Examination of the follow-up control system of two Desired Values to Suppress the Elastic Vibration in a thin steel plate

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Abstract

The magnetic levitation becomes difficult because of vibration generated in the plate due to bending and a twist. Moreover, since a steel plate is thin, magnetic saturation occurs. By making the number of an electromagnet increased, i.e., by reducing the magnetic flux density generated in the same place, magnetic saturation is avoidable. Vibration generated by each electromagnet at the time of attraction, however, causes interferences each other, and levitation becomes difficult. Then, in order to control this vibration and to perform stable levitation, the two desired values to suppress the elastic vibration is proposed. However, the factors of oscillating control have not been clarified. Therefore, the factors are examined. In this paper, the concept of the Two Desired Values to Suppress the Elastic Vibration is shown. Then, the examination of the follow-up control system of two Desired Values to Suppress the Elastic Vibration is conducted.

1. Introduction

Recently, the thin steel plate has been used in various fields, such as the body of a car, building materials, and electric apparatus. The roller transportation system is used in the manufacture process of the thin steel plate. At the time of transportation, since thin steel plate contacts rollers, the quality of a thin steel plate, however is deteriorated by friction. In order to prevent this quality from deteriorating, the process, such as a surface treatment is needed. In order to defeat this present condition, the magnetic levitation system is proposed. In the case of the magnetic levitation, by the attractive force, such as a permanent magnet and an electromagnet, the plate is levitated without contact. A magnetic levitation system, however, is in a research stage and has not been used practically. Since the steel plate is thin, a twist and bending of the plate occur easily. The magnetic levitation becomes difficult because of vibration generated in the plate due to bending and a twist. Moreover, since a steel plate is thin, magnetic saturation occurs. By making the number of an electromagnet increased, i.e., by reducing the magnetic flux density generated in the same place, magnetic saturation is avoidable.

Vibration generated by each electromagnet at the time of attraction, however, causes interferences each other, and levitation becomes difficult. Then, in order to control this vibration and to perform stable levitation, the two desired values to suppress the elastic vibration is proposed.

2. Concept of Two Desired Values to Suppress the Elastic Vibration

2-1. Independent control

Fig.1 shows Magnetic levitation system. This system consists of two electromagnets and gap sensors which measure the distance between the electromagnet and the steel plate. In this paper, the case two electromagnets is used is shown. In Fig.1, Z_1 and Z_2 are the present gap values in electromagnets 1 and 2. Fig. 2 shows the difference of a control rule. Independent control used in general is the system which defines and controls a target value on each electromagnet. Two desired values to suppress the elastic vibration have two target values to it. The electromagnet which has the decided target value (Fixed-command controlled magnet), and, the electromagnet which has the target value following the present one of the Fixed-command controlled magnet (Follow-up controlled magnet). Eq.1 shows the target value of independent control. Eq.2 shows the target value of the two desired values to suppress the elastic vibration.

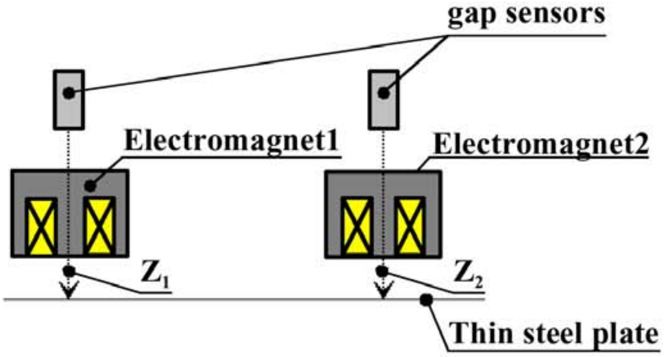
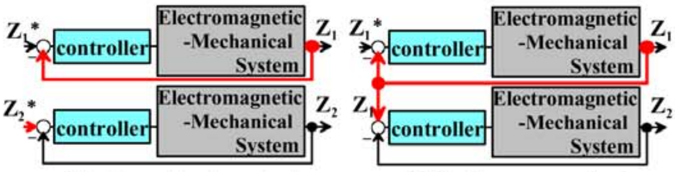


