Vibration Control for House Structures beyond 3 Story using Adjustable Pendulum-Type Controller under Ground Excitation like Traffic Vibrations or Earthquakes*  

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Abstract  
In this paper, a new vibration control device called pendulum-type tuned mass damper (P.T.M.D.) is proposed to reduce an ordinal house vibration. In recent years, three or four stories houses are built increasingly in the urban areas to obtain wide living space. These houses are subjected to a problem caused by the traffic vibration, because a dominant frequency of the traffic vibration is coincident with the natural frequency of these houses. Although tuned mass dampers (T.M.D.) are considered to solve the problem, it needs to prepare a large mass on the top floor of these houses in order to obtain effective vibration reduction. On the contrary, P.T.M.D. can be placed between the first and second floor and it acts effectively on the principle of lever mechanism, since an action of the mass is expanded. A semi-optimal design approach for the P.T.M.D. is described, while it has an adjustable mechanism to adapt to various specifications of these houses. Effectiveness of the P.T.M.D. is demonstrated theoretically and experimentally by controlled results using frequency, time and seismic responses. Also this paper shows that the P.T.M.D. is effective against random vibration like earthquakes.  

Key words: Vibration Control, Vibration Control Device, Flexible Structure, Damping, Optimal Design

1. Introduction  
In recent years, the numbers of newly built three-story houses in Japan has been on the rise in urban areas in order to maximize living spaces within a smaller housing area. These houses are subjected to problems caused by traffic vibrations, because the dominant frequency of the traffic vibration located at about 3Hz is coincident with the natural frequency of these houses. Although tuned mass dampers (T.M.D.) are considered to solve the problem, they require a heavy auxiliary mass on the top floor in order to obtain effective vibration-reduction [1]. Such masses can result in increased dangers caused by large earthquakes. As an effective method, active mass dampers (A.M.D.) are well known to control the vibration of high-rise buildings [2,3] and huge bridge tower [4] vibrations caused by wind excitation. However applying the A.M.D. to these houses is cost-restrictive, because it is very expensive at the present time [5].  

In this paper, a pendulum-type tuned mass damper, which acts on principles of lever-mechanisms, has been proposed and investigated as a possible adaptation to vibration control devices for three-story houses. Since the tuned mass damper is abbreviated to T.M.D.
in the civil-engineering field, we will also refer to the pendulum-type tuned mass damper simply P.T.M.D. An important characteristic of P.T.M.D. is that it can be used as larger control force in spite of lighter weight by the use of a pendulum effect. Therefore, the P.T.M.D. is expected to be placed between the first and the second floors in order to prevent problems caused by T.M.D.. In addition, an adjustable mechanism is needed for the adaptability to various specifications of these houses. Research on the optimization of P.T.M.D. design against a controlled object with one degree-of-freedom has been done in the past. However, this research did not take into account the necessity of adaptation to the various specifications of controlled objects. The proposed P.T.M.D. will be used to examine the effectiveness of vibration control when it is placed between the first and the second floors of a house, in addition to adjustability for adapting to their various specifications.

In this paper, a model of a three-story house with an adjustable P.T.M.D. will be presented first. Second, a semi-optimum design procedure based on the optimization of P.T.M.D. design is applied for the adjustable P.T.M.D. to the three-story house. In order to verify results obtained by simulations, an experimental model of three-story houses with P.T.M.D. has been constructed. The effectiveness of the presented P.T.M.D. is demonstrated by frequency responses and time responses using simulation and experiments.

2. The Traffic Vibration Problem in Three-Story Houses

2.1 Necessity of vibration control device

Figure 1 illustrates an example of spectrum analysis of the signal, which is measured by an acceleration sensor installed on the surface of a main road. It has been found that the dominant frequency of traffic vibrations is located at about 3 Hz and the secondary frequency at about 12 Hz despite its small size. It is well known that a vibration of about 3 Hz is caused by the passing of heavy vehicles such as dump tracks and the vibration in the vicinity of 10~12 Hz is of express trains. When a vibration is transmitted to ordinary three to four-story houses through the ground surface, a large tremor is felt on the third floor, which is caused by even the slightest resonance. Since resonance house is usually built with iron columns, the amplification ratio at a resonance frequency increases because the internal damping of such structures is generally inconsequential. As the result, an especially large tremor is felt. Therefore, it is necessary to increase the structural damping from the outside using the above-mentioned controller.

