesse W. Beams and it was reported that small steel balls rotated at speeds up to 800,000 revolutions per second [1]. Recently, the application of a single-axis magnetic suspension device to contactless small-displacement actuators has been proposed [2], but studies in the past were limited to control a suspended body within a stable suspension region. When we make a practical contactless actuator using magnetic suspension devices, a starting method to move a suspended body into the stable suspension region will be required. The problem of starting has not been studied. In this paper, we will discuss starting methods and position control methods using a variable structure controller. Two control algorithms, i.e. switching a control structure from PD to I-PD [3] and a sliding mode controller were examined. The experiment showed that the both controller can give the satisfactory performance.

STRUCTURE OF CONTROL SYSTEM AND MODELLING

A steel ball with a diameter of 19mm and a mass of 28g is moved by magnetic pull and its position is controlled around the neighborhood of an equilibrium point (5mm below the magnet pole face). The steel ball is at a starting position which is below the stable suspension region (4.5mm below the equilibrium point in the experimental setup).

The control system is shown in Fig. 2 [4,5]. A 16-bit personal

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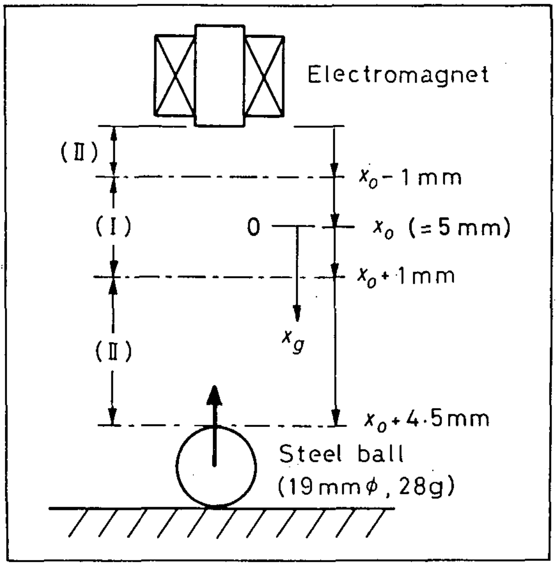


Fig. 1. Experimental single-axis magnetic suspension device (I:linear region of detector output, II:saturated region of detector output).

computer was used. The sampling period depends on control algorithms and is in the range over 500 ~ 570μs in the experiment. The magnet current can be controlled by a dc chopper of which frequency is about 12 kHz and it is high enough compared with the sampling frequencies.

The position of the ball was detected by a photodetector of which linear range is about 1mm around the equilibrium point and beyond the linear range the detector output has the saturated value as shown in Fig.3.

Introducing a small displacement about an equilibrium position to linearize the system equations, the following linear state equation can be obtained [4,5].

$$\dot{\boldsymbol{x}} = \boldsymbol{A}_c \boldsymbol{x} + \boldsymbol{B}_c \boldsymbol{i} + \boldsymbol{D}_c \tag{1}$$

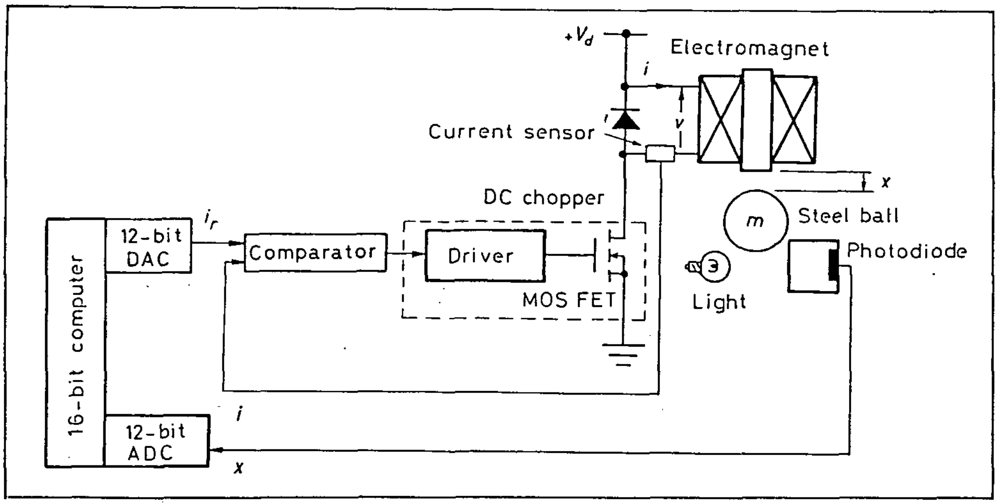


Fig. 2. Control system.

