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Design of a Gentle Damping System for a Weak Wooden House

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Abstract*— This paper proposes a control system to reduce vibrations in existing wooden houses that are insufficient in strength, using a simple semi-active damper having a variable viscous damping coefficient. A linear motion generator is used as the semi-active damping device. It is simply structured with a magnet bar and coils. When the magnet bar is linearly moved by vibrations, electromotive force is generated in the coils. The viscous damping coefficient of the semi-active damping device can be changed by adjusting the current flowing through the coils. The current is varied by PWM signal. Here, the proposed semi-active damping system is numerically equipped on a mimic column beam framework model. The performance of the semi-active damping system was simulated using real earthquake wave form data. The simulation showed that the maximum displacement of the wooden frame is reduced by about 2.5 [cm] using the proposed system in comparison with the same frame without a damping device. Furthermore, it was confirmed that the proposed damping system reduced the stress to a screw fixing anchor by up to 26.7 [N/mm2].

***Index Terms*—Semi-Active Damper, Linear Generator, Viscous Damping Coefficient, Weak Wooden House.**

I. INTRODUCTION

Because there are many active tectonic faults in Japan, many earthquakes have occurred recently, such as the Great Hanshin Earthquake, Great East Japan Earthquake and Kumamoto Earthquake [1]. Those earthquakes destroyed many houses which had low earthquake resistance [2], [3]. Such houses need to be made more earthquake resistant. Oil dampers or MR fluid dampers which are equipped on large buildings have high vibration damping capability [4], [5]. The viscous damping coefficient of an oil damper is unable to be changed. Although the viscous damping coefficient of an MR fluid damper can be changed, it needs a large amount of electricity. If those damping systems are equipped on a small, weak tenement-house that shares a wall with another room, a large amount of stress is sometimes applied to part of the house’s wall. As a result of anti-earthquake reinforcement, there is a high possibility that such a weak house would be exposed to danger of collapse [6]. Therefore, it is necessary that an inexpensive damping system appropriately reduce vibration within an allowable range that does not destroy the house.

The authors have been developing a linear-motion generator which converts traveling vibrations to electricity [7]-[10]. The damping force of the generating device can be varied by adjusting the current flowing through the coils of the device [9]. Therefore, it is applied here as a semi-active damping device for a small weak wooden house.

In this study, we designed a semi-active damping system that is controllable by electronic signals. It was numerically equipped on a mimic column beam framework model. The performance of the semi-active damping system was simulated using real earthquake wave form data.

II. MATERIALS AND METHOD

Figure 1 shows the fundamental structure of the damping device. It has a cylindrical construction including with stator coils and a permanent magnet mover. The mover is an Nd Fe-B magnet bar in the center of the device. Magnets are positioned with the same magnet poles facing each other. Because the stator coils wound in opposite directions to the next coil are connected in series, as shown Fig.1, the generated power synchronizes and becomes large.

When the mover is linearly driven, electromotive force is generated. The motion of the mover is hindered according to the value of the current that flows through the coil. Therefore, the viscous damping force can be changed by adjusting the current flowing through the coil. The damping device is designed based on dynamic analysis by magnetic-structure interaction analysis using the FEM software, ANSYS (CYBERNET SYSTEMS Co. Ltd.). As for the simulation result, the maximum damping coefficient of the damping device is 139.1 [N s/m] [9]. A resistance and a bidirectional switch are connected to both ends of the stator. The bidirectional switch consists of two MOSFETs. The bidirectional switch is driven by a PWM signal. The damping device is connected to the resistance through the bidirectional switch when the MOSFETs are turned. Because the current flowing through the coils is changed at alternating intervals by PWM signal, the viscous damping force is controlled as needed. The viscous damping coefficient of the damping device is varied from 24 [N s/m] to a maximum value of 139.1 [N s/m] when the duty ratio of the PWM signal is set from 0 [%] to 100 [%]. The maximum power consumption to drive the control circuit is only 68.2 [□W].

