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Vibration Suppression of Thin Steel by Position Control of Permanent Magnet

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Abstract
This paper describes a vibration control method using permanent magnets and linear actuators. The key to the proposed method is the force control mechanism. A linear actuator drives a permanent magnet and varies the air gap between the magnet and the object. The variation in the size of the air gap changes the attractive force. Since the control range is almost the same as the actuator stroke, we can expect the vibration control range to be correspondingly wide. First the principle of the proposed vibration suppression system will be explained. Second two types of vibration control system will be introduced and modeled. Some numerical and experimental examinations will be carried out. The results support the proposed vibration suppression mechanism which is feasible.

Key words: Mechanical control, Linear actuator, Permanent Magnet

1. Introduction

In the process of plating, coating or rolling of steel sheets, vibration in conveyance often becomes a problem, as sheets are very flexible. As a countermeasure, a vibration suppressor with mechanical contacts is not suitable in such a process. Because objects are easily damaged due to their material makeup such as iron plate which has just been rolled, coated, or plated. Therefore a noncontact suppression mechanism is more suitable for steel sheets. Problems such as deformation, peeling, and uniformless products are minimized. Noncontact vibration control methods which use attractive forces of electromagnets have already been proposed in many papers [(1)-(4)]. The principal weakness of these methods is that the control range is very constricted, because the attractive force of the magnet varies in inverse proportion to the square of air gap length. If the vibration amplitude of the object is large, it becomes impossible to control the object using electromagnets.

This paper proposes a vibration control method using permanent magnets and linear actuators. The key to the proposed method is the force control mechanism [(5)]. A linear actuator drives a permanent magnet and varies the air gap between the magnet and the object. The variation in the size of the air gap changes the attractive force. Since the control range is almost the same as the actuator stroke, we can expect the vibration control range to be correspondingly wide.

In this paper, we study the feasibility of the proposed method. The outline of the proposed method is introduced and the aim of the system is shown. The principle of the control mechanism is explained, and an experimental system is introduced and modeled. Following that, the experimental system is analyzed according to linear control theory, and controller is designed based on the results. Numerical simulations and experimental examinations are carried out to demonstrate the properties of the control method and its feasibility.

2. Proposed Vibration Suppression Mechanism

A schematic proposed system illustration of a steel sheet plating or coating process is shown in Fig. 1. The steel sheet is fed from the right side of the figure and is directed upwards by a roller moving clockwise. While the steel sheet is being fed into the solution bath, plating or coating is carried out. After the plating process is completed in this way, the steel is seasoned or cooled in the vertical feed. In the seasoning process, the steel is especially sensitive to deformation. Consequently vibration control in the seasoning process is very important.

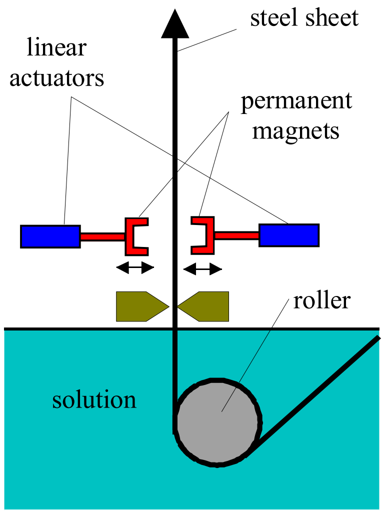

Fig. 1 Illustration of plating process

The aim of the proposed system is to reduce vibration caused by the roller feed mechanism in the plating process. Two permanent magnets and linear actuators located on opposing sides of the steel plate are used for vibration control. The magnets are actuated, by the actuator, in the horizontal direction. When the left magnet is positioned closer to the steel and the right magnet further away, a leftward force is generated. Similarly a rightward force can be generated. This force control mechanism has previously been proposed in magnetic levitation systems.

The strategy for controlling vibration in the steel sheet is as follows: A sensor measures the displacement of the steel sheet. Based on the sensor information, a controller calculates the force required to suppress the vibration. This force is created by driving the magnet and adjusting the air gap size. Thus the proposed vibration control system is realized.

3. Experimental Device

An experimental system to examine the performance of the proposed vibration control method was devised. This system was modeled in order to analyze the linear control theory and to synthesize the control system.