![Fig. 1 Example of spectroscopic analysis on traffic vibration](chart.png)

2.2 Proposed adjustable pendulum-type controller

Figure 2 illustrates a concept figure that shows how conventional T.M.D. and proposed P.T.M.D. are set up in three story-houses. Because the controlled mode of the house is usually at the 1st bending mode, T.M.D. is set up in the rooftop where an equivalent mass at the controlled mode is small as the most effective place that can be greatly taken up mass ratio. Conversely, a P.T.M.D. is installed between the first and the second floors and is supported with a support structure on the second floor. The P.T.M.D. is composed of a pendulum equipped with a weight and damper at the bottom and a connecting spring at the top. The pendulum is supported by the supporting structure that is attached with a pin. The
connected spring with spring constant $k_s$ is used to supply an adjustable function by changing the spring constant.

The P.T.M.D. has a lever mechanism that can adjust the effects of the weight and damper dynamically using a lever ratio between upper and lower side lengths of the pendulum. For example, the weight and damper act in proportion to the square of the lever ratio. So the ability to achieve a damping performance more than equal to the weight is expected, even if the acting point of the P.T.M.D. is set to the second floor although the equivalent mass of the controlled object is large. As a result, an unstable heavy weight can be put on or near the ground to avoid dangerous situations caused by large earthquakes. Although ordinary houses with three to four stories have a wide range of design specifications in weight and rigidity, the P.T.M.D. can be used for such requirements by adjusting a connecting spring with spring constant $k_s$ and changing the weight and damper. In addition, an important feature of this adjustable P.T.M.D. is the relative ease of installation inside a house. This is because the pendulum combined with the weight and damper can be integrated in the support structure. The above-mentioned advantages will be examined with simulation and experiment. However, an optimal design approach is not yet constructed for the adjustable P.T.M.D. with the connecting spring.

![Fig. 2 Three story houses equipped with T.M.D. and proposed P.T.M.D.](image)

Fig. 2 Three story houses equipped with T.M.D. and proposed P.T.M.D.

3. Optimal Design for P.T.M.D. against One Storied Structure

3.1 Transfer function of the one-storied structure equipped with P.T.M.D.

![Fig. 3 One-storied structure equipped with P.T.M.D. and its dynamic model](image)

Fig. 3 One-storied structure equipped with P.T.M.D. and its dynamic model

An optimal design approach for P.T.M.D. directly connected with the one-storied structure shown in Fig. 3 has been already constructed (7). The one-storied structure with the P.T.M.D. and its dynamic model is illustrated in Fig. 3. The P.T.M.D. is composed of a support structure and a pendulum equipped with an added mass $m_p$ and a damper with damping coefficient $c_r$ at the bottom. The one-storied structure and the supported structure are modeled by each one degree-of-freedom system with masses $M$ and $m$. 

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stiffness $K$ and $k$, respectively. The upper and lower side lengths of the pendulum connected by two bearings are expressed by $l_1$ and $l_2$. The displacements of three masses of the one-storied structure, supported structure and added mass are expressed by $x_1$, $x_2$ and $x_p$. Also $u$ is the displacement of the base. For the sake of generality, the following no dimensional factors are introduced:

$$\Omega_n = \sqrt{K/M} : \text{Natural frequency of one-storied structure}$$
$$\omega_n = \sqrt{k/m} : \text{Natural frequency of supported structure}$$
$$\lambda = l_2/l_1 : \text{Lever ratio}$$
$$\mu_s = m/M : \text{Mass ratio of supported structure to one-storied one}$$
$$\mu_p = m_p/M : \text{Mass ratio of added mass to one-storied structure}$$
$$\zeta = c_p/2\sqrt{MK} : \text{Damping ratio}$$

According to the above mentioned notations, an amplitude ratio $X_i/U$ of the displacement $x_i$ to $u$ is introduced by Eq. (1) using Newton method.

$$X_i = \frac{1}{U} \sqrt{\frac{(-C\omega^2 + 1)^2 + F^2(\zeta\omega)^2}{(A\omega^2 - B\omega^2 + 1)^2 + (-D\omega^2 + E)^2(\zeta\omega)^2}}$$