Fig.1 Magnetic levitation system



a) Independent control b) Follow-up control

Fig.2 Difference of a control rule

$$Z_1^* = Z_2^* = Z_n(const.) \qquad (1)$$

$$Z_1^* = Z_n$$
$$Z_2^* = Z_1 \qquad (2)$$

Z_1^* ,Z_2^* [mm]: The target value of electromagnets 1 and 2, Zn[mm]: The target value

2-2. Two Desired Values to Suppress the Elastic Vibration

Unlike the independent control used generally, a follow-up relation of electromagnets exists in the two desired values to suppress the elastic vibration. Fig.3 shows the concept of the two desired values to suppress the elastic vibration. The fixed-command controlled magnet has the value of a certain fixed target. The follow-up controlled magnet aims at the present gap of the fixed-command controlled magnet. The target value of this follow-up controlled magnet always changes. Therefore, it is possible to prevent the interference of the vibration which electromagnets generate.

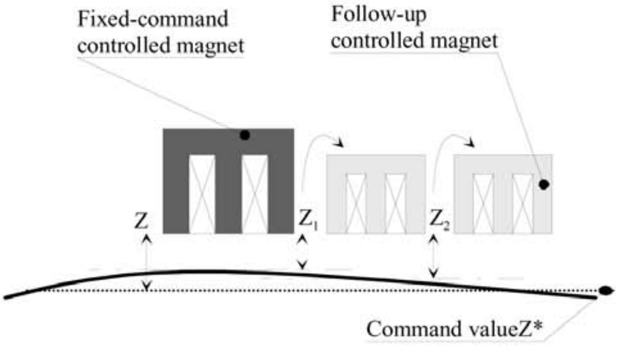


Fig.3 Concept of the two desired values to suppress the elastic vibration.

3. Experimental Device

3-1. Block diagram

In order to verify the usefulness of two desired values to suppress the elastic vibration, stability characteristic and transient responses are acquired. Fig.4 shows the block diagram of the two desired values to suppress the elastic vibration. Eq.3 shows the equation of motion and the electric circuit. Eq.3 shows the systems shown in Fig.2. Table.1 shows used parameter.

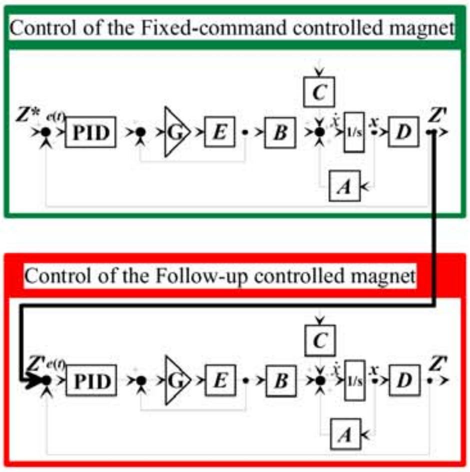


Fig.4 Block diagram of the two desired values to suppress the elastic vibration.

Table.1 The used parameter

$$
\begin{aligned}
& M\frac{d^2 z}{dt^2} = \frac{2kI^2}{Z^3}z' - \frac{2kI}{Z^2}i' + f_d \\
& v' = L\frac{di'}{dt} + Ri'
\end{aligned}
\qquad (3)
$$

E is calculated by conducting the Laplace transformation about the equation of a circuit. Eq.4 shows the equations that Laplace conversion is carried out to Eq.3.

$$
\begin{aligned}
& v' = \frac{1}{Ls+R}i' \\
& v' = Ei'
\end{aligned}
\qquad (4)
$$

Eq.4 contains the element of a primary delay system. Therefore, a current minor loop is prepared in a circuit. In the Fig.4, G is the gain of current amplifier. This gain is decided by the resistance ingredient of an electric circuit. As the gain creates high, transfer function of the electric circuit parts can be regarded as 1. Next, the equation of motion is examined. The equation of motion is a differential equation with the second order terms. Alignment approximation of the equation of motion is carried out. Eq. 5, 6, 7 are defined as a state variable, an output equation, a state equation, respectively.