3.1 Experimental system

A photograph of an experimental system is shown in Fig. 2. The outline of vibration suppression mechanism is illustrated in Fig. 3. As the first step toward realization of the proposed method, an experimental design which uses one actuator was created as shown in the Figure.

The vibration body supported by two parallel plate springs is the controlled object to suppress vibration. These springs can be replaced and an arbitrary stiffness can be determined. The control force is created by two permanent magnets which are located in slider actuated by a linear actuator. Two iron plates are installed in the vibration body. They are installed so that the faces to the permanent magnets as attractive forces act on the body. The linear actuator is a voice coil motor which is called a VCM. The actuator has a stroke length of 15 mm. The motions of the vibration body and the VCM are measured by eddy current sensors.

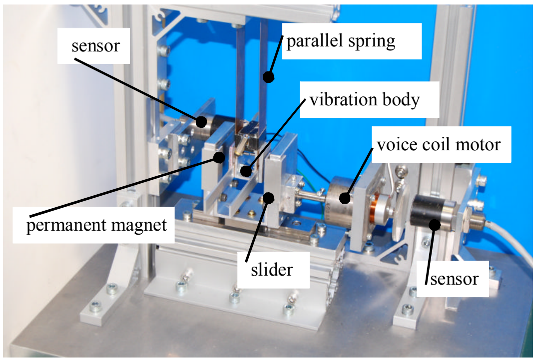

Fig. 2 Photograph of experimental setup

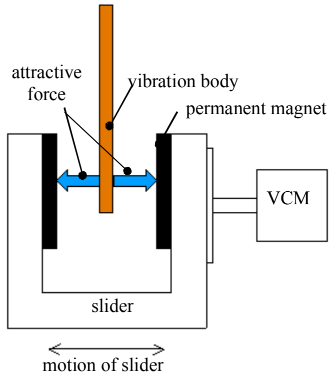

Fig. 3. System structure

3.2 Modeling of System

Modeling of the experimental system is needed in order to confirm stability, calculate the feedback gains, and permit a numerical simulation. In the model, the motion of the vibration body is assumed to be translational, as it supported by parallel springs. The positive direction is the rightward direction in Fig. 3. Modeling is carried out for two types of model. One is for 1 actuator system which is shown in Fig. 2 and Fig. 3. Another is for two actuator system which is shown in Fig. 1. Two actuator systems can drive the left and right magnets individually. The illustrations of the models are shown in Fig. 4 and Fig. 5 respectively. Symbols used in the model are:

z_0, z_1, and z_2 are displacements of the body and the magnets,
d_1 and d_2 are the air gaps between the body and the magnets,
k_0 is the spring constant of the vibration body,
c_0 is damping coefficient of the vibration body,
m_0, m_1, and m_2 are the equivalent masses of the body and magnets,
f_{m1} and f_{m2} are the attractive forces,

and f_{a1} and f_{a2} are the forces of the actuators. The attractive force is determined as the inverse square of the air gap. The generating force acting on the vibration body is

$$f_m = f_{m2} - f_{m1} = \frac{k}{(d_0 + z_2 - z_0)^2} - \frac{k}{(d_0 + z_0 - z_1)^2} \quad (1)$$

where, k is the constant of the magnet and d0 is the air gap in the equilibrium state.

The equation for the motion of the body is

$$m_0 \ddot{z}_0 = f_m - k_0 z_0 - c_0 \dot{z}_0 + f_d \quad (2)$$

where, f_d is the external disturbance.