Where, $A, B, C, D, E$ and $F$ are as follows,

$$A = \left[1 + \mu^2 \lambda^2 + \frac{(1 + \lambda)^2}{\mu_s} \right] \frac{1}{\Omega_n^2\omega_n^2}$$
$$B = \left[1 + \mu^2 \lambda^2 + \left(\frac{\Omega_n}{\omega_n}\right)^2 \left[1 + \frac{(1 + \lambda)^2}{\mu_s}\right] \right] \frac{1}{\Omega_n^2}\omega_n^2$$
$$C = \mu (1 + \lambda) \lambda + \left(\frac{\Omega_n}{\omega_n}\right)^2 \left[1 + \frac{(1 + \lambda)^2}{\mu_s}\right] \frac{1}{\Omega_n^2}\omega_n^2$$
$$D = \left[\lambda^2 + \frac{(1 + \lambda)^2}{\mu_s} \right] \frac{2}{\Omega_n \omega_n^2}$$
$$E = F = \left[\lambda^2 + \left(\frac{\Omega_n}{\omega_n}\right)^2 \left(1 + \lambda\right)^2 \right] \frac{2}{\Omega_n^2}\omega_n^2$$

For obtaining the optimum design condition of the P.T.M.D., the optimum design approach for the dynamic vibration absorber is applicable, because it has the similar transfer function with Eq.(1). According to the approach, the optimum tuning condition to keep two fixed points at the same amplitude level and the optimum damping condition to keep maximum amplitudes near to two fixed points are required to satisfy under the six design parameters $\Omega_n, \omega_n, \mu_s, \mu, \zeta$ and $\lambda$.

### 3.2 Optimum tuning condition

Two fixed points means two intersection ones of two amplitude caves when $\zeta = 0$ and $\zeta = \infty$ are substituted in Eq. (1). This condition is achieved by satisfying the following equation.

$$2EAF = D\left(BF + D - EC\right)$$

Introducing Eq. (2) ~ (6) in to Eq. (7), the mass ratio $\mu$ of added mass to one-storied
structure is obtained as the function of four parameters. This is defined as the optimum mass ratio \( \mu_{\text{opt}} \):

\[
\mu_{\text{opt}} = \left[ 1 - \left( \frac{\Omega_2}{\Omega_1} \right)^2 \right] \left[ 2 \left( \frac{\Omega_1}{\mu_s} \right)^2 \left( \frac{(1 + \lambda)^2}{\mu_s} \right)^2 \right] + \frac{(1 + \lambda)^2}{\mu_s} \lambda^2 - \lambda^4 \right]^{1/2}
\]

(8)

By calling two fixed points as P and Q, two frequencies \( \omega_P \) and \( \omega_Q \) are expressed as,

\[
\begin{align*}
\omega_P^2 &= \frac{BF + CE + D}{CD + AF} \\
\omega_Q^2 &= \frac{BF + CE + D}{CD + AF} - \frac{4(E + F)}{(CD + AF)}
\end{align*}
\]

(9)

### 3.3 Optimum damping condition

For obtaining the optimum damping condition to maximize the amplitude curves nearby the fixed points P and Q, the amplitude ratio \( X_1 / U \) is differentiated with \( \omega^2 \) and after that \( \omega_P \) and \( \omega_Q \) obtained by Eq. (9) are substituted into the following equation.

\[
\frac{\partial}{\partial \omega^2} \left( \frac{X_1}{U} \right) = 0
\]

(10)

A solution of Eq. (10) is expressed by a polynomial of \( \zeta \) as follows:

\[
K_4 \zeta^4 - K_2 \zeta^2 + K_0 = 0
\]

(11)

where, \( K_4, K_2 \) and \( K_0 \) are coefficients of the polynomial concerned with \( \omega \).

Although two solutions of a cubic equation (11) concerned with \( \omega \) are obtained, one solution \( \zeta_P^2 \) concerned with \( \omega = \omega_P \) and other \( \zeta_Q^2 \) concerned with \( \omega = \omega_Q \) are expressed as follows:

\[
\begin{align*}
\zeta_P^2 &= \left( K_2 / 2K_4 \right) - \sqrt{\left( K_2 / 2K_4 \right)^2 - \left( K_0 / K_4 \right)} \\
\zeta_Q^2 &= \left( K_2 / 2K_4 \right) + \sqrt{\left( K_2 / 2K_4 \right)^2 - \left( K_0 / K_4 \right)}
\end{align*}
\]

(12)

(13)