$$x = \begin{bmatrix} z' \\ v \end{bmatrix} \tag{5}$$

$$\begin{aligned} y(t) &= (1,0)\begin{bmatrix} z' \\ v \end{bmatrix} \\ y(t) &= Dx(t) \end{aligned} \tag{6}$$

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} z' \\ v \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ \dfrac{2kI^2}{MZ^3} & 0 \end{bmatrix}\begin{bmatrix} z' \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{2kI}{MZ^2} \end{bmatrix} i' + \begin{bmatrix} 0 \\ \dfrac{1}{M} \end{bmatrix} fd \\ \dot{x} &= Ax + Bi' + Cfd \end{aligned} \tag{7}$$

Transfer functions of blocks from A to D in the Fig.4 are defined as Eq.6, 7.

3-2. Calculation of a PID gain

The PID gain was computed by using the partial model matching method. Fig.5 shows the block figure of the thin steel plate levitation control system. The design specification is that a regular deviation becomes zero. Moreover, the design has a suitable damping characteristic. In addition, it computes so that rise time may become the minimum. Eq.8 shows the expression of the desirable control system which is satisfied with the above-mentioned design specification.

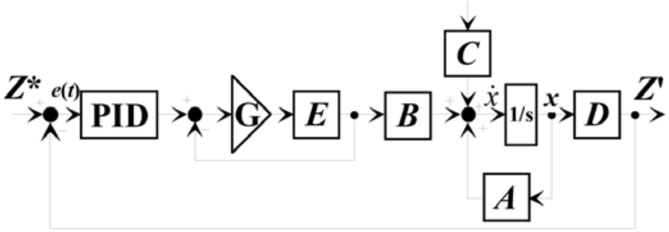


Fig.5 Block figure of thin steel plate

$$W_d(s) = \frac{1}{\alpha(s)} = \frac{1}{\alpha_0 + \alpha_1 \sigma s + \alpha_2 \sigma^2 s^2 + \cdots} \tag{8}$$

In order to obtain the system which makes Integral Time Absolute Error (ITAE) evaluation the minimum mostly and considers the amount of going too far as about 10% of step response, it is assumed that it is shown in an Eq.9.

$$\{\alpha_0, \alpha_1, \alpha_2, \alpha_3, \cdots\} = \left\{1, 1, \frac{1}{2}, \frac{3}{20}, \frac{3}{100}, \frac{3}{1000} \cdots\right\} \tag{9}$$

Fig.6 shows Model of a PID control system. A right block is a candidate for control and a left block is a control part. Here, Eq.10 shows a PID control rule.

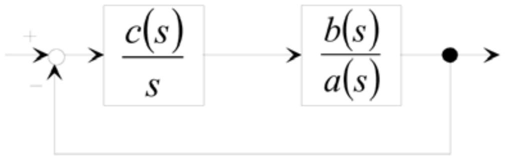


Fig.6 Model of a PID control system

$$G_C(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{10}$$

Eq.11 shows the Laplace equation of the control device.

$$\frac{c(s)}{s} = \frac{c_0 + c_1 s + c_2 s^2}{s} \tag{11}$$

Eq.12 shows the candidate for control is transformed.

$$h(s) = \frac{a(s)}{b(s)} = h_0 + h_1 s + h_2 s^2 + h_3 s^3 \tag{12}$$

It will become an Eq.13 supposing the transfer function of a closed loop control system is equal to the model of Fig. 6.

$$1 + s\frac{h(s)}{c(s)} = \alpha(s) \tag{13}$$

A desired PID control system design can be obtained by forming an Eq.14. Here, calculation of a PID gain uses an Eq.14. The equation which fills σ is an Eq.15.

