Harmonic Response of Adjacent Structures Connected by Viscous Damper

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Abstract—**The response behavior of two adjacent single degree-of-freedom (SDOF) structures connected at their floor level by viscous damper under base excitation is studied. The equations of motion of coupled structures are derived and solved for harmonic excitation. The response parameters considered are relative displacement and absolute acceleration. It is observed that by increasing the damping coefficient of damper the peak responses are decreases and after certain value it again increases. There is some optimum value of damping coefficient of damper for which peak response is minimum. A parametric study is also carried out to investigate the effect of system parameters on optimum damping coefficient of damper and corresponding responses. The system parameters considered are mass ratio and frequency ratio. It is found that viscous damper is quite effective for harmonic response control of adjacent coupled structures. It has been observed that the frequency ratio has significant effect on the response control of the coupled structures, where as the effect of mass ratio is marginal.**

Key words: Adjacent structures, Harmonic response, Optimum damping, Viscous damper.

I. INTRODUCTION

Structural responses to base excitation can be mitigated by implementing energy dissipation devices. The subject of structural control deal with modifying the response of structures to undesirable excitation. Damper connected to the structural frame dissipates the seismic input energy, thereby reducing the kinetic energy and vibration of the building. The external excitations add the additional energy to the structure, whereas the control devices dissipate some of the energy by either transforming it in to the heat or transferring it directly to any connected structure. The control strategies are able to modify dynamically the response of the structure in a desirable manner, thereby termed protective system for the new structures and existing structures can be retrofitted or strengthened effectively to withstand future seismic activity. In last decade, significant effort has been given for design of engineering structures with various control strategies to increase their safety and reliability against strong earthquakes. According to the energy consumptions, control system can be classified as active, passive, semi-active and hybrid control system.

Active control system may be defined as a system, which provide additional energy to the controlled structure and opposite to that delivered by the dynamic loading. The control forces are supplied to the structure by means of electro-hydraulic or electro-mechanical actuators, which require a large power source for their operation. Control forces are developed based on the feedback from sensors that measure the excitation and/or the response of the structure. The feedback from the structural response may be measured at locations remote from the location of the active control system. As a result, active control mechanisms are more complex mechanism, requiring sensors and evaluator/controller equipments. Cost and maintenance of such system is also significantly higher than that of passive devices The various active control mechanisms are active mass/tuned mass dampers, active tendon system, and active tuned liquid damper.

Passive control system may be defined as a system, which does not require an external power source for operation and utilizes the response of the structure to develop the control forces. Control forces are developed at the location of the passive control system, as a function of the response of the structure. The various passive vibration control mechanisms are viscous dampers, visco-elastic dampers, friction dampers, tuned mass dampers, tuned liquid dampers, metallic yielding dampers, and base isolators. More complete details on the mechanics and working principles of these devices can be found in reference [1].

Semi-active control system may be defined as a system which is combination of passive and active control mechanism. Semi-active control system require a small external power source for operation (e.g. a battery) and utilize the motion of the structure to develop the control force, the magnitude of which can be adjusted by external power source. The advantage is that in case of power failure the passive component of the control will still offer some protection. Control forces are developed based on feedback from sensors that measure the excitation and/or the response of the structure. The feedback from the structural response may be measured at locations remote from the location of the semi-active control system. The various semi-active mechanisms are variable orifice dampers, variable friction dampers, variable stiffness dampers, controllable tuned liquid dampers, controllable fluid dampers (Electorheological (ER) and Megnetorheological (MR)) dampers.

Hybrid control system consists of combination of passive and active devices or combined passive and semi-active devices. Because multiple control devices are operating, hybrid control system can alleviate some of the restriction and limitations that exist when each system is acting alone. Thus, higher level of performance may be achievable. An additional benefit of hybrid system is that, in the case of power failure, the passive components of the control still offer some of protection. The various hybrid mechanisms are hybrid mass dampers and hybrid base isolation.

The control system and the structure do not behave as independent dynamic systems but rather interact with each other. In addition, interaction effects also occur between the excitation and structure (i.e. soil-structure interaction) and between the sensors and structures.