The optimum damping condition \( \zeta_{\text{opt}} \) is obtained as the mean value of above two solutions.

\[
\zeta_{\text{opt}} = \frac{\zeta_P + \zeta_Q}{2}
\]

(14)

### 3.4 Maximum amplitude ratio equipped with the optimum tuning and damping conditions

When the optimum tuning condition is satisfied by Eq. (7) and the optimum damping condition by Eq. (14), the maximum amplitude ratio is attempted by Eq. (15).

\[
\frac{X}{U_{\text{max}}} = \frac{F}{-D\omega^2 + E}_{\mu = \mu_{\text{opt}}, \zeta = \zeta_{\text{opt}}}
\]

(15)
Above presented optimum design procedure is called as a semi-optimum design in this paper, because a desirable optimum design for P.T.M.D. is to control vibration of the three storied structure.

4. Modeled Three Storied Structure and its Dynamic Characterizes

4.1 Experimental model of the three-story structure and its vibration characteristics

An experimental model of the three-story structure to be controlled is shown in Fig.4. Each floor is made with an acrylic plate 300 mm in width, 20mm in thickness and 20 kg in weight. Each column is made with an aluminum pole of 6 mm in diameter, 920 mm in height. Therefore the stiffness of the column between each floor is 6500 N/m.

![Fig. 4 Experimental model of the three-story structure and its vibration mode shapes and natural frequencies](image)

The calculated first third vibration mode shapes and corresponding natural frequencies are shown in Fig 4. Using these vibration mode shapes and the equivalent mass estimation method (8), the equivalent mass at the $j$th point of the $i$th mode $M_{ij}$ is obtained as follows:

$$M_{ij} = m_i \left(\frac{X_{i1}}{X_{ij}}\right)^2 + m_2 \left(\frac{X_{i2}}{X_{ij}}\right)^2 + \cdots + m_j \left(\frac{X_{ij}}{X_{ij}}\right)^2 + \cdots + m_n \left(\frac{X_{in}}{X_{ij}}\right)^2 \tag{16}$$

Supposing that $m_1$, $m_2$ and $m_3$ express masses of the second, third floors and the roof where $x_1$, $x_2$ and $x_3$ are displacements of the second, third floors and the roof, respectively. Then equivalent masses of second floor ($j = 1$), third floor ($j = 2$) and roof ($j = 3$) at the first mode are obtained as,

$$M_{11} = 29.08 \text{ kg}, \quad M_{12} = 7.06 \text{ kg}, \quad M_{13} = 4.36 \text{ kg}$$

As seen from the above value, the equivalent mass is lighter at the roof and 6.67 times heavier from the second floor to the roof. This is a one reason why the T.M.D. should be set-up in a roof position.

4.2 Dynamic model of three-story structure and its motion of equation

The dynamic model of a three-story house equipped with the P.T.M.D. as shown in Figure 2 (B) is also shown in Figure 5, where $m_1$, $m_2$ and $m_3$ express masses of the second, third floors and the roof where $x_1$, $x_2$ and $x_3$ are displacements of the second, third floors and the roof, respectively. Also, $k_1$, $k_2$ and $k_3$ and $c_1$, $c_2$ and $c_3$ are the stiffness of each and the internal damping of the columns at the first, second and third
Fig. 5 Dynamical model of three-story structure with P.T.M.D.

The upper and lower side lengths of the pendulum supported by a supported structure are expressed by \( l_1 \) and \( l_2 \), where \( x_f \) and \( \theta \) inform the displacement and rotation angle of the pendulum at a supporting point. Also \( m_s \) and \( c_s \) is the mass and damping constant of the added mass and damper set at the bottom of the pendulum. The supported structure is modeled by a one degree-of-freedom system with mass \( m_f \), damping constant \( c_f \) and stiffness \( k_f \). The spring constant of the connecting spring is expressed as \( k_b \) as one of the key parameters. When P.T.M.D. is set up in the first floor of the three-story houses, the equation of motion is led as follows.

\[
M\ddot{x} + C\dot{x} + Kx = f
\]  

(17)

