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Study on parameters of hybrid passive control system for building structures

Wu Zongliang[1], Han Aihong[1,2]

Abstract. This paper applies both tuned mass damper (TMD) and rubber bearing base isolation in architectural structure simultaneously to constitute the hybrid passive control system. Features and interplay of the two passive control units are considered and good equivalent damping ratio can be obtained by reasonably selecting damping ratio and mass scale of the rubber bearing base isolation system and the TMD system. Consequently, the displacement of isolating layer can be reduced and collision brought by great displacement of such layer can be overcome. Analysis of examples shows: displacement of isolating layer can be reduced either by increasing isolation layer damp or applying TMD system; satisfactory overall damping effects of the hybrid passive control system can be obtained when the added mass of TMD control system is 1% of the original structural mass.

Key words. Hybrid passive control system, tuned mass damper, rubber bearing base isolation.

1. Introduction

Structural passive control is an energy-free control system consisting of mainly three modes: base isolation, vibration absorption and energy dissipation, which reduce structural vibration by reducing, isolating, transferring and dissipating energy. China put forward with the concept of base isolation in the 1950s and some researches on structural control were conducted in the middle 1980s. Passive control is widely favored in the engineering sector since it can be easily realized in engineering practice, together with its simple design and good control effects. However, it's worth noting that to medium- and short-cycle structure under the influence of short-cycle ground motion, base isolation brings good damping effects and acts sensitively to the input characteristics of ground motion but cannot eliminate risk of sympathetic vibration; for base isolation, increase of damping ratio of the isolation layer may reduce structural relative displacement and deformation, but lead to increase of

[1]North China University of Water Resources and Electric Power, Henan, Zhengzhou, 450011, P. R. China

[2]Corresponding Author, e-mail: 4367954@qq.com

absolute speed and acceleration of the structure and consequently result in adverse influence to internal equipments and workers; in the contrast, decrease of damping ratio will lead to great displacement of isolation layer and collisions or even oversized deformation and then reduced capacity of the rubber bearing. Zhang Yan-nian et al. [1, 2] proposed, for application of mere sliding base isolation and rubber bearing base isolation, the hybrid control method by combining the foresaid with magnetic resonance damper (MRD) to reduce dynamic response effects of the structure. However, as a semi-active control unit, MRD requires external energy control and will play no use if no external energy is available in disaster emergencies. In the contrast, TMD has low cost and can hardly change the overall dynamic characteristics of the structure and requires no external energy, it is capable to transfer risks of base isolation resonance through rational design and obtains nice equivalent damp and consequently reduce dynamic response of the structure. Nevertheless, TMD has big volume and mass and thus can be easily restrained by the original structure et al. [3–5]. To solve these problems, this paper proposes the hybrid passive control integrating rubber bearing base isolation and TMD for structural control, trying to get nice control effects by coordinating the horizontal stiffness and damp of rubber bearing, as well as the mass, stiffness and damp of TMD.

2. Set up structural kinetic equation of the hybrid control system

2.1. The rubber bearing base isolation system

The rubber bearing base isolation system refers to the isolation system installed between the superstructure and base in order to isolate the same for the purpose to prolong the natural vibration period of the whole structural system, increase damp and reduce delivery of horizontal ground motion to the superstructure and finally realize the target of reducing superstructure vibration.

For base isolation structure, the interlayer stiffness of superstructure is far greater than the horizontal stiffness of isolation system (such as brick-concrete structure, shear wall structure, frame-shear structure or frame structure) and thus seismic action can lead to small horizontal displacement of superstructure, and horizontal displacement of the whole structural system will concentrate at the base isolation unit. Therefore, it can be summarized that superstructure has only horizontal overall displacement under seismic action, and the structure can be simplified to a single-point dynamic analysis model of isolation structure, and the stiffness and damp of isolation unit can be roughly represented by stiffness and damp of the isolation structural system.