In the case that a part of a wooden house is reinforced, stress by an earthquake sometimes concentrates on the reinforced part, as mentioned above. Figure 2 illustrates a mimic column beam framework model. The proposed damping system is numerically applied to the framework model. The motion equation of the model is as follows:

$$\begin{bmatrix} m_1+m_2 & m_2 \\ m_2 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{bmatrix}+\begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix}+\begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}=\begin{bmatrix} F_1(t) \\ F_2(t) \end{bmatrix}$$

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(1)

Here, x_1 and x_2 are the displacement of the frame from the base line and the displacement of concentrated mass, respectively.

The developed damping device is equipped as a damper c_2 in Fig. 2. Therefore, the value of c_2 is changed by the PWM signal, which is described in equation (2).

$$c_2(k) = c_{con} + c_{act}(k) \qquad (2)$$

The parameter c_{con} is the smallest value of the viscous damping coefficient of the damper c_2 in the case that the current of the stator is zero. The changeable parameter $c_{act}(k)$ is determined by equation (3). A PI controller is designed to calculate the change value of controlling input $\Delta c(k)$. However, the damping system never decreases $c_2(k)$ less than c_{con}.

$$c_{act}(k) = c_{act}(k-1) + \Delta c(k) \qquad (3)$$

$$\Delta c(k) = K_i e(k) + K_p \{e(k) - e(k-1)\} \qquad (4)$$

$$e(k) = x_d - x_1(k) \qquad (5)$$

In the aforementioned equations, $e(k)$ is the amount of error in the position from a desired value of the position of the wall x_d and $\Delta e(k)$ is the change in the amount error $e(k)$.

In this system, the viscous damping coefficient is considered as an input. On the other hand, an earthquake vibration is assumed as a large disturbance. The whole system is described as a bilinear system which has a product of the input and the state variable. Therefore, the proposed system has nonlinear and time-varying characteristics. Parameters K_i and K_p are determined by trial and error. The parameters are shown in Table 1.

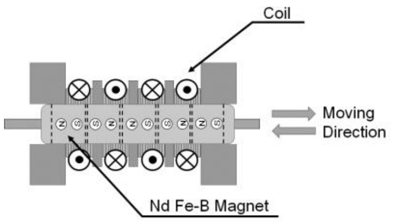

Fig. 1: Fundamental structure of the damping device.

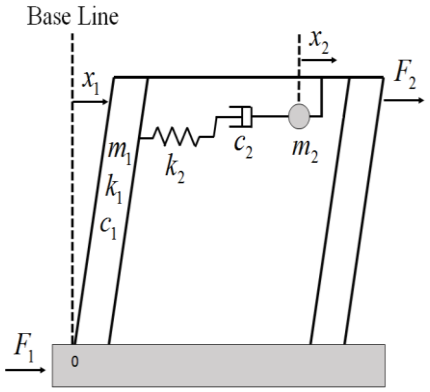

Fig. 2: Analytical model

III. SIMULATIONS AND RESULTS

The damping devices, which are connected in parallel, are equipped on the mimic column beam framework model, as mentioned above. A simulation is performed by MATLAB (The MathWorks, Inc.). The control result is shown in Fig. 3, when a pulsed input force of 130 [N] is given to the frame as an external force for 0.1 [s]. Figure 3 (b) shows the change of displacement x_1(t). In Fig. 3 (b), the solid line is the controlled displacement and the dotted line is the displacement with no damping system. When the proposed damping system is used, the vibration of the frame is reduced more gently compared with the vibration with no controller.

Real earthquake vibration is used as an external input in the experiment illustrated in Fig. 4. From the simulation result, the proposed system also decreases the vibration of 2.5 [cm] at most. Furthermore, stress applied to screws fixing anchors of frames is also analyzed by a simulation [11]. Figure 5 (a) shows a model for a structural analysis. By the simulation, the proposed damping system reduces the stress to a screw fixing anchor by up to 26.7 [N/mm^2]. Therefore, the proposed damping system decreases the effect by applied repeatedly small stress and contributes to reduce damage of a weak house in an earthquake.