$$\begin{aligned} c_0 &= \frac{h_0}{\sigma}, c_1 = \frac{h_1}{\sigma} - \alpha_2 h_0 \\ c_2 &= \frac{h_2}{\sigma} - \alpha_2 h_1 + \left(\alpha_2^2 - \alpha_3\right) h_1 \sigma \end{aligned} \tag{14}$$

$$\begin{aligned} &\left(\alpha_2^3 - 2\alpha_2\alpha_3 + \alpha_4\right) h_0 \sigma^3 \\ &- \left(\alpha_2^2 - \alpha_3\right) h_1 \sigma^2 + \alpha_2 h_2 \sigma - h_3 = 0 \end{aligned} \tag{15}$$

A uses the minimum positive thing among the solutions which solve the equation of an Eq.15 and are obtained. Then, the optimal gain is computed from the relation of Eq.10 and 11. Table.2 shows Computed condition and gain. This value is made reference and it adjusts at the time of an experiment.

Table.2 Computed condition and gain

an electric current[A]	2.69
Mass of a thin steel plate[g]	380
Gap length[mm]	3
proportional gain[A/m]	2000
Differential gain[As/m]	30
Integral gain[A/sm]	1000

4.2 Examination of the follow-up control system of two Desired Values to Suppress the Elastic Vibration

4-1. A one-side support experiment of two desired values to suppress the elastic vibration and independent control

Comparison with independent control and two desired values to suppress the elastic vibration is performed. Fig.7 shows the experimental device. A gap is acquired by the gap sensor. Moreover, as compared with a target value, an instruction value is calculated with PC. The attractive force makes generate with an electromagnet. Fig.8 shows the experimental condition. The advance

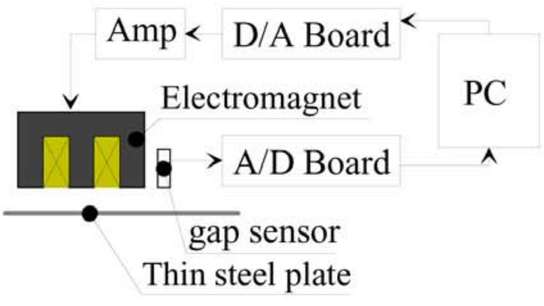


Fig.7 Experimental device

direction of the elastic wave of a thin steel plate is made only into one dimension with a hinge. The electromagnet interval was installed between 130 millimeters and 350 millimeters. It experimented during this period by moving an electromagnet at intervals of 10 millimeters. Moreover, the gap between a thin steel plate and an electromagnet is Z_n=2[mm]. Fig.9 shows comparison of a stability characteristic. Fig.10 shows comparison of a transient response. Fig.11 shows transition of a proportionality gain. In order to compare a control system, the result of the electromagnet with which target values differ is shown. Moreover, in order to examine the response of each control system, and oscillating control, it experiments, without putting in Integral gain. First, Fig. 9 shows the characteristic of the amplitude of the vibration at the time of a thin steel plate surfacing stably, and the interval of an electromagnet. The gain is adjusted at every electromagnet interval. At the time of independent control, when an electromagnet interval was more than 230 millimeters, stable levitation was not able to be performed. It does not depend for two desired values to suppress the elastic vibration on an electromagnet interval from this result. It was able to be shown that stable levitation can be performed. Fig. 10 has shown the time of the response at the time of disturbance insertion, and the characteristic of an electromagnet interval. The disturbance insertion method dropped the