2.2. The MD passive control system

The tuned vibration damping control system is made up of the structure and attached sub-structures with mass, stiffness and damp. Natural vibration frequency of substructures can be adjusted to get close to fundamental frequency or excitation frequency of the main structure. In this way, when the main structure vibrates due to excitation, substructures will generate inertia force in the opposite direction on the main structure so that to make vibration response of the main structure attenuate and be controlled. Since this system requires no traditional reinforcement measures (such as increase cross section, add reinforcing bars, strengthen stiffness and add members, etc), shows significant damping effects and can be easily realized, it attracts wide and increasing attention from academic circle and engineering circle as a brand new anti-seismic measure and has been widely applied in domestic and overseas projects. As an effective tool for passive damp, TMD is featured with simple structure, easy constructible ability and low cost and has widely used in the vibration damp and disaster prevention of high-rises and big-span bridges.

TMD system is a classic dynamic vibration absorber whose first application was in a Frahm anti-swing water tank installed on a German liner in 1909. It generally consists of mass blocks added to the structural top, together with spring and dampers for connection, to control some vibration modes of the structure according to the resonance principle. Its principle of work: when the TMD vibration frequency tuning to achieve a certain relation with the main structure of the frequency or the excitation frequency, the main structure subjected to dynamic action and vibration, added mass block also generates a relative inertial motion; the TMD system will dissipate some energy of the disturbing force input structure and the vibration response of the main structure will reduce through the spring, damper applied to reverse direction to the main structure. Therefore, the control force of TMD depends on the relative motion between its structure and main structure, is generated with the structure vibration. Actually, the TMD system can be said to be using resonance principle, control on the reaction of some vibration structure et al. [3–5].

2.3. The hybrid passive control system

For base isolation structure, the interlayer stiffness of superstructure is far greater than the horizontal stiffness of isolation system (such as brick-concrete structure, shear wall structure, frame-shear structure or frame structure). Thus, it can be summarized that superstructure has only horizontal overall displacement under seismic action, and the structure can be simplified to a single-point dynamic analysis model of isolation structure, and the stiffness and damp of isolation unit can be roughly represented by stiffness and damp of the isolation structural system. Thus, the calculation model of hybrid passive control system can be obtained, as shown in Figure 1.

Defining m, k, c as the quality of the upper structure, the stiffness of isolation layer and damping respectively; m_d, k_d, c_d as the mass, stiffness and damping of the TMD control system. Introducing the following notation $\omega^2 = k/m$, $c = 2\xi\omega m$, $\omega_d^2 = k_d/m_d$, $c_d = 2\xi_d\omega_d m_d$, where ω, ξ denote the base isolation structure frequency and the damping ratio respectively, ω_d, ξ_d denote the circular frequency and the damping ratio of the TMD control system.

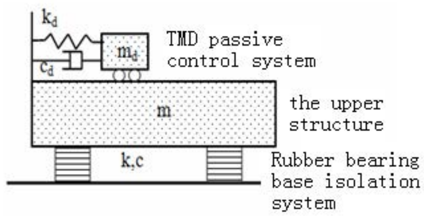


Fig. 1. The analysis model of hybrid passive control system

3. Dynamic analysis of hybrid control system

3.1. Dynamic analysis of hybrid control system under periodic excitation [6]

Defining $\bar{m}$ as mass scale and $\bar{m} = m_d/m$. When the period excitation $p = P\sin\theta t$ acts on the superstructure, the structural kinetic equilibrium equation of hybrid control system can be set up as follows according to the Lagrange mechanics principle:

Structural kinetic equation of the base isolation structure:

$$(1+\bar{m})\ddot{x} + 2\xi\omega\dot{x} + \omega^2 x = \frac{p}{m} - \bar{m}\ddot{x}_d\,. \tag{1}$$

Structural kinetic equation of the TMD system:

$$\ddot{x}_d + 2\xi_d\omega_d\dot{x}_d + \omega_d^2 x_d = -\ddot{x}\,. \tag{2}$$

Thus response of the system is:

$$x = X\sin(\theta t + \delta_1)\,, \tag{3}$$

$$x_d = X_d\sin(\theta t + \delta_1 + \delta_2)\,. \tag{4}$$

X, δ_1 are displacement response amplitude and phase angle of the superstructure, respectively