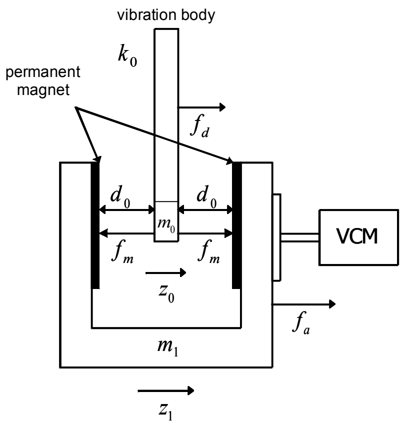

Fig. 4 Model of 1 VCM

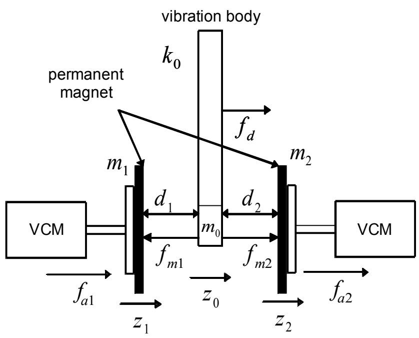

Fig. 5 Model of 2 VCMs

The equation of the motion of the magnet in Fig. 4 is

$$m_1\ddot{z}_1 = -f_m + f_a \tag{3}$$

When the input of the system is defined by the force of the actuator, the model is represented by Eq. (1), (2) and (3). The system input is the actuator force f_a and the outputs are the displacements of the body and the magnets.

The equations of the motions of the magnets in Fig. 5 are

$$m_1\ddot{z}_1 = f_{m1} + f_{a1} \tag{4}$$

$$m_2\ddot{z}_2 = -f_{m2} + f_{a2} \tag{5}$$

Two inputs are applied for this system. The model is represented by Eq. (1), (2), (4), and (5).

3.3 Setup of System

For vibration suppression control, a digital controller was used for examinations. The system structure is shown in Fig. 6. A DSP board is used for the controller. The sensor signals are converted to the digital values by A/D converters and they are inputted to the controller. The controller calculates appropriate value of the actuator force and the value is outputted to the current amplifier through a D/A converter.

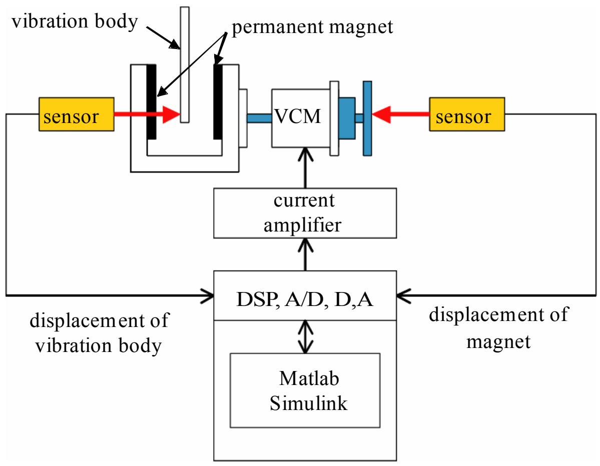

Fig. 6 Illustration of Experimental Setup

The controller for the vibration control system is a regulator with two PD feedback loops. The feedback gains are calculated by MATLAB on the state space model. The state variables are assumed to be gained precisely without delay. The feedback rule for 1 actuator system is simple PD control as

$$f_a = -(k_{p0}z_0 + k_{d0}\dot{z}_0 + k_{p1}z_1 + k_{d1}\dot{z}_1) \tag{6}$$

And the feedback rules for 2 actuator system are

$$f_{a1} = -(k_{p0}z_0 + k_{d0}\dot{z}_0 + k_{p1}z_1 + k_{d1}\dot{z}_1) \tag{7}$$

$$f_{a2} = -(k_{p0}z_0 + k_{d0}\dot{z}_0 + k_{p1}z_2 + k_{d1}\dot{z}_2) \tag{8}$$

where, k_{p0}, k_{d0}, k_{p1}, and k_{d1} are feedback gains. Parameters used in simulations are equivalent values to the actual experimental device. There are: m_0=0.1 [kg], m_1=0.366 [kg], d_0=0.007 [m], k_0=41.7 N/m, c_0=0.05 [Ns/m], k=3.67 10^{-7} [Nm^2], k_m=4.29 [N/m].

4. Examinations

4.1 Numerical Simulation

To investigate the performance of the prototype system, numerical simulations were carried out with the lever initially set to 3 [mm] and so that it vibrates freely. One simulation was done without feedback control. In this simulation, the magnet was set to stand still to the original position. The result of the simulation is shown in Fig. 7. The motions of the magnet and the vibration body were recorded. In the figure, the red line indicates the movement of the magnet and the blue line indicates the movement of the vibration body. In this case, as there is no feedback control, the position of the magnet is fixed to the same position. And we can see that the vibration continued over 10 seconds. This result shows that this system is an under dumping system.