Because of limited availability of land and preference for centralized services, buildings in a modern city are often built closely to each other. Some tall buildings are often built with podium structures to achieve a large open space for parking shops, restaurants, and hotel lobbies at the ground level. If the separation between adjacent structures is not sufficient, or if they are not separated with proper structural connections mutual pounding may also occur during an earthquake, which has been observed during Loma Prieta earthquake [2] and many more past earthquake events.

The concept of linking adjacent structures using passive dampers, active dampers and semi-active dampers has thus been proposed to improve their dynamic performance. Using special energy dissipation devices of appropriate capacity and at proper position, the energy dissipation capacity of the adjacent structures can be increased. The concept is allow two dynamically dissimilar structure to exert control force upon one another. It improves the performance of the system by reducing overall response of the system. Moreover, it also overcomes the problem of pounding, which is more sever load condition than the case of the vibration without pounding. The dynamic behaviors of two SDOF structures connected with a friction damper under harmonic ground acceleration have been investigated [3]. The seismic response of dynamically similar adjacent building connected with viscous dampers has been investigated [4]. A full-scale 5-story building specimens with passive dampers has been tested using E-Defense, the test results shows that the passive dampers are effective to keep building deformation even small even against the strong ground motion recorded during the 1995 Kobe earthquake[5]. Now a day, passive control scheme are typically used in Japan for major buildings, and even for many small residential buildings, in order to better protect the building and its contents [6].

In this paper the behavior of adjacent structures connected with viscous damper under harmonic excitation is studied, and the effectiveness of the viscous damper for harmonic response reduction of adjacent structure is investigated.

II. MODELING OF CONNECTED STRUCTURES

Let us consider two adjacent structures connected with a viscous damper as shown n Fig.1. The adjacent structures are idealized as SDOF systems and referred as Structure1 and 2. The two structures are assumed to be symmetric with their symmetric planes in alignment. The ground motion is assumed to occur in one direction in the symmetric planes of the structures so that the problem can be simplified as a two-dimensional problem as shown in Fig.1. Both the structures are assumed to be supported on stiff ground and subjected to the same ground acceleration. The viscous damper is modeled as linear dash pot, in which the force is proportional to the relative velocity of its both ends. The corresponding mathematical model of the damper connected structure is shown in Fig. 2. Let m_1, c_1, k_1 and m_2, c_2, k_2 be the mass, damping coefficient and stiffness of the Structure 1 and 2, respectively. The natural frequency of the structure is given by $\omega_1 = \sqrt{k_1/m_1}$ and $\omega_2 = \sqrt{k_2/m_2}$ for Structure 1 and 2, respectively. The damping ratio of Structure 1 and 2, is given by $\xi_1 = c_1/2m_1\omega_1$ and $\xi_2 = c_2/2m_2\omega_2$, respectively. Let β and μ be the frequency and mass ratio of two structures defined as

$$\mu = \frac{m_1}{m_2} \tag{1}$$

$$\beta = \frac{\omega_1}{\omega_2} \tag{2}$$

Let c_d be the damping coefficient of the damper, which is expressed in the mathematical form as

$$\xi_d = \frac{c_d}{2m_1\omega_1} \tag{3}$$

where ξ_d is the normalized damping coefficient of damper. The governing equations of motion for the damper connected system can be written as

$$m_1 x_1 + c_1 x_1 + k_1 x_1 + c_d (x_1 - x_2) = -m_1 x_g \tag{4}$$

$$m_2 x_2 + c_2 x_2 + k_2 x_2 - c_d (x_1 - x_2) = -m_2 x_g \tag{5}$$

respectively; and x_g is the ground acceleration.

