The Magnetic Levitation System with Two Desired Values to Suppress the Elastic Vibration of the Thin Steel Sheets

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Keywords

Thin steel sheets, PID-Control, vibration, simulation and experiment

Abstract

High quality and high efficiently transfer of the manufactual process are required with thin steel sheets of the thickness 0.3-1.2mili-meters that is in demand the highest in the steel industry. The thin steel sheets should be transported without cracks on the surface and the unevenness of lubricating oil in the field of producing steel-ware. The non-contact transportation of thin steel sheets by magnetic levitation is one of the solutions. It is proposed in this paper that the levitation system with two desired values to prevent transverse waves from propagating along the plate. The system with two desired values can set up a differentiation gain highly, therefore, vibration can be controlled rather than the independent system. The system with two desired values can control progressive wave. These experiments prove the system with two desired values is more effective than the independent system.

1 Introduction

High quality and high efficiency transfer of the manufactural process are required with thin steel sheets of 0.3-1.2 millimeters thickness that is the highest demand in the steel industry. The roller carried the steel boards in the steel factory in the manufactural process of the product. This system has a problem, however, frictions occur between the roller and the thin steel sheet, and the wounds occur in the thin steel sheet. The cracks of the surface cause the degradation of the luster of a painted body. The thin steel sheets are plated before the coating process because of the crack. The magnetic levitation technology can improve the quality of the thin steel sheets and efficient carriage as non-contact transportation of thin steel sheets because the wound of the thin steel sheets do not occur at the time of the carriage and the process of the plating of the thin steel sheets can be omitted.

The rigidity of the thin steel sheets is lower than the one of thick steel plate. The thin sheets vibrate more easily than the thick one in the magnetic levitation control. The system of a linear induction motor is studied [1], however, it is not realized.

It therefore is proposed that the levitation system with two desired values can keep levitate steadily [2]. All of the magnets in one group are connected as the cascade control system. It is the advantage of this system that can keep thin steel sheets horizontally by only adding the follow-up controlled electromagnets and the construction of this following control is very simple.

These experiments prove the system with two desired values is more effective than the independent system.The device of the levitation system with two desired values are considered in this paper. The characteristics of the vibration system in one magnet-group are measured and simulated.

2 The Magnetic levitation system with two desired values

The plural electromagnets control the attractive forces independently in the case of the conventional levitation system apply the thin steel sheets. State variables of each electromagnet are not kept independently.

The interactions of plural magnets decrease the frequency and amplitude of elastic wave. The thin steel sheets can levitate steadily by restraining elasticity energy. The levitation system with two desired values of one dimension is shown in Fig. 1.

Some groups of electromagnets suspend the thin steel sheets. One group is consisted of one fixed-command controlled magnet and several follow-up controlled magnets. The fixed-command controlled electromagnet input state variables of itself to the follow-up controlled magnets. The systems of the follow-up controlled electromagnets are servomechanism in which the aim order values change. All of groups of the electromagnets are connected as the cascade control system.

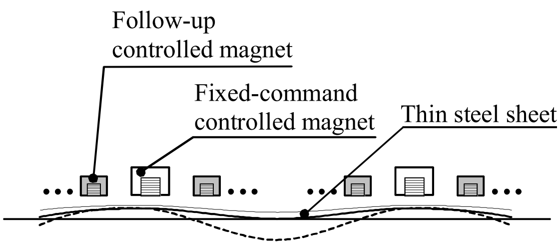


Fig.1. The levitation system with two desired values.

The advantages of proposed system are that it can keep thin steel sheets horizontally by only adding the follow-up controlled electromagnets and that the construction of this following control is very simple.

3 A one-side support experiment of magnetic levitation system with two desired values and independent system

It is necessary to examine the validity of the system with two desired values to the general control(following; The independent system) with the equal instruction value of all electromagnets. Then, in order to check validity of system with two desired values, a one-side support experiment is tested. The square thin steel sheet of thickness is 0.8 millimeter, and size is 500×100 millimeter. The device of the levitation systems with two desired values is shown in Fig. 2.