Numerical simulations with feedback control were also carried out. Systems using one actuator and two actuators were examined. The feedback gains for one actuator system are k_{p0}=500, k_{d0}=50, k_{p1}=800, and k_{d1}=10, and those for two actuator system are k_{p0}=250, k_{d0}=25, k_{p1}=400, and k_{d1}=5 those are half of the one actuator system. .The results are shown in Fig. 8 and Fig. 9 respectively. With feedback control, the movement of the vibration body converges to zero rapidly within about 3 seconds. These results show that the feedback control using permanent magnets is effective for suppression of the vibration. The results using one actuator and using two actuators are almost same. The advantage that using two actuators is not recognized. The two actuator system is considered that it has an advantage that when there is no vibration two magnet can be apart from the vibration body and the eddy current losses by running steel can be reduced. The novel proposals for using

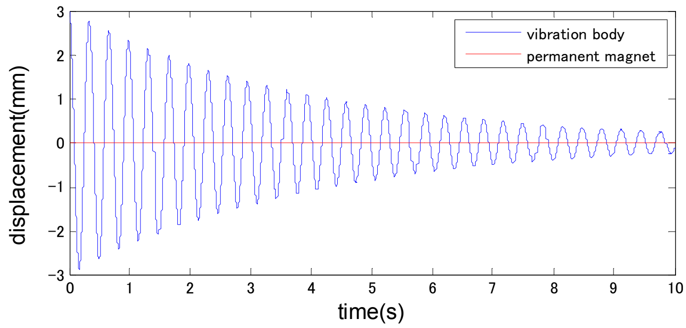

Fig. 7 Numerical simulation result without feedback control

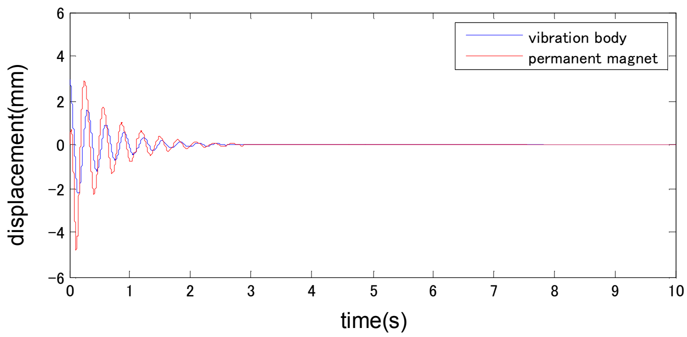

Fig. 8 Simulation result with feedback control (1 actuator was used)

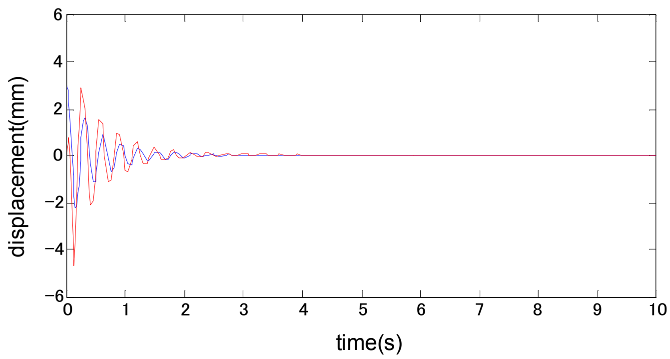

Fig. 9 Simulation result with feedback control (2 actuators were used)

redundant mechanism, however, are desired.

4.2 Experimental Examination

For experiment, we carried out the same examination as numerical simulations. One experiment was done without feedback control. The permanent magnet was controlled as the position in the origin. Another experiment was with feedback control and the gains were the same as they were in the simulation. The results are shown in Fig. 10 and Fig. 11.

In the experiment without feedback control, almost same result was observed as the simulation. The vibration converged to the original position; however it takes much time as shown in Fig. 10. As shown in Fig. 11, the result with feedback control indicates the feedback control is effective for vibration suppression. The performance is, however, relative low, as we can see the convergence time is relative longer than the simulation result in Fig. 8. It may be caused by the omitted vibration mode of the parallel springs and the delay of the response of the actuator. Both results of the simulation and the experiment support the feasibility of the proposed vibration suppression mechanism.