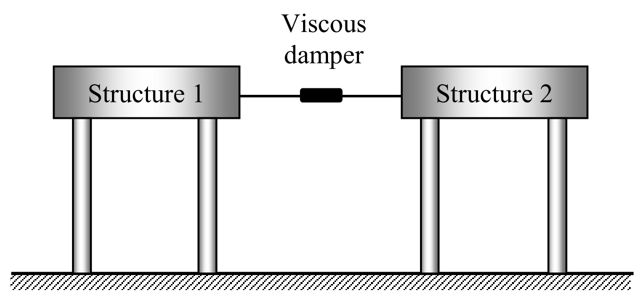

Fig. 1 Adjacent Structures with viscous damper

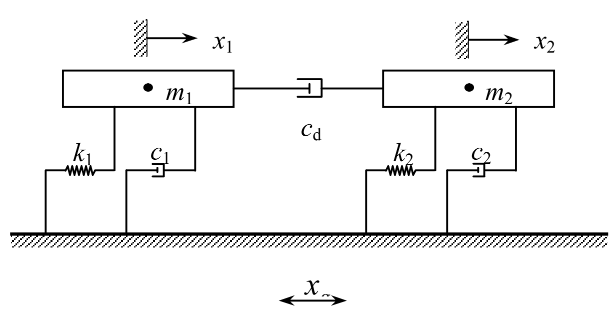

Fig. 2 Mathematical model

where x_1 and x_2 are the displacement responses, relative to the ground of Structures 1 and 2, respectively; and x_g is the ground acceleration.

III. RESPONSE TO HARMONIC BASE ACCELERATION

The analytical expressions for displacement and acceleration responses of the damper connected system to the harmonic base excitation are derived. The structural control criteria depend on the nature of dynamic loads and the response quantities of interest. Minimizing the relative displacement or absolute acceleration of the system has always been considered as the control objective. In case of flexible structures, displacement are predominant that need to be controlled. On contrary to this, in case of stiff structures, accelerations are of more concern generating higher inertia forces in structures, which should be mitigated. In view of this, the study aims to arrive the distinct expressions for optimum parameters of damper for minimizing exclusively displacement as well as acceleration responses. Let us consider the coupled system subjected to harmonic base acceleration given by

$$x_g = a_0 e^{i\omega t} \tag{6}$$

where a_0 and ω are the amplitude and excitation frequency, respectively of the harmonic ground motion. Thus, from Eqs. (4) and (5) the steady-state responses x_1 and x_2 are obtained as

$$x_1 = \frac{N_1}{D} a_0 e^{i\omega t} \text{ and } x_2 = \frac{N_2}{D} a_0 e^{i\omega t} \tag{7a,b}$$

where

$$N_1 = \omega^2 - \omega_2^2 - i\omega(\Delta_d + \Delta_2) \tag{8a}$$

$$N_2 = \omega^2 - \omega_2^2 - i\omega(\Delta_d + \Delta_1) \tag{8b}$$

$$\begin{aligned} D = {} & \omega^4 + (i\omega)^3(\Delta_1 + \Delta_2 + \Delta_d) \\ & + (i\omega)^2(\omega_1^2 + \omega_2^2 + \Delta_1\Delta_2 + \Delta_1\Delta_{d2} + \Delta_2\Delta_{d1}) \\ & + (i\omega)(\omega_1^2\Delta_2 + \omega_1^2\Delta_1 + \omega_1^2\Delta_{d2} + \omega_2^2\Delta_{d2}) + \omega_1^2\omega_2^2 \end{aligned} \tag{8c}$$

with

$$\begin{aligned} & \Delta_1 = c_1/m_1; \Delta_2 = c_2/m_2; \Delta_{d1} = c_d/m_1; \\ & \Delta_{d2} == c_d/m_2; \Delta_d = \Delta_{d1} + \Delta_{d2} \end{aligned} \tag{8d}$$