The distance from a fulcrum to the center of fixed-command controlled magnet is 580 millimeter and the distance from the center of the fixed-command controlled magnet to the center of follow-up controlled magnet is 362.5 millimeter. These distances are positions where vibration is suppressed most. The system with two desired values can control even if the distance between two electromagnets is shorter than the wavelength of mode vibration. The response of an electromagnet is more important when these distances are short and the speed of propagation of vibration.

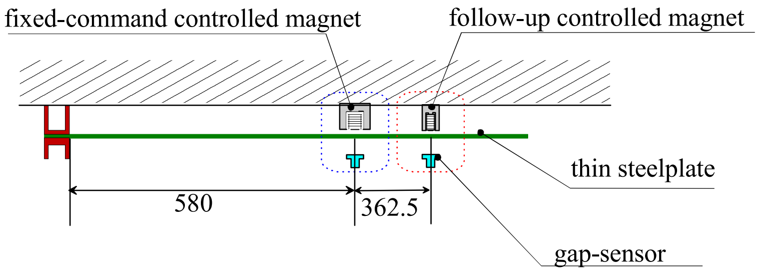


Fig.2. The device of one-end support magnetic levitation.

PID controls order these electromagnets current. The used gains of PID controls are most controllable value. The gains of system with two desired values and independent system are shown in table 1. The instruction value of the gap length from an electromagnet to a thin steel plate is 3 millimeter. In this case the distance from an electromagnet to a gap-sensor is 7 millimeter. Fig.3 shows the block diagram of system with two desired values.

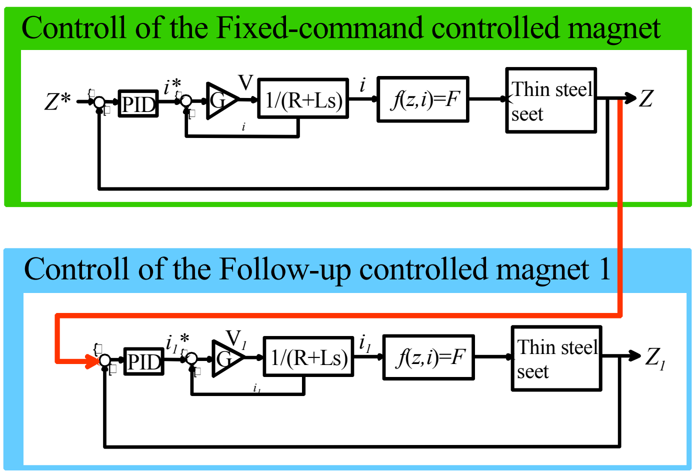


Fig. 3. The block diagram of system with two desired values.

The characteristics of suppressing vibrations of independent system is shown in Fig.4 and system with two desired values is shown in Fig.5. The experiment result prove that compared with independent system, system with two desired values can control convergence of vibration early. And the amplitude of the system with two desired values is smaller.

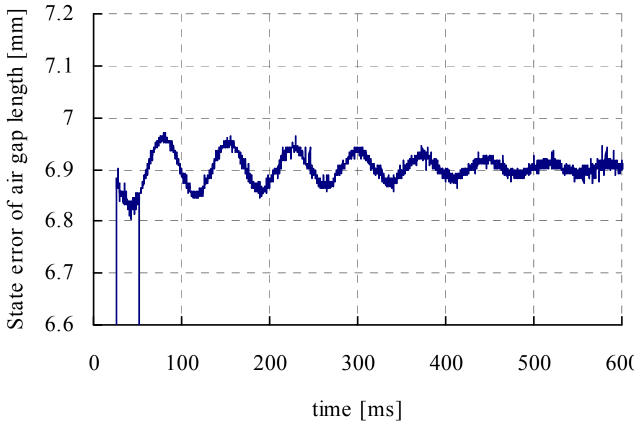


Fig.4. The gap response of independent system.