Where mass matrix, damping matrix, stiffness matrix, displacement vector and force vector are as follows:

\[
M = \begin{bmatrix}
m_1 & 0 & 0 & 0 & 0 \\
0 & m_2 & 0 & 0 & 0 \\
0 & 0 & m_3 & 0 & 0 \\
0 & 0 & 0 & m_f + m_d & m_d l_2^2 \\
0 & 0 & 0 & m_d l_2^2 & m_d l_2^2
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
c_1 + c_2 & -c_2 & 0 & 0 & 0 \\
-c_2 & c_2 + c_3 & -c_3 & 0 & 0 \\
0 & -c_3 & c_3 & 0 & 0 \\
0 & 0 & 0 & c_f + c_d & c_d l_2^2 \\
0 & 0 & 0 & c_d l_2^2 & c_d l_2^2
\end{bmatrix}
\]

\[
K = \begin{bmatrix}
k_1 + k_2 + k_b & -k_2 & 0 & -k_b & k_b l_1 \\
-k_2 & k_2 + k_3 & -k_3 & 0 & 0 \\
0 & -k_3 & k_3 & 0 & 0 \\
-k_b & 0 & 0 & k_b + k_f & -k_3 l_1 \\
k_b l_1 & 0 & 0 & -k_3 l_1 & m_2 g l_2 + k_b l_1^2
\end{bmatrix}
\]

\[
x = \begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_f \\
\theta
\end{bmatrix}^T, 
\]

\[
f = \begin{bmatrix}
c_1 \dot{u} + k_b u \\
0 \\
(c_f + c_d) \dot{u} + k_f u \\
c_d l_2 \dot{u}
\end{bmatrix}^T
\]

stories, respectively.
5. Simulation

5.1 Frequency response of one-storied structure

According to the equivalent mass estimation method, the equivalent mass of second floor is 29.08 kg at the first mode with 4.04 Hz. Therefore, the mass and stiffness of the one-storied structure shown in Fig.3 are determined as follows,

\[ M = 29.08 \text{ kg,} \quad K = 18.74 \text{ kN/m}. \]

If the mass and stiffness of the supported structure are selected as,

\[ m_f = 0.165 \text{ kg,} \quad k_f = 4300 \text{ N/m}, \]

and also the upper and lower side lengths of the pendulum are selected in,

\[ l_1 = 0.03 \text{ m,} \quad l_2 = 0.15 \text{ m}, \]

the optimum mass ratio \( \mu_{opt} \) and the optimum damping ratio \( \zeta_{opt} \) are determined through Eq. (8) to Eq.(14) as follows:

\[ \mu_{opt} = 0.0049, \quad \zeta_{opt} = 0.0012. \]

Finally, the optimum values of the added mass and damper of the pendulum is designed as the below values using dimensional factors

\[ m_d = 0.142 \text{ kg,} \quad c_d = 1.82 \text{ Ns/m}. \]

Figure 6 shows three kinds of simulated frequency responses depended on damping values of optimum, zero and infinite damping. It is found that two fixed points of two amplitude curves indicated by red line and blue line take the same amplitude ratio in order to satisfy the optimum tuning condition. In addition, an amplitude curve indicated by black line takes two maximum amplitude ratios in the neighborhood of the two fixed points to satisfy the optimum damping condition. It means that the optimal design for P.T.M.D. against one storied structure is available using Eq. (1) to (14) when the spring constant of the connecting spring takes an infinite value.

Next problem is to examine the usefulness of above mentioned optimum design procedure for optimum design of P.T.M.D. against the three-storied structure with the connecting spring.

\[ m_f = 0.165 \text{ kg,} \quad k_f = 4300 \text{ N/m}, \]

5.2 Frequency response of three-storied structure

Using the motion of equation of three-story structure shown in Eq. (17), frequency responses are simulated with and without the P.T.M.D., while an exciting point is the base and measuring point is the top of the three-story structure. Then optimal parameters indicated in the section 5.1 are used to optimal ones of the P.T.M.D. for the three-story structure. It has been found as shown in Fig.7 that the P.T.M.D. can do well in the suppression of the first resonance peak as compared without P.T.M.D.. Even though the optimum design parameters for one storied structure are used for controlling three-storied structure, the result is very well in the suppression of the first resonance peak. It seems that
the semi-optimum design is useful for designing the P.T.M.D. equipped in the three-storied structure. An even larger reduction is possible if the lever ratio is increased.