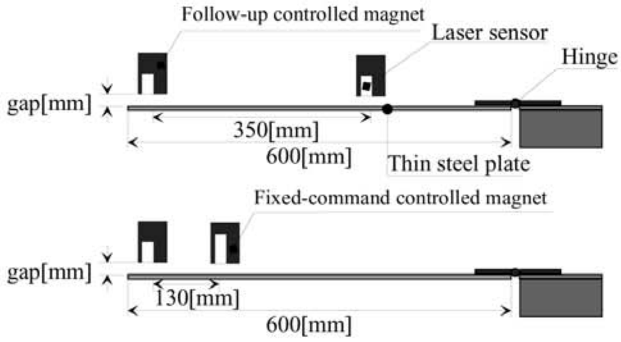


Fig.8 Experimental condition

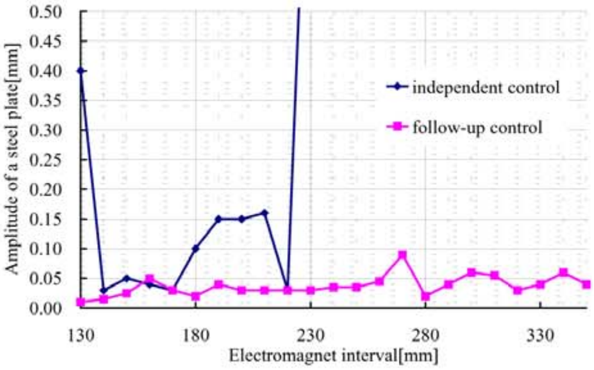


Fig.9 Comparison of a stability characteristic

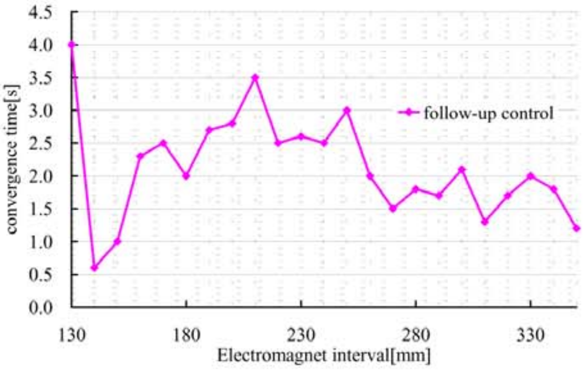


Fig.10 Comparison of a transient response

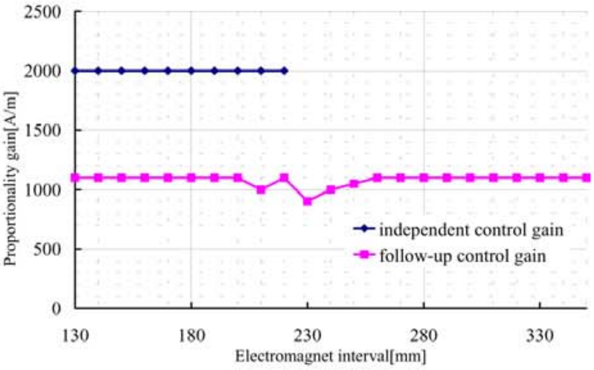


Fig.11 Transition of a proportionality gain

5g object from between the two electromagnets. In independent control, when disturbance was inserted, it was not able to carry out levitation. Furthermore, since the interval which cannot perform stable levitation also existed, disturbance was not able to be inserted. The proportionality gain of Fig.11 is the value used at the time of comparison of stable levitation. In independent control, the proportionality gain 2000 was able to levitation. Moreover, two desired values to suppress the elastic vibration have levitated at the proportionality gain 1100. In independent control, since levitation was not completed, more than the electromagnet interval 230 millimeters was not able to be shown. It was able to be shown that two desired values to suppress the elastic vibration are high in the vibration control effect.

4-2. Comparison of the target value of a Follow-up controlled magnet

Here, the rate of the target value of the Follow-up controlled magnet which is the feature of two desired values to suppress the elastic vibration is examined. The usefulness of this control is examined from the rate of the target value. Eq.16 shows the setting method of the rate of a target value. Fig.11 shows the concept of a target value setup. Fig.12 shows the concept of target value change. Fig.13 shows the target value setting method.