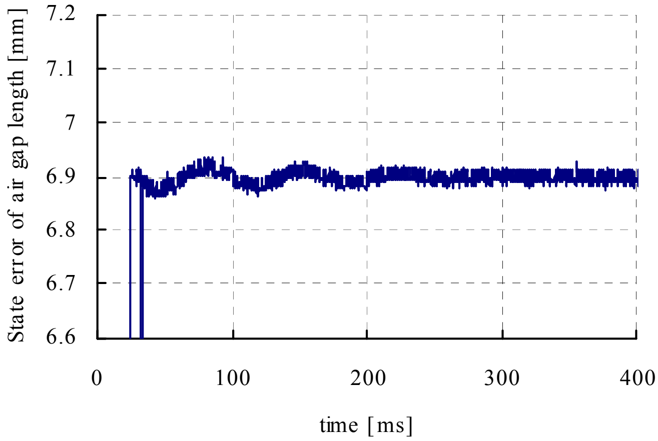


Fig.5. The gap response of system with two desired values.

These results show that the oscillating inhibition capability of 2 orders is high. Table 1 shows the used gains of the system with two desired values and the independent system Fig.6 shows the control system of device.It is necessary to confirm that an experiment result is theoretically right. The simulation of general magnetic surfacing is based on the Fig. □

Table 1. The used PID control gains of the system with two desired values and the independent system

Controls	Electromagnets	Proportional gain	Differential gain	Integral gain
The independent system	Fixed-command controlled magnet	14000	100	300
	Follow-up controlled magnet	14000	70	300
The system with two desired values	Fixed-command controlled magnet	12000	250	300
	Follow-up controlled magnet	12000	200	300

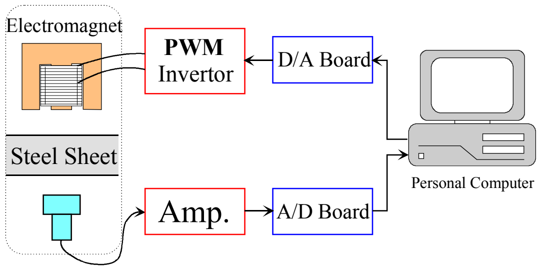
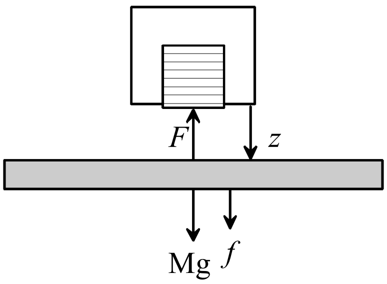


Fig.6.The control system of device.



voltage	E
electric current	i
fixed number of electromagnet	k
position	z
velocity	v
mass	M
force	F
external force	f

Fig.7 The model of magnetic levitation.

The control power to act on the pale steel board is $F = k\left(\frac{i}{z}\right)^2$.

A movement equation (1) and a voltage equation (2) are necessary for the simulation.

$$M\frac{d^2 z}{dt^2} = k\left(\frac{i}{z}\right)^2 - Mg + f \tag{1}$$

$$E = iR + L_{(z)}\frac{di}{dt} + i\frac{dL_{(z)}}{dz}\frac{dz}{dt} \tag{2}$$

Upper equations are both Nonlinears. It is, therefore, necessary to make alignment to apply the alignment theory of the control.

$$z = Z + z' \qquad i = I + i' \tag{3}$$

The term to which ' was attached is minute displacement.

$$M\frac{d^2z'}{dt^2} = k\left(\frac{I+i'}{Z+z'}\right)^2 - Mg + f \tag{4}$$

It carries out tailor expansion of this formula, takes even the first term, and compute eq.(5)

$$M\frac{d^2z'}{dt^2} = \frac{2kI^2}{Z^3}z' - \frac{2kI}{z^2}i' + f \tag{5}$$

Electrical motive force of the third term has the function which stabilizes levitation condition. That this clause is disregarded becomes considering a severer state. The model of magnetic levitation shown was used for the simulation.