The absolute acceleration (x_{a1} and x_{a2}) can be calculated by differentiating Equation (7) twice and adding it to the ground acceleration as given below

$$x_{a1} = \frac{N_{a1}}{D} a_0 e^{i\omega t} \text{ and } x_{a2} = \frac{N_{a2}}{D} a_0 e^{i\omega t} \tag{9}$$

$$\begin{aligned} N_{a1} = {} & (i\omega)^3(\Delta_1) \\ & + (i\omega)^2(\omega_1^2 + \Delta_1\Delta_2 + \Delta_1\Delta_{d2} + \Delta_2\Delta_{d1}) \\ & + (i\omega)(\omega_1^2\Delta_2 + \omega_1^2\Delta_1 + \omega_1^2\Delta_{d2} + \omega_2^2\Delta_{d2}) + \omega_1^2\omega_2^2 \end{aligned} \tag{10a}$$

$$\begin{aligned} N_{a2} = {} & (i\omega)^3(\Delta_2) \\ & + (i\omega)^2(\omega_2^2 + \Delta_1\Delta_2 + \Delta_1\Delta_{d2} + \Delta_2\Delta_{d1}) \\ & + (i\omega)(\omega_1^2\Delta_2 + \omega_1^2\Delta_1 + \omega_1^2\Delta_{d2} + \omega_2^2\Delta_{d2}) + \omega_1^2\omega_2^2 \end{aligned} \tag{10b}$$

IV. NUMERICAL STUDY

Consider the two SDOF connected structures with their mass ratio $\mu = 1$ and frequency ratio $\beta = 2$. Thus, the Structure 1 is said to be soft structure and Structure 2 is said to be stiff structure. The variation of displacement amplitude response and absolute acceleration amplitude response against excitation frequency for five values of the damper damping coefficient (i.e. $\xi_d = 0, 0.1, 0.25, 0.5, 1$) are shown in Fig. 3 for undamped and damped connected structures with damping

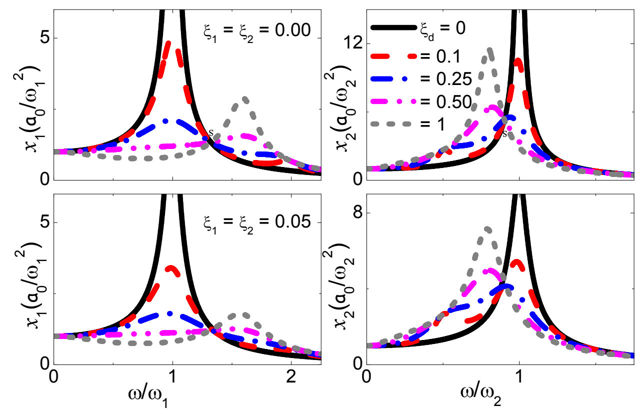

Fig. 3 Variation of displacement against excitation frequency for different damper damping coefficient ($\mu = 1$ $\beta = 2$)

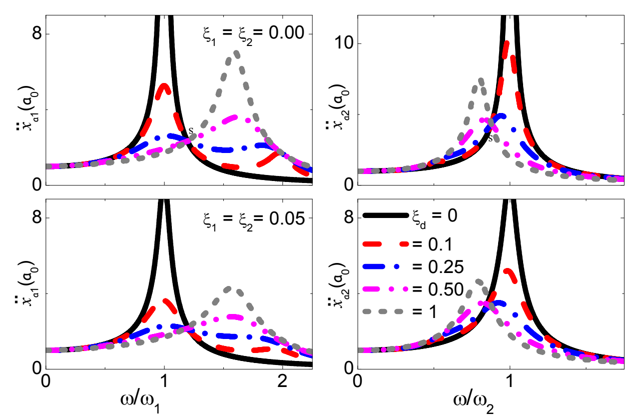

Fig. 4 Variation of acceleration against excitation frequency for different damper damping coefficient ($\mu = 1$ $\beta = 2$)