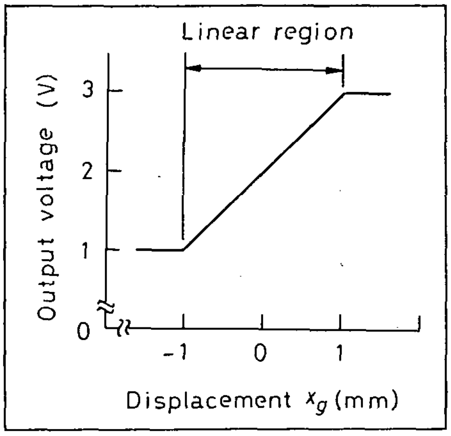


Fig. 3. Output characteristics of position detector.

$$x=[x_i \quad x_g \quad v]^T, \quad B_c=[0 \quad 0 \quad -k_2]^T, \quad D_c=[x_r \quad 0 \quad 0]^T$$

$$A_c=\begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & k_1 & 0 \end{bmatrix},$$

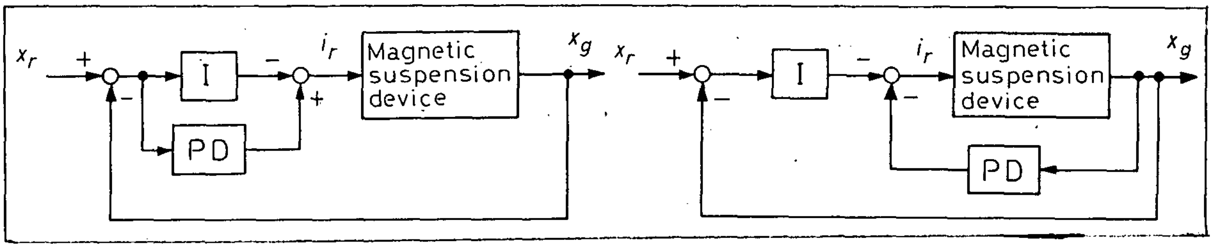
$$x_i=\int_0^t (x_r - x_g)\, dt \;, \quad v=\dot{x}_g \tag{2}$$

where x_g:a displacement of the gap length between a steel ball and an electromagnet, x_i:an integrated value of the controlled deviation, i:a displacement of the magnet current, x_r:a reference value, k_1, k_2: constants determined by the electromagnet structure and the mass of a steel ball [4,5].

The controller is required to have an integrator to eliminate steady state errors for step inputs. Then, an I-PD controller shown in Fig. 4 will be discussed in addition to a PID controller used widely at present. The control input i_r is given by the following equations.

For PID control;

$$i_r=-f[x_i \quad x_g \quad v]^T=-f\,x \tag{3}$$



(a) (b)

Fig. 4. Structure of control system;(a)PID control, (b)I-PD control.