The beam of Bernoulli-Euler was used as the model of the simulation of the thin steel plate.Eq.(6) shows basic equation of Bernoulli-Euler.

$$m\frac{\partial^2 z}{\partial t^2} + CI\frac{\partial^5 z}{\partial t \partial x^4} + EI\frac{\partial^4 z}{\partial x^4} = f \tag{7}$$

The left side of an equation (7) consists of an inertia force and the damping power inside the thin steel plate, and the elastic stability by bending, and rihgt side is a disturbance. It is the same as that of an experiment to use a 1-dimensional model for a simulation. Table 2 shows the constant which it uses for a simulation. Fig. 8 shows the simulation model of the thin steel plate. Eq. (8) is calculated for every minute time based on an equation (7).

Table 2. The used parameter.

ρ	density[kg/m^2]
h	thickness[m]
C	Internal attenuation coefficient [Ns/m^2]
I	Geometrical moment of inertia [m^4]
E	Young's modulus
z	The amount of bending of the direction of z [m]
f	Power per unit length of the direction of x [N/m]

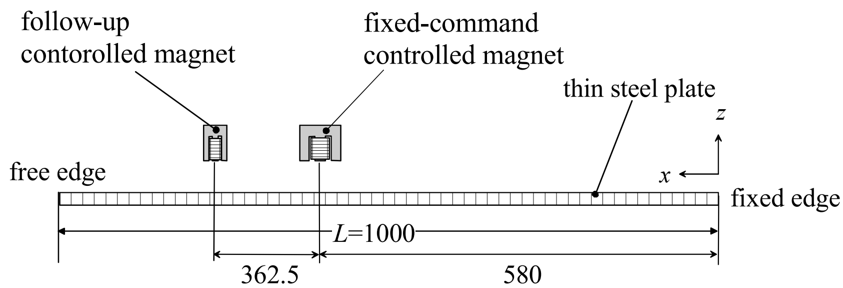


Fig.8. The model of thin steel plate.

$$M\ddot{z} + C\dot{z} + Kz = f \tag{8}$$

M: Mass matrix, C: Damping matrix, K: Elastic matrix, $\ddot{z}, \dot{z}, z$: Acceleration, Velocity, Position vector,f: External-force vector

Finite element method (following; FEM) was used in order to make into the form of the eq. (8) the manoeuver equation of a continuum shown in the eq. (7). Eq.(9),(10),(11) show the mass matrix, the damping matrix and the elastic matrix dispersed by the width dx of the direction of x.

$$M = diag[\rho h] \tag{9}$$

$$C = \frac{CI}{dx^4}\begin{bmatrix} 6 & -4 & 1 & 0 & \Lambda & \Lambda & \Lambda & 0 \\ -4 & 6 & -4 & 1 & O & & & M \\ 1 & -4 & 6 & -4 & 1 & O & & M \\ 0 & O & O & O & O & O & O & M \\ M & O & O & O & O & O & O & 0 \\ M & & O & 1 & -4 & 6 & -4 & 1 \\ M & & & O & 1 & -4 & 5 & -2 \\ 0 & \Lambda & \Lambda & \Lambda & 0 & 1 & -2 & 1 \end{bmatrix} \tag{10}$$

$$K = \frac{EI}{dx^4}\begin{bmatrix} 6 & -4 & 1 & 0 & \Lambda & \Lambda & \Lambda & 0 \\ -4 & 6 & -4 & 1 & O & & & M \\ 1 & -4 & 6 & -4 & 1 & O & & M \\ 0 & O & O & O & O & O & O & M \\ M & O & O & O & O & O & O & 0 \\ M & & O & 1 & -4 & 6 & -4 & 1 \\ M & & & O & 1 & -4 & 5 & -2 \\ 0 & \Lambda & \Lambda & \Lambda & 0 & 1 & -2 & 1 \end{bmatrix} \tag{11}$$

It substitutes the equation (12) and (13) showing in the equation (8) which consists of an equation (9), (10), and (11) below. And it transforms into primary equation of only displacement.

