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A Numerical Study on Semi-Active Control of a Bridge Deck under Seismic Excitation

A. Yanik, U. Aldemir

Abstract**—**This study investigates the benefits of implementing the semi-active devices in relation to passive viscous damping in the context of seismically isolated bridge structures. Since the intrinsically nonlinear nature of semi-active devices prevents the direct evaluation of Laplace transforms, frequency response functions are compiled from the computed time history response to sinusoidal and pulse-like seismic excitation. A simple semi-active control policy is used in regard to passive linear viscous damping and an optimal non-causal semi-active control strategy. The control strategy requires optimization. Euler-Lagrange equations are solved numerically during this procedure. The optimal closed-loop performance is evaluated for an idealized controllable dash-pot. A simplified single-degree-of-freedom model of an isolated bridge is used as numerical example. Two bridge cases are investigated. These cases are; bridge deck without the isolation bearing and bridge deck with the isolation bearing. To compare the performances of the passive and semi-active control cases, frequency dependent acceleration, velocity and displacement response transmissibility ratios $T_a(\omega)$, $T_v(\omega)$, and $T_d(\omega)$ are defined. To fully investigate the behavior of the structure subjected to the sinusoidal and pulse type excitations, different damping levels are considered. Numerical results showed that, under the effect of external excitation, bridge deck with semi-active control showed better structural performance than the passive bridge deck case.

Keywords**—**Bridge structures, passive control, seismic, semi-active control, viscous damping.

I. Introduction

Civil engineering structures including the bridges have traditionally been built as passive structures with no adaptability to uncertain dynamic loads. Indeed, ‘solidity’ and ‘massiveness’ have been considered as a measure of the ‘safety’ and ‘reliability’ and the bridges have been designed based on the strength theory. This approach can sometimes be untenable both economically and technologically. It is known that the structures dissipate the seismic energy through their inherent damping or inelastic deformation. The revised new design criteria for bridges have placed heavier emphasis on controlling the behavior of bridge structural response to seismic forces. For many years, significant contributions have been made by the structural engineering community to search for innovative ways to control how seismic input energy is absorbed by the structure and controlling its response to seismic forces. These efforts have resulted in development of new alternative approaches such as supplemental damping, passive, semi-active and active control techniques to design new bridges or to strengthen existing ones against earthquakes, severe winds and traffic loading. As this study is about semi-active control and passive viscous damping, the definitions of these systems are given in the next two paragraphs with bullets for important points.

Passive systems include base isolation systems, tuned mass dampers and other mechanical energy dissipaters such as bracing systems, viscoelastic dampers, viscous fluid dampers and metallic dampers. It is known that the isolators have limited effect for bridges on relatively soft soils. In addition to isolation damping, energy dissipating devices can also be used to reduce the excessive deformation of isolators and improve the seismic performance of the bridges. Base isolation systems incorporating viscous, friction or hysteretic damping have been studied and applied widely in practice. The successful application of abutment base isolators and the energy dissipating devices in bridge structures have offered great promise. However, the effectiveness of these passive systems may still be limited since they are required to operate over a wide band load and frequency range and the fundamental frequency of the isolated bridge cannot vary to respond favorably to different types of earthquakes with different characteristics.

Semi-active control: if the mechanical properties of abutment isolators can be adjusted actively based on the measured bridge responses, this kind of controlled bearing will then be known as semi-active control system. Semi-active control systems are a class of control systems in which the control actions are applied by changing the mechanical properties (i.e., stiffness and damping) of the control device.

- The external energy requirements of the semi-active control devices are orders of magnitude smaller than typical active control systems. In fact, many of them can be operated on battery power, which is most suitable during seismic events.
- They do not destabilize the bridge structural system since no mechanical energy is injected into the system.
- Semi-active control devices can only absorb or store vibration energy in the structure by reacting to its motion.
- They seem to combine the best futures of passive and active systems.
- Magneto-rheological dampers (MR damper), electro-rheological dampers (ER damper), controllable friction devices, and controllable viscoelastic dampers are some examples for semi-active dampers. Recent analytical and

A. Yanik was with Oregon State University, Corvallis, OR 97331, USA. He is now with the Civil Engineering Department, Istanbul Technical University as an Asst. Prof. Dr., Maslak, Istanbul 34469 Turkey (phone: +90 212-285-3708; +90 212-285 6587, e-mail: yanikar@itu.edu.tr).

U. Aldemir (Prof. Dr.) is the Dean of Istanbul Technical University, Civil Engineering Faculty, Maslak, Istanbul 34469 Turkey (phone: +90 212-285-3855; fax: +90 212-285-3855; e-mail: aldemiru@ itu.edu.tr).

experimental studies of MR damper have shown that they can be used effectively for seismic response control. ER dampers, which are essentially electric analogs of MR dampers, have recently been modeled and tested for vibration control of civil engineering structures.

Some recent studies and some research that has been conducted during the last two decades on semi-active control subject are given in the next paragraph. Most of the literature given in the next paragraph considers the effect of seismic excitations.