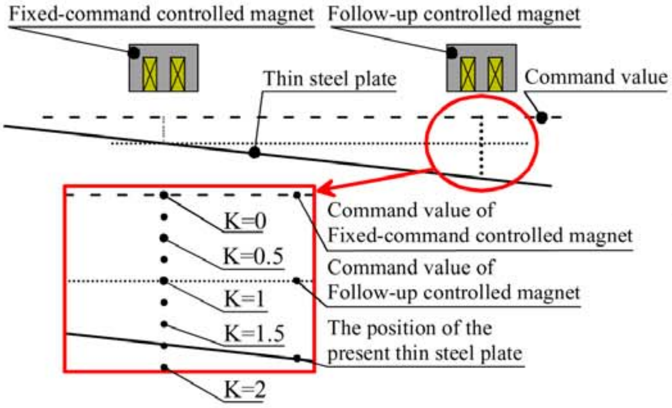


Fig.11 Concept of a target value setup

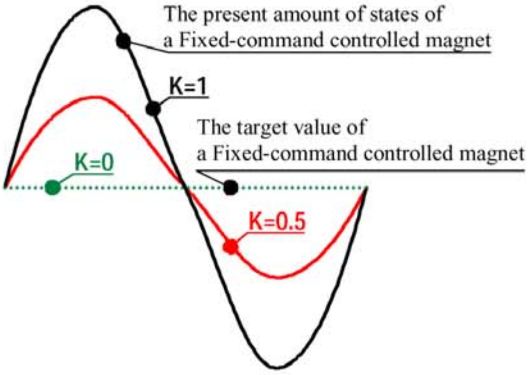


Fig.12 Concept of target value change

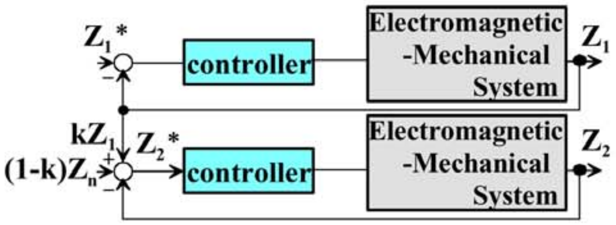


Fig.13 Target value setting method

$$Z_2^* = KZ_1 + (1-K)Z_n \qquad (16)$$

From these relations, the difference in the characteristic of two desired values to suppress the elastic vibration and independent control is considered. Fig.14 shows an experiment situation. Here, an electromagnet interval is set to 230 millimeters. Since the characteristics differed greatly, this electromagnet interval is used. Integral gain is also used for this comparison. Fig.15 shows comparison of a stability characteristic. In the target value of two desired values to suppress the elastic vibration, levitation is impossible. In order to consider this cause here, accelerator was installed in the fixed end and the vibration characteristic was acquired. Fig.16 shows an experiment state. Fig.17 shows comparison of the displacement. When K= 0.8 is compared with the case of K= 0, it turns out that the action of vibration of a thin steel plate is completely different. Since the target value is always changed, as for a Follow-up controlled magnet, in the case of K= 0.8, there is not enough control to target value change. Or it is thought that vibration will be promoted. It experiments without putting in Integral gain from now on.