$$v(t) = \frac{z(t) - z(t - \Delta t)}{\Delta t} \tag{12}$$

$$a(t) = \frac{v(t) - v(t - \Delta t)}{\Delta t^2} \tag{13}$$

It substitutes an eq. (12) and (13) for an eq. (8), and obtains an eq. (14).

$$\overline{K}z = \overline{F} \tag{14}$$

Eq.(15),(16) show $\overline{K}, \overline{F}$ of eq.(8).

$$\overline{K} = \left[\frac{M}{\Delta t^2} + \frac{C}{\Delta t} + K\right] \tag{15}$$

$$\overline{F} = F + M\left(\frac{\{z(t-\Delta t)\}}{\Delta t^2} + \frac{\{v(t-\Delta t)\}}{\Delta t}\right) + C\frac{\{z(t-\Delta t)\}}{\Delta t} \tag{16}$$

The displacement of each component of voluntary time is computable by solving an equation (16). The displacement of each component of voluntary time is computable by solving an equation (16). The magnetic levitation simulation of thin steel sheet becomes possible by using these models and equations. The initial condition of a thin steel sheet is a position lower 3[mm] than order value. One side of the boundary condition of a black sheet is a fixed end, and an opposite edge is a free edge. The boundary condition of one side is a fixed end, and an opposite side is a free edge. And the electromagnets are the same position as the one side support experiment. Table 3 shows the gains used for the simulation.

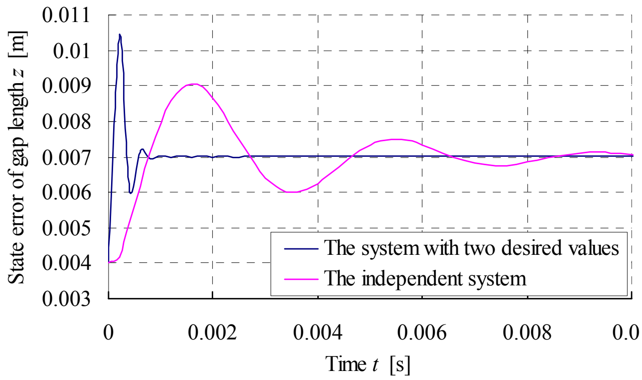


Fig.9. The gap response of the independent system and the system with two desired values.

The proportional gain and differential gain of fixed command controlled electromagnet differ from the experiment. The number of components of the thin steel sheet is 50.

Table 3. The used PID control gains in the simulation for one-end support magnetic levitation.

Controls	Electromagnets	Proportional gain	Differential gain	Integral gain
The independent system	Fixed-command controlled magnet	12000	50	300
	Follow-up controlled magnet	14000	70	300
The system with two desired values	Fixed-command controlled magnet	20000	100	300
	Follow-up controlled magnet	12000	200	300

F

Fig. 9 shows the result of an one side support simulation about the independet system and the system with two desired values. It was proved like the experiment that the system with two desired values can make convergence of vibration quick. The system with two desired values can set up a differentiation gain highly, therefore, vibration can be controlled rather than the independent system. In the independent system, the thin steel plate became more unstable when the differential gain which controls the response of an electromagnet was raised. However, in the case of the system with two desired values, it was able to maintain stability. The system with two desired values can inhibit, therefore, vibration of a thin steel sheet more.The vibrations of various frequencies exist on a thin steel plate during surfacing. The examination to frequency of a thin steel plate is, therefore, required. The following chapter is that accelerator gives vibration to the thin steel plate, and shows the verification about the oscillating inhibition effect.