For I-PD control;

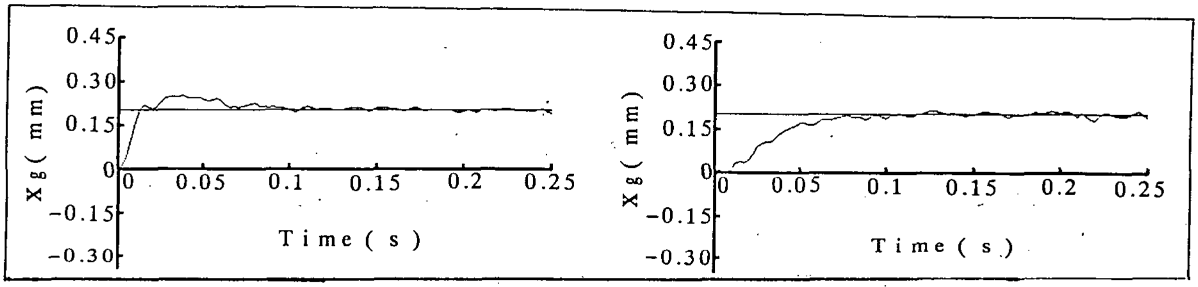
$$i_r = -\boldsymbol{f}[x_i \quad x_g - x_r \quad v - x_r]^T = -\boldsymbol{f}\boldsymbol{x} \tag{4}$$

where $\boldsymbol{f}$:a feedback gain. The difference state equation can be obtained from Equ. 1 using the sampling period, T. The controller can be designed by the pole assignment method.

COMPARISON OF STEP RESPONSE OF PID CONTROL WITH I-PD CONTROL

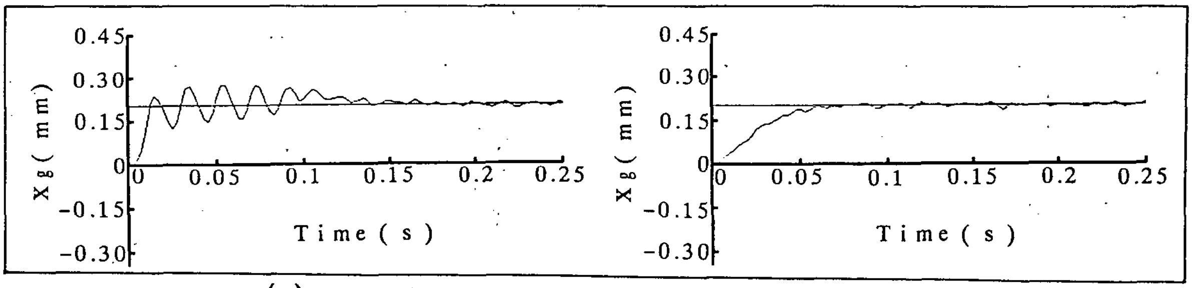
Fig. 5 shows the responses of the displacement when a step command of 0.2mm below from the equilibrium point using a PID or an I-PD controller. The feedback gain was determined so that the natural angular frequency, ω_n equals 90 and the damping factor, ζ equals 1 for the both controllers by setting the two dominant roots. Hence, the settling time becomes equal for both cases. Although the PID controller could provide a shorter rise time than the I-PD controller, the former caused larger overshoot than the latter. The reason why the PID controller can give quick response is that the PID controller produces larger control input, because the change of command affects all state variables as shown in Equ. 2. The quick response is desirable, but it causes large overshoot and may cause collision with a pole face. When we set a large value of the damping factor to get a small overshoot, it will make the settling time for step inputs and the transient time for disturbance larger.

Next, the feedback gain was set to be a larger value so that ω_n = 120 and ζ = 1 to shorten the transient response time. The measured step responses are shown in Fig. 6. The PID controller shows oscillating components corresponding to the detector noise, because it becomes subject



(a) (b)

Fig. 5. Step responses;(a)PID control, (b)I-PD control.



(a) (b)

Fig. 6 . Step responses when the feedback gains were set to be larger than those in Fig. 5;(a)PID control, (b)I-PD control.

to noise contained in the position detector output due to the large feedback gain. Whereas, it is seen from Fig. 6 that the I-PD controller gives quicker response than before and in addition, it was not affected by the noise. Thus, the I-PD controller can give much better performance about step responses around the equilibrium point than conventional PID controllers.