![Graph of frequency responses](image1.png)

**Fig. 7** Simulated frequency responses of three-storied structure with and without P.T.M.D.

![Graph of adjusted frequency responses](image2.png)

**Fig. 8** Effect of connected spring

Figure 8 illustrates the adjustability of the P.T.M.D. by changing the value of the connecting spring, when the stiffness of the column is reduced to 20% from a pre-design stage. Although the frequency response of the pre-design stage indicated by dotted line is shifted to low frequency and got out of shape by reducing the column as shown in red line, the frequency response adjusted by the connecting spring $k_b$ is recovered again to the optimum design condition as shown in black line.

### 5.3 Impulse response of three-storied structure

Figure 9 shows compared impulse responses with and without P.T.M.D. corresponded to Fig.7, where the damping coefficient of the column between each floor is given to 0.5 Ns/m taking into consideration of measured data of an experimental model. It is evident that the P.T.M.D. has good damping effect at the first vibration mode.

A very interesting advantage of the P.T.M.D. has been indicated in impulse responses. Figures 10 shows compared impulse responses observed at the third story, when T.M.D. is mounted at roof and P.T.M.D. at 1st floor. In fairness to both, the same weight of added mass is used in the T.M.D. and P.T.M.D.. The T.M.D. has been adjusted using its optimum design procedure. Since the T.M.D. acts after the motion of the third stories, a vibration suppression effect at the initial step does not appear immediately. In contrast, because the P.T.M.D. acts immediately at the initial step, the vibration is quickly suppressed as shown in figure 10. This feature is very important for the suppression of random vibrations such as seismic waves or sizeable tremors caused by traffic vibrations.
6. Experiment

6.1 Experimental setup

The experimental model of the three-story house has been constructed to have the same dimension as mentioned in Sections 4.1 and 5.1. The vibration mode shapes and corresponded natural frequencies are also the same as Fig.4. How to realize the weight and damper prepared to the bottom of the pendulum is very important to construct the P.T.M.D. A magnetic damper \(^9\) consisted of a pair of high performance permanent magnets and a copper plate is used as both the weight and the damper. The magnetic damper is very easy to adjust the damping coefficient by changing a gap between these magnets. As the advantages, the damper is able to set without any friction and very stable under the temperature changing. The detailed photograph is shown in Fig.11.

![Magnetic damper](image)

Fig.11 Magnetic damper used as both a weight and damper plate

6.2 Experimental results

To confirm the vibration-control effect of the rooftop floor with the adjusted P.T.M.D. at
the first vibration mode shown by the simulation, the corresponded effect measured at the rooftop floor of the experimental apparatus is shown in Fig.12. The P.T.M.D. used in experiment has the same dimensions as used in the simulation. Black line demonstrates the case of optimal adjustment of the P.T.M.D., because the maximum values of the frequency response are located near two fixed points, and the best attenuation can be attempted. The measured frequency response is agreed with the simulation shown in Fig.7. Since a measured impulse response is also agreed with the simulation shown in Fig.8, it is omitted in this paper.

In order to demonstrate experimentally a usefulness of the P.T.M.D. described in the simulation, two measured time responses are shown in Fig.13 and Fig.14. Figure 13
represents a time response measured at the roof under the random excitation at the base. Since the P.T.M.D. acts immediately at the initial step, the vibration is quickly suppressed as shown in black line of Fig.13. It is found that the measured acceleration amplitude with P.T.M.D. is reduced less than 1/3 compared without one. Figure 14 is very important for the suppression of seismic waves. The seismic wave used in the experiment is analogous to that of the 1995 Kobe moving in the east-west direction. This earthquake wave is normalized so that a dominant frequency is brought close to the first natural frequency of the structure. This figure shows that the P.T.M.D. has a favorable effort on the three-storied structure.

7. Conclusions

The P.T.M.D., which acts on principles of lever-mechanisms, has been proposed and investigated as a possible adaptation to vibration control devices for three-story houses. The following results were obtained.

(1) The optimum design for P.T.M.D. against one-story houses is useful for designing three-story houses with the P.T.M.D.

(2) The P.T.M.D. is adjustable and recoverable by changing the value of the connecting spring, even if the optimum design condition is got complicated.

(3) The magnetic damper consisted of a pair of high performance permanent magnets and a copper plate is very useful to adjust the damping coefficient by changing a gap between these magnets.

(4) Since the P.T.M.D. acts immediately at the initial step, the vibration is quickly suppressed. This feature is very important for the suppression of random vibrations such as seismic waves or sizeable tremors caused by traffic vibrations.

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