4. Comparison with system of two desired values and independent system by experiment of one-end support magnetic levitation attached to accelerator

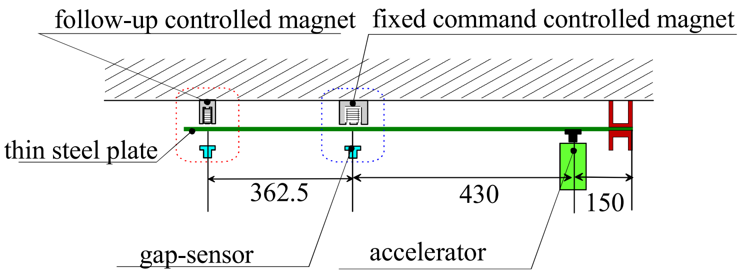


Fig. 9. The device of one-end support magnetic levitation attached accelerator.

Table 4. The gains of in the experiment and simulation for one-end support magnetic levitation attached accelerator.

In control system with two desired values and independent control system, it is necessary to obtain the capability that can control vibration over the frequency of the vibration on a thin steel plate. It is examined the capability of control over vibration added to the thin steel plate by accelerator. Fig.9 shows the device of one-end support magnetic levitation attached to accelerator. The vibration inputted from accelerator was about 1 millimeter independent on frequency.

The gap sensor directly under an electromagnet measures the amplitude of vibration that spreads the thin steel plate outputted. The *amplitude ratio of vibration* is a parameter of the vibration control effect. The capability that control vibration is high when the *amplitude ratio of vibration* is low value. The gains of PID control set up at the time of the experiment of one-end support magnetic levitation using accelerator are shown in Table 4. The experiment used the fixed gain shown in Table 4 in every frequency. Fig. 10 shows characteristic of amplitude ratio of vibraton - frequency of the system with two desired values and the independent system. Fig. 10 shows the gain is high when the frequency of the thin steel plate is high, in both systems. In both cases, the capability that can control vibration of the system with two desired values and independent system is also low, when a vibration on thin steel pate is high frequency. Fig. 11 shows a simulation result. In the simulation, it was proved similarly that the oscillating inhibition effect of the system with two desired values is high in which frequency. It is shown, therefore, that frequency is high when the capability that can control vibration of the system with two desired values is high.

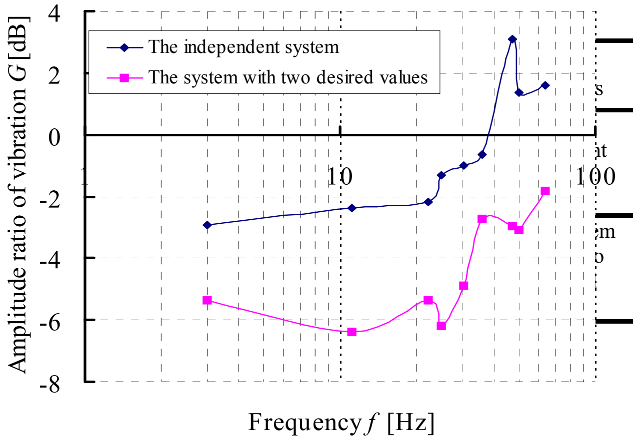


Fig.10. The characteristics of amplitude ratio of vibration-frequency by experiment.

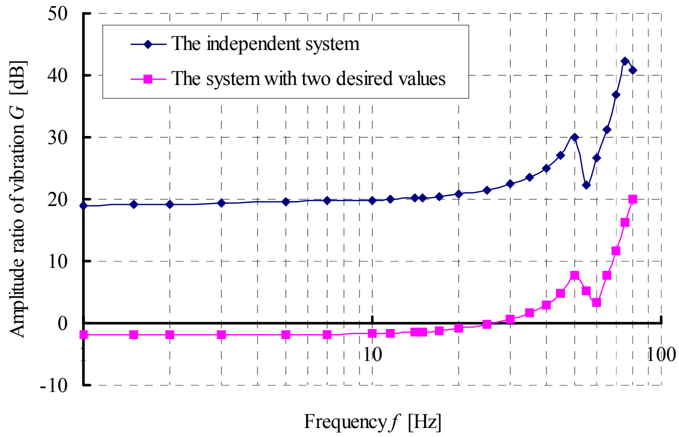


Fig.11. The characteristics of amplitude ratio of vibration-frequency by simulation.