STARTING AND POSITION CONTROL OF A STEEL BALL

An integrator in the controller is required to control the position without steady state errors. However, the controller output becomes too large until the ball reaches the linear region when we use the integrator and then the ball collides with the magnet pole. The experiment was carried out using four types of digital controllers;PD, PID, PI-D, and I-PD. We could successfully move the ball into the linear region using only the PD controller as shown in Fig. 8(a). While the rest of the controller could not start the ball without causing collision. Thus, we can start the ball into the stably-suspended region using the PD controller, but the PD controller resulted in steady state errors as shown in Fig. 8(a). We adopted the variable structure controller shown in Fig. 7 to solve both problems of starting and the steady state errors. We used an I-PD controller, because it gave the best step responses among the three controllers with an integrator. Fig. 8 shows the starting processes

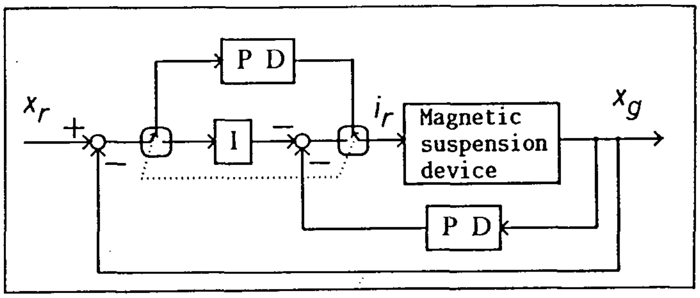
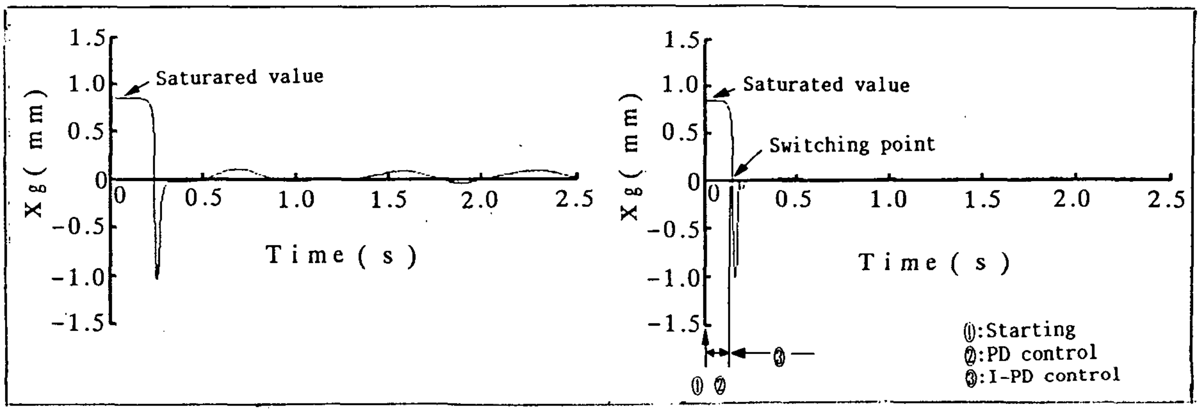
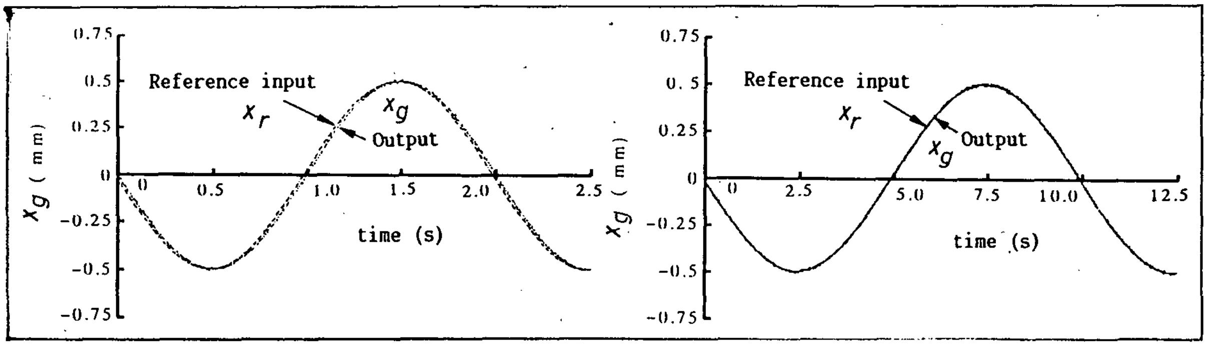


Fig. 7. Variable structure control system (changed from PD control to I-PD control).