$X_d, \delta_1+\delta_2$ are displacement response amplitude and phase angle of TMD system, respectively

The purpose to add TMD system is to reduce response of base isolation system under the $k_d = \bar{m}k$.frequency of TMD system is $\omega_d = \omega$ and thus the optimal stiffness of the same is action of external excitation p. It is known from Reference [4] that the quasi-optimal Substitute formula (3) and formula (4) into basic equation (1) and (2) of the hybrid passive control system and the corresponding displacement amplitude can be obtained:

$$X = \frac{P}{k\bar{m}}\sqrt{\frac{1}{1+\left(\dfrac{2\xi}{\bar{m}} + \dfrac{1}{2\xi_d}\right)^2}} = \frac{P}{k}\left(\frac{1}{2\xi_e}\right)\,, \tag{5}$$

$$X_d = \frac{1}{2\xi_d} X \,, \tag{6}$$

Where: $\xi_e = \frac{\bar{m}}{2}\sqrt{1 + \left(\frac{2\xi}{\bar{m}} + \frac{1}{2\xi_d}\right)^2}$.

It can be seen from formula (5) that a big equivalent damping ratio ξ_e must be obtained if to reduce the displacement amplitude of superstructure. ξ_e is associated with $\bar{m}$, ξ and ξ_d and when $\bar{m}$ is fixed, ξ_e increases along the increase of ξ and decrease of ξ_d. However, when ξ and ξ_d are fixed, along with increase of $\bar{m}$, ξ_e doesn't always increase but increase first and the decrease. Thus, nice equivalent damping ratio can be obtained by adjusting damping ratio and mass scale of the base isolation system of rubber bearing base and the TMD system and finally reduce the interlayer displacement of the base isolation structure.

3.2. Dynamic analysis of hybrid control system under seismic action

1In the earthquake, structural dynamic equilibrium equation is established for hybrid control systems by Lagrange for mechanical principle:

$$\begin{bmatrix} m & 0 \\ 0 & m_d \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{x}_d \end{Bmatrix} + \begin{bmatrix} c + c_d & -c_d \\ -c_d & c_d \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{x}_d \end{Bmatrix} + \begin{bmatrix} k + k_d & -k_d \\ -k_d & k_d \end{bmatrix} \begin{Bmatrix} x \\ x_d \end{Bmatrix} = \\ = - \begin{bmatrix} m & 0 \\ 0 & m_d \end{bmatrix} \begin{Bmatrix} \ddot{x}_g \\ \ddot{x}_g \end{Bmatrix} \,. \tag{7}$$

Introducing the following notation: $x(1) = \begin{Bmatrix} x \\ x_d \end{Bmatrix}$, $x(2) = \begin{Bmatrix} \dot{x} \\ \dot{x}_d \end{Bmatrix}$, then the equation can be transformed into:

$$\dot{x} = \begin{bmatrix} \dot{x}(1) \\ \dot{x}(2) \end{bmatrix} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}\mathbf{C} \end{bmatrix} \begin{bmatrix} x(1) \\ x(2) \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} \ddot{x}_g \,. \tag{8}$$

The response is given by:

$$\begin{cases} \dot{x} = Ax + \mathbf{B}\ddot{x}_g \,, \\ y = Cx + D\ddot{x}_g \,, \end{cases} \tag{9}$$

where: $A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}\mathbf{C} \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} 0 \\ I \end{bmatrix}$, $\mathbf{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\mathbf{D} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$, $I = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$.

For the Equation (9), through the establishment of Simulink model in Matlab software, we get the mixed system analysis, research on the influence of different parameters.

(2) The simulation block diagram of Simulink model, as shown in Figure 2.