However, the progressive wave added by accelerator and the reflected wave from a free end side generate standing wave. Therefore, interception of vibration that is the peculiarity of the system with two desired values could not be confirmed.

5. The experiment of one-end support magnetic levitation attached accelerator for confirming control of an advance wave.

In order to investigate the capability that can control progressive wave on the thin steel plate, the vibration absorbent was attached to the opposite side of accelerator and the one end support experiment was tested. The system with two desired values can control progressive wave. The response of follow-up controlled magnet is so required when the interval of the fixed-command controlled magnet and the follow up controlled magnet is narrow and the speed of the progressive wave is quick. The amplitude ratio of vibration-frequency characteristics of the system with two desired values in the each position of an electromagnet ware measured. Fig. 11 shows the device of one-end support magnetic levitation attached accelerator for confirming controls of progressive wave. The position of the fixed command controlled magnet was fixed and the follow-up controlled magnet changed an interval *l* of two electromagnets. Table 5 shows the gains of the system with two desired values. Fig. 12 shows the characteristics of gain-frequency in the system with two desired values by experient.

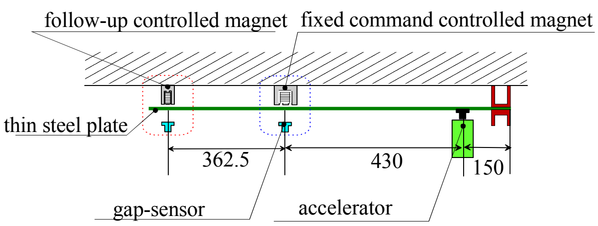


Fig.11. The characteristics of attached acceleratorfor confirming controls of progressive wave by experiment.

Table 5. The gains of the system with two desired values in the experiment of one-end support magnetic levitation attached accelerator.

Electromagnets	Proportional gain	Differential gain	Integral gain
Fixed-command controlled magnet	21000	250	1200
Follow-up controlled magnet	30000	280	1200

It turns out that this system can control vibration if an electromagnet interval is narrow. The values of amplitude ratio of vibration *G* in which interval is 90 millimeter in low frequency are lower than 200 millimeter. It is, however, high value when an electromagnet interval is 90 millimeter in high frequency. It is the influence by the response of follow-up controlled magnet. In the experiment, amplitude ratio of vibration climbed in 20 [Hz] at the time of l= 90 [mm], and in 30 [Hz] at the time of l= 200 [mm].The result of experiment proves the system with two desired values can suppress progressive wave when the interval of experiments prove the system with two desired values is more effective than the independent system.

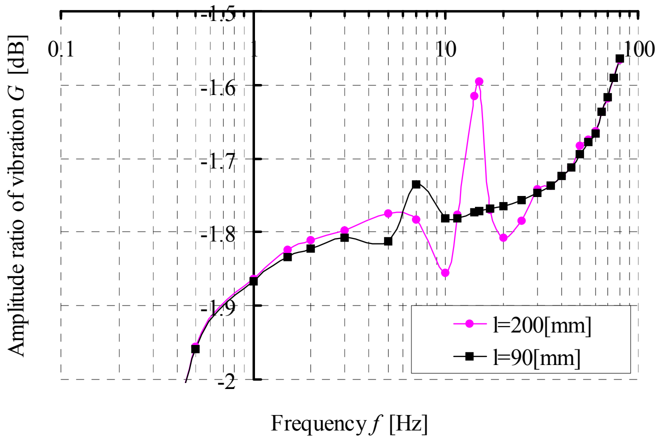


Fig.12. The characteristics of attached accelerator for electromagnets is narrow. These confirming controls of progressive wave by experiment.