To examine the further performance of vibration suppression, the experiments that system has sine wave disturbance were carried out. As the external disturbance, motor rotation with the imbalance axis was used. About 7.5 Hz and 20 Hz sin wave disturbances were applied. The results are shown in Fig. 12 and Fig. 13. In the figures, the left figure is the result without feedback control and the right figure shown the results with feedback control. As shown in these figures, A little vibration suppression effect can be seen, when 7.5 Hz disturbance was applied. The results show the limitation of the fixed gain feedback method. Advanced control methods should be applied.

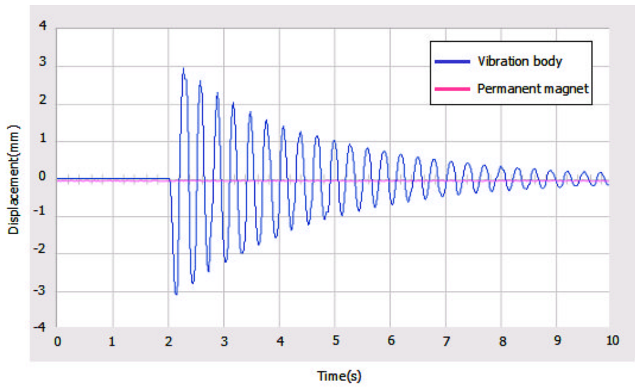

Fig. 10 Experimental results without feedback control

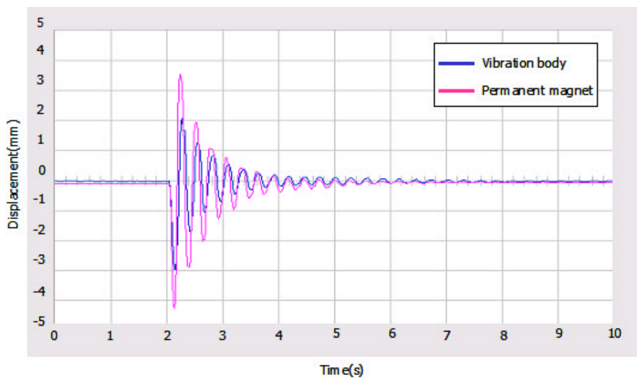

Fig. 11 Experimental result with feedback control (one actuator system)

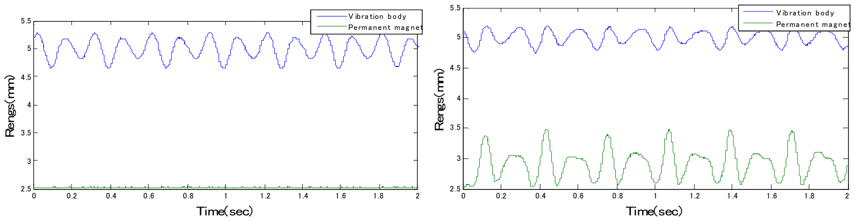

Fig. 12 Experimental result when external disturbance of 7.5 Hz was applied
(left: without feedback control, right: with feedback control)

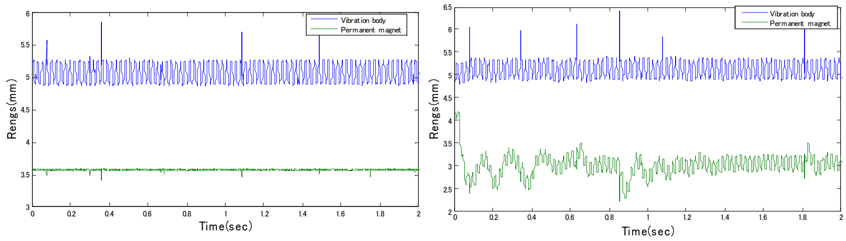

Fig. 13 Experimental result when external disturbance of 20 Hz was applied
(left: without feedback control, right: with feedback control)

5. CONCLUSION

A vibration control method which uses a linear actuator and a permanent magnet has been proposed. An experimental system has been introduced and modeled. The vibration control system has been modeled and the model haves been verified to be controllable and observable. From numerical simulations, it has been proven that the force feedback control system can suppress vibration. Same results have been obtained in experimental examinations. However the performance was relative low because of spillover the vibration of the supported springs and lack of the actuator response. As the result, the proposed vibration suppression mechanism has been proven to be feasible.

Further studies involving consideration of the external disturbance force and investigation of more robust high performance controller will be ongoing.

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