Table 1: The parameters of simulation

The mass of the entire pillar m_1 [kg]	16
The displacement of concentrated mass m_2 [kg]	16
The viscous damping coefficient of the entire pillar c_1 [N s/m]	50
The Viscous damping coefficient in damping device c_{con} [N s/m]	50
The spring constant of the entire pillar k_1 [N / m]	1875
The spring constant in damping device k_2 [N / m]	1000
Integral gain K_i	1.43
Proportional gain K_p	6.31

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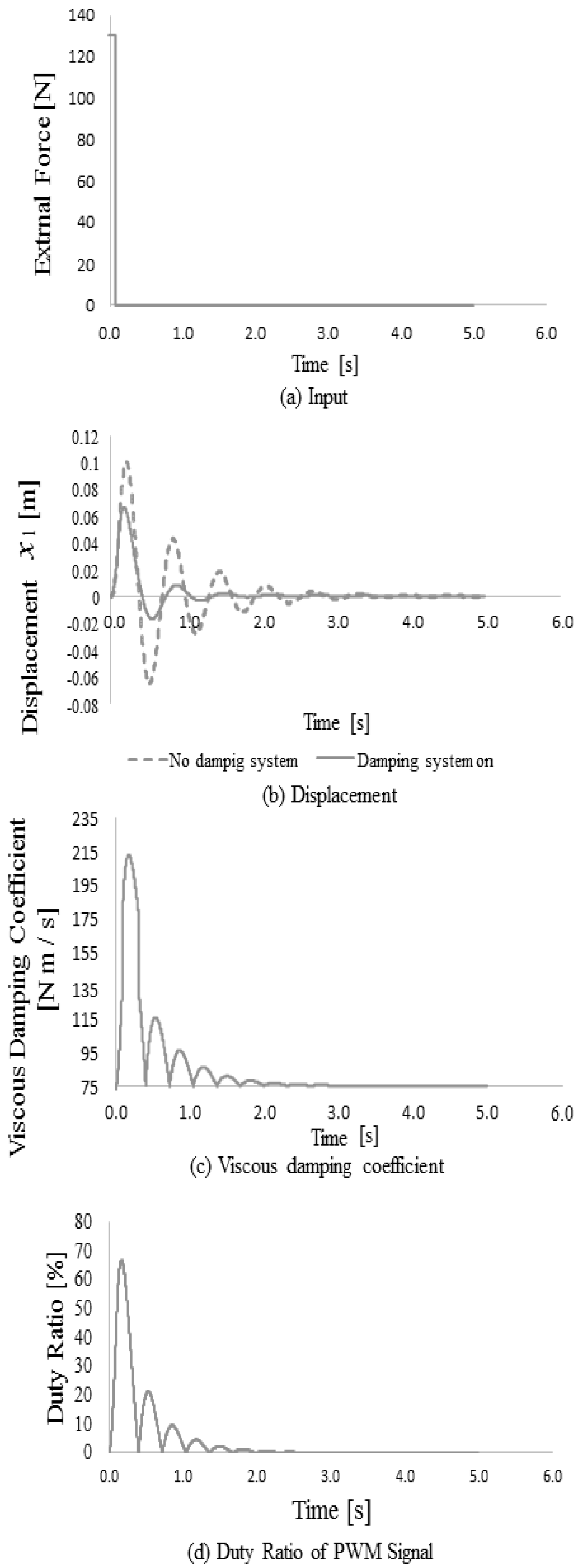

Fig. 3: Vibration control simulation in the case that a pulsed input force of 130 [N] is given to the frame as an external force for 0.1 [s]