(a) (b)

Fig. 8. Starting process of a steel ball;(a)PD control, (b)variable structure control (from PD to I-PD control).



(a) (b)

Fig. 9. Position responces to sinusoidal command under I-PD control;(a)the period of 2s, (b)the period of 10s.

comparing with two methods. It can be seen that the variable structure controller gives better performance than the PD controller. Fig. 9 shows the experimental results of position control when the reference input varied sinusoidally and the I-PD controller was used. Thus, we can contactlessly control the position of a suspended body from a starting position to a stable position.

APPLICATION OF SLIDING MODE CONTROL

Sliding mode controller [6, 7] is inherently a kind of a variable structure controller and can provide a robust magnetic suspension device which is insensitive for system parameter variation and disturbance. In addition, two control algorithms are not required such as the case of changing PD- to I-PD control. Hence, we will make the experiment of moving the steel ball and position control by the application of a sliding mode controller shown in Fig. 10.

Upon achieving an ideal sliding mode,

$$\sigma(\boldsymbol{x}) = \boldsymbol{C}\boldsymbol{x} = 0 \tag{5}$$

the switching vector C can be expressed by

$$C = (C_i \quad C_s \quad 1) = (-\omega_n^2 \quad 2\zeta\omega_n \quad 1) \tag{6}$$

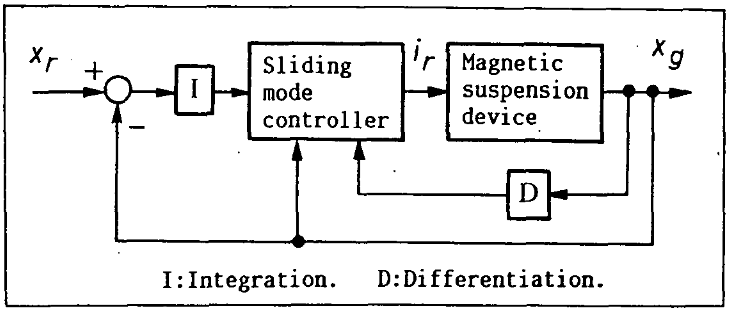


Fig. 10. Sliding mode controller including an integrator.

and Equ. 1 can be rewritten as follows [8]:

$$\frac{d}{dt}\begin{bmatrix} x_i \\ x \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ -C_i & -C_g \end{bmatrix}\begin{bmatrix} x_i \\ x \end{bmatrix} + \begin{bmatrix} x_r \\ 0 \end{bmatrix} \tag{7}$$

A unit-vector sliding mode control [6,7] is applied in order to enhance the robustness to the system parameter variation and disturbance. A control input i_r consists of the two parts: a linear part of $i_L(x)$ and a nonlinear part $i_v(x)$.

$$i_r = i_L(\boldsymbol{x}) + i_v(\boldsymbol{x}) \tag{8}$$

$$i_L(\boldsymbol{x}) = \boldsymbol{f}_L \boldsymbol{x} \tag{9}$$

$$i_v(\boldsymbol{x}) = \rho \frac{\boldsymbol{C}\boldsymbol{x}}{|\boldsymbol{C}\boldsymbol{x}| + \delta} \qquad (\rho > 0,\ \delta > 0) \tag{10}$$

$$\boldsymbol{f}_L = (-1/k_2)[\ C_i \phi^* \quad -C_i + C_g \phi^* - k_1 \quad -C_g + \phi^*]$$

ϕ^*: a negative scalar.