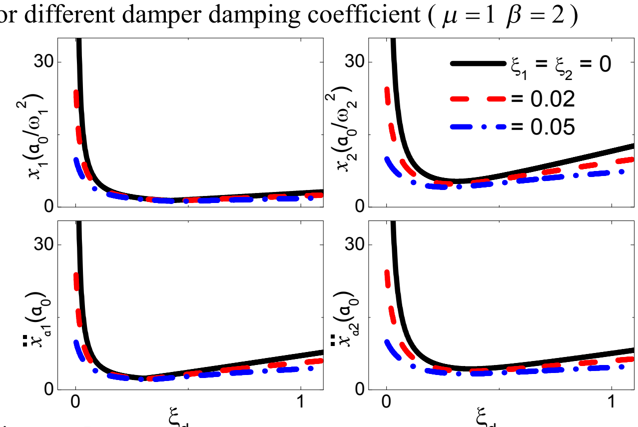

Fig. 5 Variation of peak responses against damping coefficient of damper ($\mu = 1$ $\beta = 2$)

ratio $\xi_1 = \xi_2 = 0.05$. From Fig. 3, it is observed that the peak displacement of both structures is reduced up to certain value of the damper damping coefficient after which they are increased. This is because, the higher damper damping coefficient reduces the relative velocity of the damper and hence the energy absorbing capacity from damping force decreases.

When the damper damping coefficient is too high, the relative and displacement of the two structures become nearly zero so that the two structures behave as though they are almost rigidly connected. Significant reduction can be achieved in response of both structures when they are connected with viscous damper of optimum damping implying that the viscous damper are quite effective in enhancing the harmonic performance of connected structures. Similar effects of damper damping on absolute accelerations of connected structures are depicted in Fig. 4, which shows the variation of absolute acceleration, represented in terms of a_0, against excitation frequency.

The variation of peak displacement and the peak acceleration responses of two structures against the damping coefficient of damper (mass ratio $\mu = 1$ and frequency ratio $\beta = 2$) are shown in Fig. 5 for different damping ratios

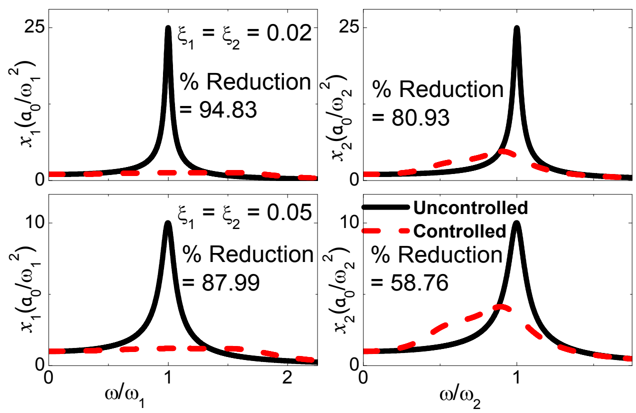

Fig. 6 Displacement response without and with viscous damper of optimum damping coefficient ($\mu = 1$ $\beta = 2$)

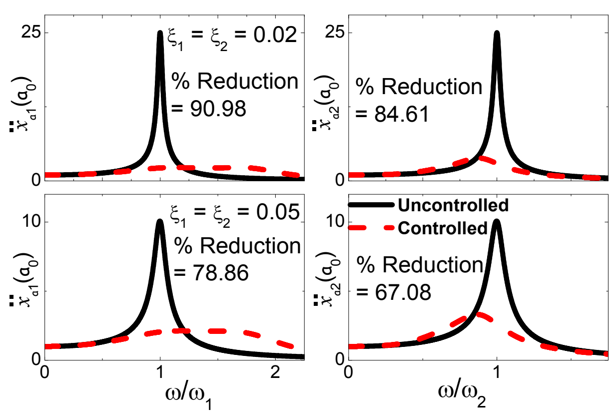

Fig. 7 Acceleration response without and with viscous damper of optimum damping coefficient ($\mu = 1$ $\beta = 2$)

in connected structures (i.e. $\xi_1 = \xi_2 = 0, 0.02,$ and 0.05). It is clear from graphs that there exists an optimum value for the damper damping coefficient to yield minimum responses. Figures 6 and 7 show the response without and with viscous damper of corresponding optimum damping for two damping ratios ($\xi_1 = \xi_2 = 0.02$ and 0.05) in the connected structures.