Although the differential gain of PID control is high enough, the amplitude ratio of vibration goes up below to 10 hertzes. This shows the drop of levitation stability and is a problem in a controllability. A simulation, therefore, needs to examine the oscillating amplitude ratio below 10 hertzes. Fig. 13 shows the simulation model. In a simulation model, the dampoing coefficient of the thin steel sheet increases gradually instead of an vibration absorber, and the amplitude of vibration becomes close infinite 0 finally. The number of components is 50. And the gain of PID is the same as that of an experiment. Fig.14 shows simuration result. In the simulation, resonance appeard 7 [Hz] at the time of l= 90 [mm], and i 1.5 [Hz] at the time of l= 200 [mm]. As mentioned above, in the system with two desired values, to the size of a black sheet, resonance appears on a low frequency, when an electromagnet interval is narrow. It turns out that the amplitude ratio of vibration also becomes low.

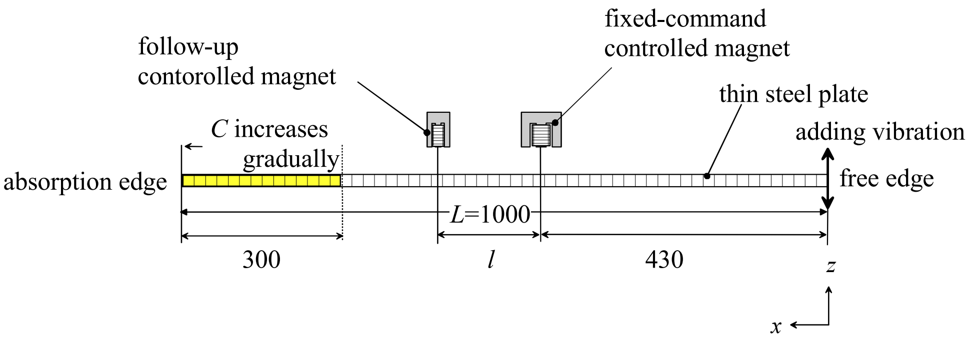


Fig.13. The one-end absorbed model for simulation.

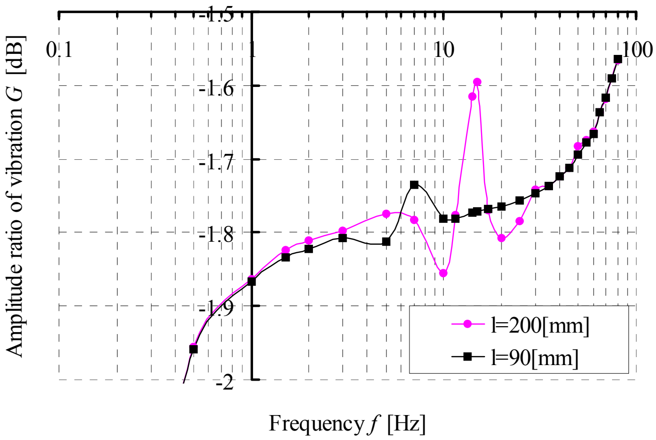


Fig.15. The characteristics of attached accelerator for confirming controls of progressive wave by simulation.

6. Conclusion

The thin steel sheets should be transported without cracks on the surface and the unevenness of lubricating oil in the field of producing steel-ware. The non-contact transportation of thin steel sheets by magnetic levitation is one of the solutions. The thin sheets vibrate more easily than the thick one in the magnetic levitation control. It therefore is proposed that the levitation system with two desired values can keep levitate steadily. The vibrations of various frequencies exist on a thin steel plate during surfacing. The examination and simulation to frequency of a thin steel plate is, therefore, required. In control system with two desired values and independent control system, it is necessary to measure capability that can control vibration over the frequency of the vibration on a thin steel plate. In both controls, the system with two desired values and independent system of vibration control capability is also low when a vibration on thin steel pate is high frequency. Examination and simulation result show that the vibration control capability of the system with two desired values is high compared with the independent system when frequency is high. The system with two desired values can set up a differentiation gain highly, therefore, vibration can be controlled rather than the independent system. Although a controllability changes with resonance frequency, these experiment and simulation of attached accelerator show that controllability of the system sith two desired values is not depend on an electromagnet interval and high compared with the independent system. These experiments prove, threfore, the system with two desired values is more effective than the independent system.

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