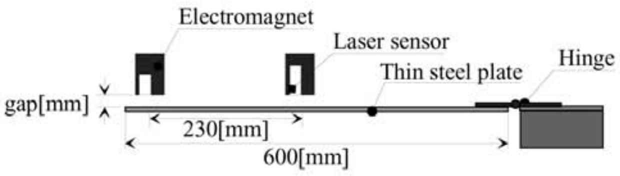


Fig.14 Experiment situation

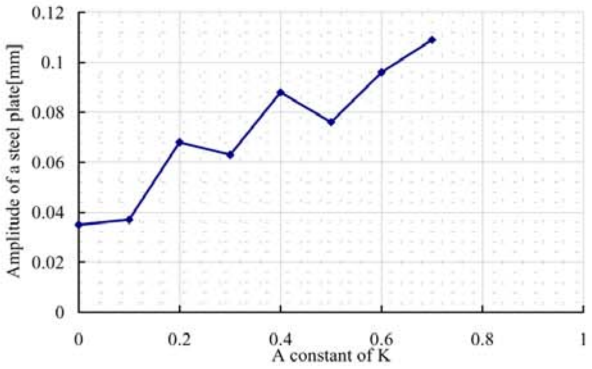


Fig.15 Comparison of a stability characteristic

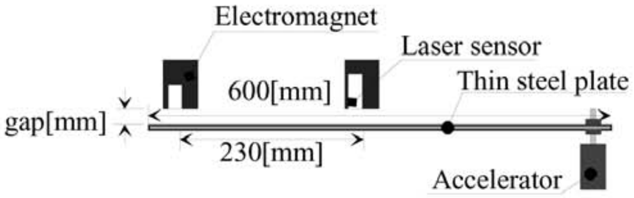


Fig.16 Experiment situation

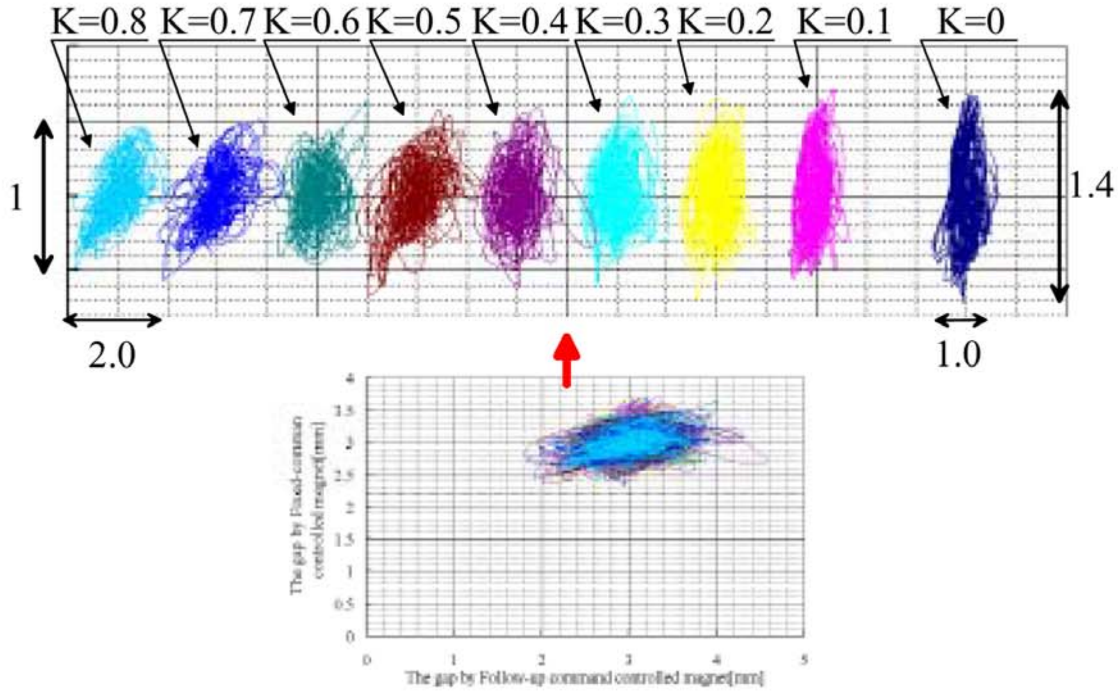


Fig.17 Comparison of the displacement

5. Conclusion

Since the steel plate is thin, it is easy to generate a twist and bending. Levitation becomes difficult because bending and a twist generate vibration. Moreover, since a steel plate is thin, it generates magnetic saturation. However making an electromagnet increase, magnetic saturation is avoidable by reducing the magnetic flux density generated in the same place. Nevertheless, vibration generated by each electromagnet at the time of attraction causes interferences each other, and levitation becomes difficult. Then, in order to control this vibration and to perform stable levitation, A system that using two desired values to suppress the elastic vibration is proposed. Comparison of independent control and Follow-up control is performed. The comparison could show that Follow-up control is better effect in controlling the vibration. Moreover, the rate of the target value of the Follow-up controlled magnet which is the feature of two desired values to suppress the elastic vibration is examined. In the target value of two desired values to suppress the elastic vibration, levitation is impossible. There is not enough control to target value change, or it is thought that vibration will be promoted. It experiments without putting in Integral gain from now on.

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