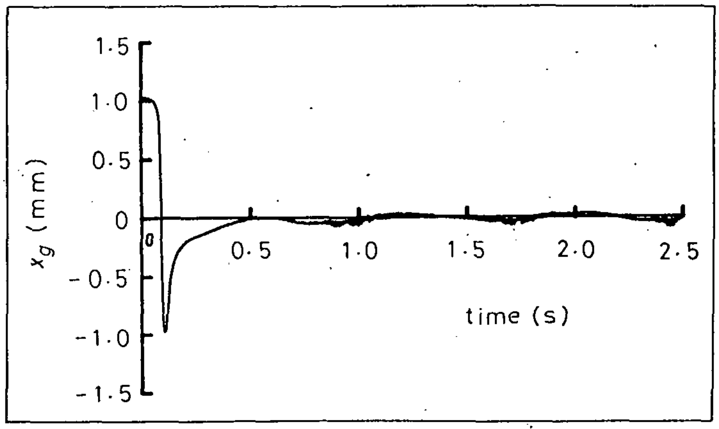
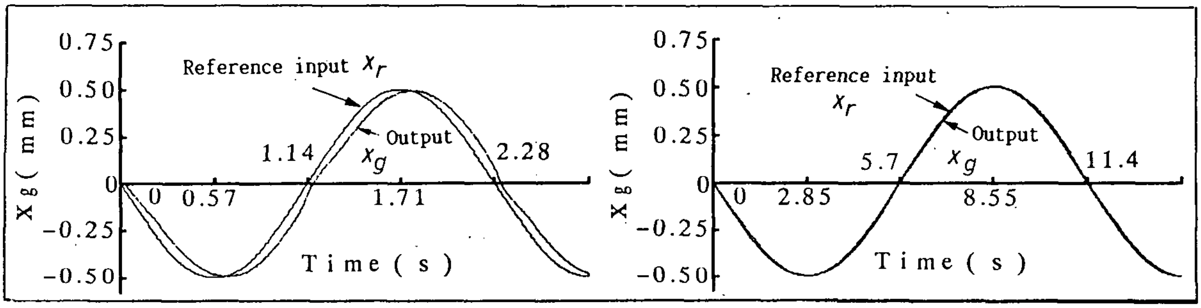


Fig. 11. Starting process of a steel ball using the sliding mode controller.



(a) (b)

Fig. 12. Position responses to sinusoidal command under sliding mode control;(a)the period of 2.28s, (b)the period of 11.4s.

The feedback gain was determined so that $\omega_n = 50$, $\zeta = 3$, $\phi^* = -10$, $\rho = 0.1$, $\delta = 0.01$. Fig. 11 shows the starting process and Fig. 12 shows the experimental results of position control. Comparing with Figs. 8 and 9, we can see that the sliding mode controller can give roughly the same performance as the switching controller did, although the transient time seems to be slightly longer. The sliding mode controller can give a system which is insensitive to variation of system parameter such as mass of a suspended body, and disturbance such as external forces [8].

EFFECTS OF POWER SUPPLY CIRCUIT OF ELECTROMAGNET

The very large overshoot of the position of the suspended body occurred as shown in Figs. 8 and 11 when the body was moved from the starting position. One of the reason is that the magnet current cannot faithfully follow the command because a single-quadrant chopper was used in which the current can decay exponentially due to the coil resistance. Then, a voltage-reversible two-quadrant chopper shown in Fig. 13 was used. Fig. 14 shows the starting process when a sliding mode controller was used. It can be seen from Figs. 14 and 11 that the overshoot of the position becomes slightly smaller, the improvement was insufficient. The current variation is shown in Fig. 15. The two-quadrant chopper gave good current responses over the positive range of the current command. In this case, since a linearization was done near an equilibrium point, the negative current command means the controller requested braking force. For the good performance of position control over wide position range, it is required to use a four-quadrant chopper in which current and voltage can be reversible and a permanent magnet added to a suspended body to produce braking forces.

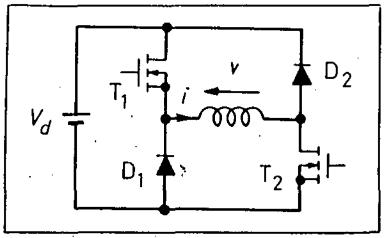


Fig. 13. Two-quadrant voltage reversible chopper.