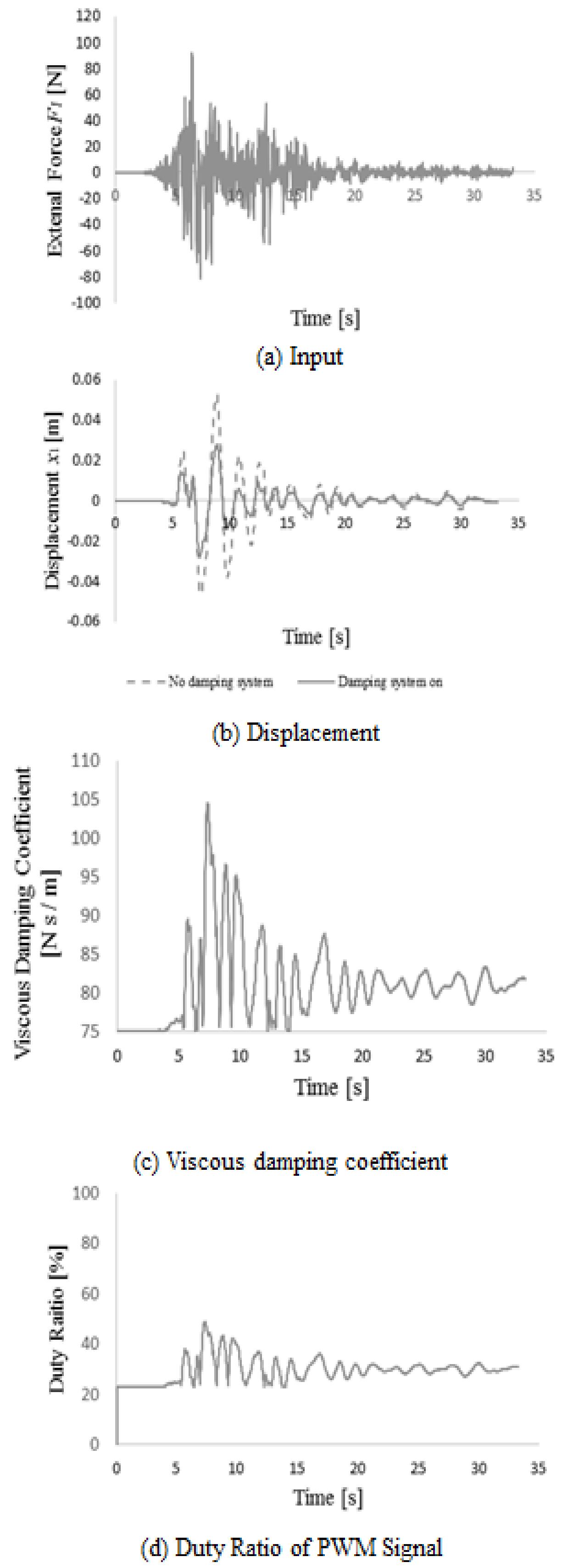

Fig. 4: Vibration control simulation in the case that a real vibration of the Hanshin Earthquake is given to the frame as an external input

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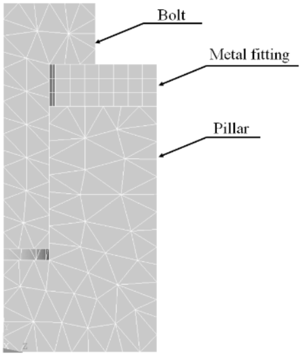
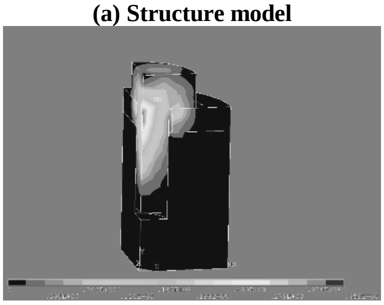


(a) Structure model


(b) Analysis results of stress (No damping system)

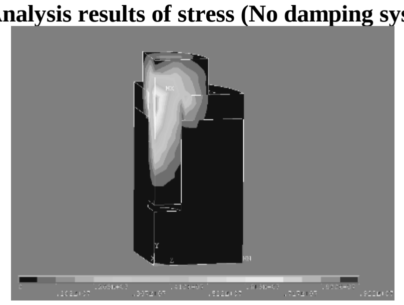

(c) Analysis results of stress (Damping system on)

Fig.5: Structure model of screw

IV. CONCLUSION

This paper proposed a semi-active damping device and a damping system for reducing vibration of existing wooden houses supposed to be insufficient in strength. The proposed system applied to the mimic column beam framework model numerically. The proposed system was confirmed to be useful for gently reducing the vibration of the framework model when the real earthquake wave form is given as the external force by the simulations.

The characteristics of the vibration are thought to be changed due to mounting position of the damping devices. Therefore, the authors are investigating the design of a modified control system for cooperation action by plural damping devices. In the future, we will produce a prototype of the semi active damping system including a control system. Furthermore, we will design desired reducing vibration form models and a control system based on the model.

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