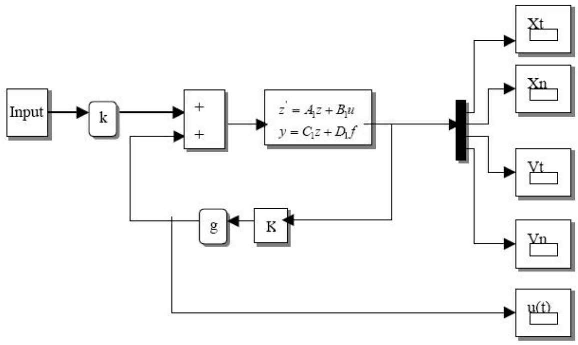


Fig. 2. The diagram of simulation analysis

4. Analysis of examples

Example: design TMD system as the quasi-optimal frequency under excitation of El-Centro wave, to analyze the displacement and acceleration of the rubber bearing base isolation structure and the hybrid control structure under different mass scales and damping ratios. See Table 1 for structural characteristics under different working conditions.

Table 1. The structural characteristics under different working conditions

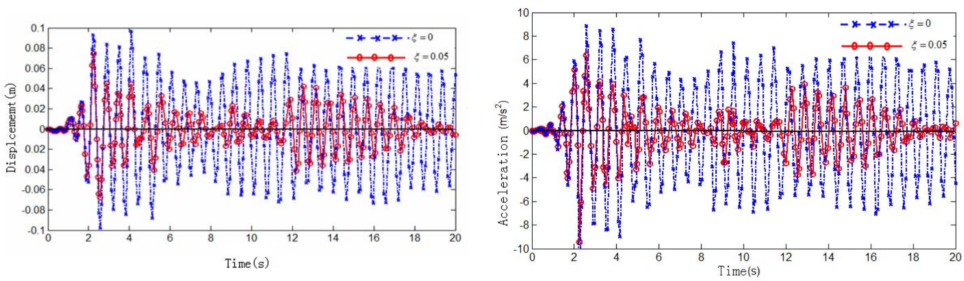
working condition	m (kg)	k (N/m)	ξ	m_d (kg)	$\bar{m}$	k_d (N/m)	ξ_d
1	3000	300000	0	30	0.01	3000	0.05
2	3000	300000	0	60	0.02	6000	0.05
3	3000	300000	0	150	0.05	15000	0.05
4	3000	300000	0.05	30	0.01	3000	0.1
5	3000	300000	0.05	60	0.02	6000	0.1
6	3000	300000	0.05	150	0.05	15000	0.1

4.1. The simulation results:

4.2. The result analysis:

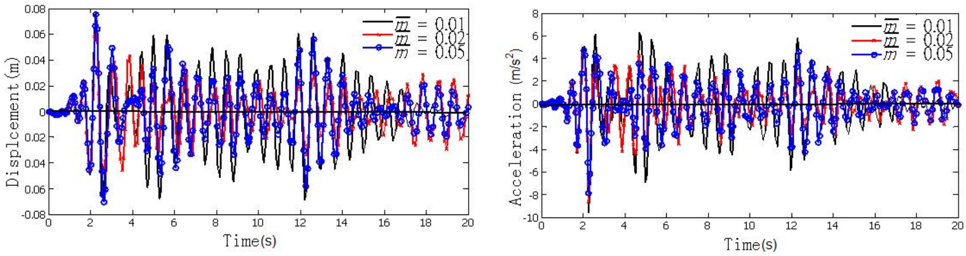
(1) It can be seen from Fig. 3 that for base isolation structure without TMD control system, when $\xi = 0$, the displacement of isolation layer is generally within $[-0.08\,\mathrm{m}, 0.08\,\mathrm{m}]$ while the acceleration of superstructure within $[-8\,\mathrm{m/s^2}, 8\,\mathrm{m/s^2}]$; when $\xi = 0.05$, displacement of most isolation layer is within $[-0.05\,\mathrm{m}, 0.05\,\mathrm{m}]$ while the acceleration of superstructure within $[-5\,\mathrm{m/s^2}, 5\mathrm{m/s^2}]$ except when several peak points are close to that when $\xi = 0$.