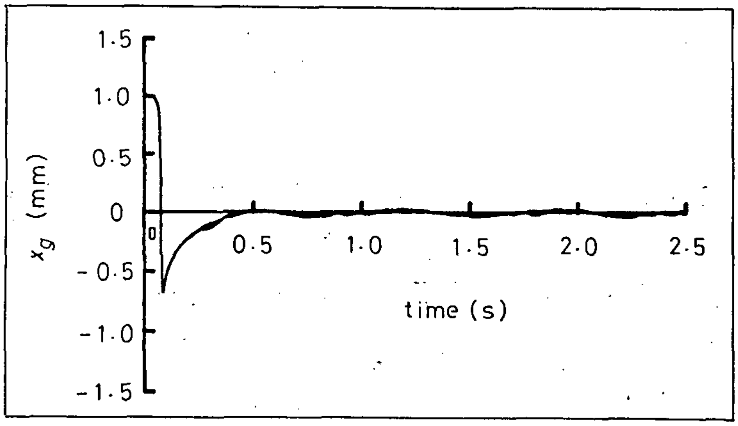
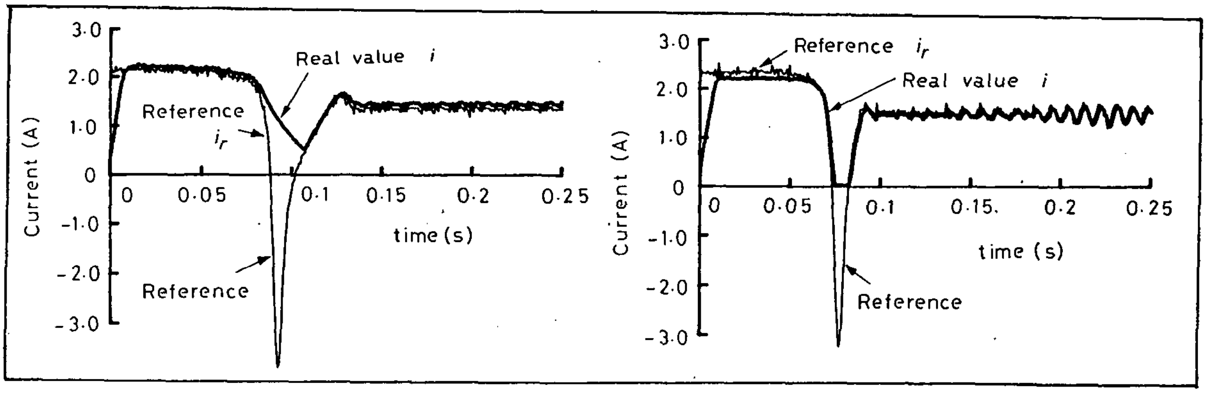


Fig. 14. Starting process of a steel ball using a two-quadrant chopper was used under sliding mode control.



(a) (b)

Fig. 15. Time variation of the magnetic coil current;(a)single quadrant chopper, (b)two-quadrant chopper.

CONCLUSION

The results obtained in this study are summarized as follows:

(1) The application of variable structure control allows that we can move a steel ball located beyond the stable suspended range into the stable range.

(2) We discussed two kind of VSS control; (a) switching the control system structure from PD to I-PD, (b) sliding mode control. Both systems can give satisfactory performance of starting and positioning. The latter has the advantages of single control algorithm through starting and positioning, and robust characteristics.

(3) We discussed the two kinds of power control circuit for electromagnet, i. e. a single- and a two-quadrant chopper. The experimental results showed that a single-quadrant chopper is enough for controlling of a suspended body around the neighborhood of an equilibrium position, but for a wide operating range of position, a two-quadrant chopper must be used.

(4) In order to obtain good position control performance, a braking force is required. Hence, it is recommended that a permanent magnet is added to a suspended body and a four-quadrant chopper is used.

Further studies will be required to realize contactless actuators and contactless robot hands by the development of this study.

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