These figures show how effective the viscous damper are in mitigating the displacement and acceleration responses, respectively of connected system. It is clear from graphs that significant reduction can be achieved in responses of both structures when they are connected with viscous damper of optimum damping. For present example considered here (i.e. mass ratio $\mu = 1$ and frequency ratio $\beta = 2$), the reduction are ranging from 59% to as much as up to 95%. This concludes that the viscous dampers are quite effective in enhancing the harmonic performance of connected structures.

V. EFFECT OF SYSTEM PARAMETERS

The variation of optimum damping coefficient of damper and corresponding displacement response against the frequency ratio β for different value of mass ratio (i.e. $\mu = 1, 1.5, 2$) are shown in Fig. 8.

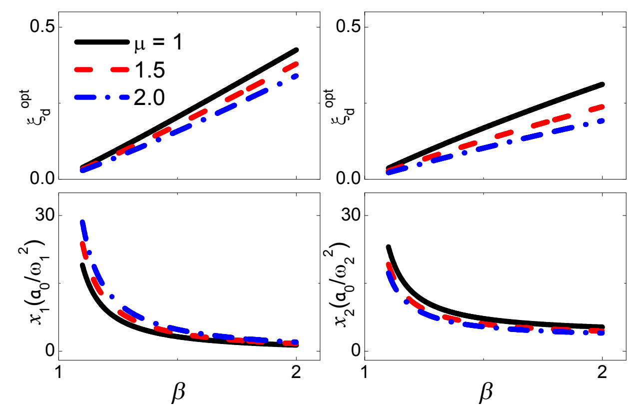

Fig. 8 Effect of frequency ratio and mass ratio on the optimum damping of damper and on corresponding displacement response

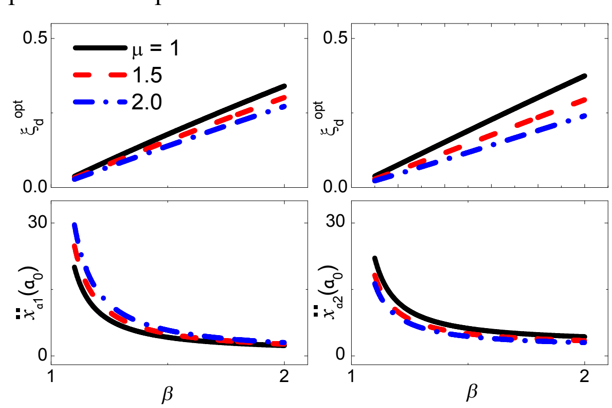

Fig. 9 Effect of frequency ratio and mass ratio on the optimum damping of damper and on corresponding acceleration response

It is observe that increase in frequency ratio increases the optimum damping coefficient of damper, where as it decreases the optimum responses. An increase in mass ratio decreases the optimum damping coefficient of damper for both structures. An increase in mass ratio increases the optimum displacement response of the flexible structure, where as it decreases the optimum displacement

The variation of optimum damping coefficient and corresponding acceleration response against the frequency ratio β for different value of mass ratio (i.e. $\mu = 1, 1.5, 2$) are shown in Fig. 9.

It is observed that increase in frequency ratio increases the optimum damping of damper and decreases the corresponding acceleration responses. An increase in mass ratio decreases the optimum damping of damper. An increase in mass ratio increases the optimum response of the flexible structure where as it decreases the optimum acceleration response of stiff structure.

VI. CONCLUSIONS

The dynamic response of two adjacent SDOF structures connected with viscous damper subjected to harmonic excitation is investigated. The effect of system parameters such as frequency ratio and mass ratio on the optimum damping of damper and corresponding displacement and acceleration response is investigated. From the trends of the results of present study, the following conclusions are drawn.

1 The viscous damper is found quite effective for harmonic response control of adjacent SDOF coupled structures.
2 For a given structural system connected with viscous damper, there exists an optimum damper damping for which the displacement and absolute acceleration of connected structures attains the minimum value.
3 The optimum damping of the viscous damper increases with the increase in the frequency ratio and decrease with the increase in the mass ratio. The corresponding responses at optimum damper damping decreases with the increase in the frequency ratio.
4 The effect of mass ratio on optimum displacement and acceleration responses is marginal.

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