(2) It can be seen from Fig. 4 that if $\xi = 0$ and $\xi_d = 0.05$, the displacement of isolation layer is generally within $[-0.06\,\mathrm{m}, 0.06\,\mathrm{m}]$ while the acceleration of super-



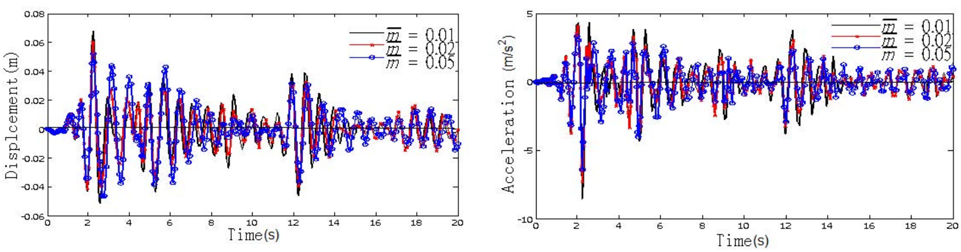
(a) (b)

Fig. 3. The isolation layer displacement (a) and acceleration of superstructure (b) under different damping ratio without the TMD control system



(a) (b)

Fig. 4. The isolation layer displacement (a) and acceleration of superstructure (b) of the hybrid passive control system in the working conditions 1-3



(a) (b)

Fig. 5. The isolation layer displacement (a) and acceleration of superstructure (b) of the hybrid passive control system in the working conditions 4-6

structure within $[-5\,\mathrm{m/s^2},\ 5\,\mathrm{m/s^2}]$ when $\bar{m} = 0.01$; when $\bar{m} = 0.05$, displacement of most isolation layers drops apparently, with the displacement of isolation layer generally within $[-0.04\,\mathrm{m},\ 0.04\,\mathrm{m}]$ while the acceleration of superstructure within $[-4\,\mathrm{m/s^2}, 4\,\mathrm{m/s^2}]$ except several peak points are close to that when $\bar{m} = 0.01$; when $\bar{m} = 0.01$, the control effect may reach that when $\bar{m} = 0.05$ and the displacement of the isolation layer and acceleration of the superstructure changes gently.

(3) It can be seen from Fig. 5 that when $\xi = 0.05$ and $\xi_d = 0.1$, size of $\bar{m}$ has little influence to displacement of the isolation layer and acceleration of the superstructure and the two drops apparently when compared to those in absence of TMD system

control. That is, the displacement of isolation layer is generally within [−0.04 m, 0.04 m] while the acceleration of superstructure within [$-3\,\mathrm{m/s^2}$, $3\,\mathrm{m/s^2}$].

(4) Comparison between Fig. 4 and Fig. 5 shows that when $\bar{m}$ is fixed, displacement of the isolation layers and acceleration of superstructure can be reduced by increasing damping ratio of both the insulation layer and the TMD control system.

5. Conclusion

(1) For base isolation structure, increasing damping ratio of the isolation layer can apparently reduce displacement of the isolation layer and acceleration of the superstructure.

(2) When $\xi = 0$ and $\xi_d = 0.05$, the increase of $\bar{m}$ may reduce the displacement of isolation layer and acceleration of the superstructure in certain degree. However, big $\bar{m}$ indicates big added mass of the TMD system, which makes construction inconvenient and shows relatively great influence to the original structural characteristics and no good control effect can be obtained under random excitation; thus it is recommended to define $\bar{m} = 0.01$, that is, define the added mass of TMD control system to be 1% of the original structure mass.

(3) When $\xi = 0.05$ and $\xi_d = 0.1$, the size of $\bar{m}$ has little influence to the displacement of the isolation layer and acceleration of superstructure. But in any case, such displacement and acceleration are apparently lower than those without TMD system control. Therefore, small $\bar{m}$ can be adopted when the isolation layer has certain damp and the TMD has relatively great damp.

In a word, by rationally selecting damp of the isolation layer and characteristic parameters of TMD control system, the hybrid passive control system can significantly reduce displacement of the isolation layer and acceleration of the superstructure and satisfactory damping effects can be obtained.

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