A new tunable FPS (TFPS) isolator was proposed and developed to act as a semi-active control system by combining the traditional FPS and semi-active control concept in [1]. In their study, a series of numerical simulations of a base-isolated structure equipped with the proposed TFPS isolator and subjected to earthquake ground motions were also conducted. A semi-active control technique is presented to mitigate the seismic vertical response of suspension bridges using Magneto-Rheological (MR) dampers [2]. Benefits of implementing the semi-active control systems in relation to passive viscous damping in the context of seismically isolated structures were investigated in [3]. Frequency response functions are compiled from the computed time history response to pulse-like seismic excitation in their study. Three semiactive control policies, i.e. pseudonegative-stiffness control, continuous pseudoskyhook-damping control, and bang-bang pseudoskyhook-damping control, in terms of their effectiveness in addressing the deficiencies of passive isolation damping were compared in [4]. The optimal performance of semi-active tuned mass dampers (magneto-rheological dampers) was studied in [5]. A 3-degree of freedom (3-DOF) per floor tier building analytical model, which can incorporate models of either traditional tuned mass dampers (TMD) or MR mass dampers (MR-MD) was investigated in [6]. In addition, dynamic behaviour of the 3-DOF building incorporating magneto-rheological dampers has been numerically investigated under a real earthquake excitation in their study. Full-scale applications of active or semi-active devices for wind and earthquake-induced motion control were reviewed whether large and severe earthquake levels were targeted as control objectives in [7]. A wavelet neural network-based semi-active control model was proposed in order to provide accurately computed input voltage to the magneto rheological dampers to generate the optimum control force of structures [8]. Their model was optimized by a localized genetic algorithm and then applied to a nine-story benchmark structure subjected to 1.5x El Centro earthquake. A semi-active control strategy, in which H infinity control algorithm was used and magneto-rheological dampers were employed for an actuator, was presented to suppress the nonlinear vibration in [9]. A fuzzy-rule-based semi-active control of building frames using semi-active variable orifice dampers (VODs) is presented. Additionally, the consequences of well-known characteristics of near-fault ground motions, forward directivity and fling step, on the seismic response control was investigated in [10]. A study that focused on the vibration control of long-span reticulated steel structures under multidimensional earthquake excitation was presented in [11]. The control system and strategy were constructed based on Magneto-Rheological (MR) dampers in their study. A study that focuses on the development of a semi-active control algorithm based on several performance levels anticipated from an isolated building during different levels of ground shaking corresponding to various earthquake hazard levels was given in [12]. The seismic response of a bridge with three-span continuous girder is numerically studied, and the semi-active control is successfully realized in ABAQUS in [13]. They mentioned that the proposed method can be used to carry out the refined simulation of the seismic response of the structures with semi-active control set. A quadratic output regulator that minimizes the total structural acceleration energy was developed and tested on a realistic non-linear, semi-active structural control case study in [14]. They used suites of large scaled earthquakes to quantify statistically the impact of this type of control in terms of changes in the statistical distribution of controlled structural response. The safety performances of various types of hybrid control systems for nonlinear buildings against near-field earthquakes were presented in [15]. The hybrid control systems in their study considered consist of mainly the base isolation system and either the passive control devices or the semi-active dampers or the combination thereof.

In this study, the dynamic behavior of a bridge deck system with isolation bearing and semi-active damper is investigated. The dynamic analysis is performed under the effect of pulse, harmonic and seismic type of excitations. The bridge deck is idealized by a single degree of freedom (SDOF) dynamic model. Two control cases are considered for comparison purposes. These cases are passive damping control and semi-active control. For semi-active control case, two semi-active control policies are used. These policies are continuous (pseudo-skyhook) control and bang-bang control. Different damping levels are analyzed to fully understand the behavior of the bridge deck system. The control performance of the bridge deck system with semi-active damper and continuous control policy outperformed the performance of the system with passive damping control. However, it is also observed that bang-bang control was not very effective in reducing the responses of the bridge deck system.

II. Formulation of the Passive Controlled Bridge Deck

A. Uncontrolled (Conventional) Bridge-Deck

This section of the paper is inspired by Ref. [16]. A single degree of freedom (SDOF) bridge deck model is shown in Fig. 1 [16]. Fig. 1 represents the conventional bridge deck dynamic model without any control element. The dynamic model in Fig. 1 can be presented by stiffness k_0 and damping c_0 elements.

Dynamic equation of the motion of the structure (SDOF bridge deck in Fig. 1) subjected to seismic excitation can be written as

$$m_0\ddot{x} + c_0\dot{x} + k_0 x = -m_0\ddot{x}_g \tag{1}$$

where m_0, c_0, and k_0 are the mass, damping, and stiffness of the bridge deck respectively. In (1), $\ddot{x}$, $\dot{x}$, and x represent the acceleration, velocity, and displacement of the bridge deck in a respective way. For the bridge deck without bearing the circular frequency ω_n and natural period of motion T_n can be expressed as

$$\omega_n = \sqrt{\frac{k_0}{m_0}} \quad , \quad T_n = 2\pi\sqrt{\frac{m_0}{k_0}} \tag{2}$$

The critical damping c_c and the damping c_0 of the bridge deck can be presented as

$$c_c = 2\sqrt{m_0 k_0} \quad , \quad c_0 = 0.05\ c_c \tag{3}$$

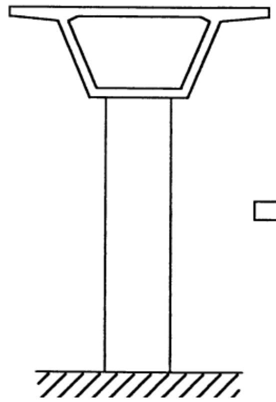

Fig. 1 SDOF Bridge deck dynamic model (figure taken from [16])

B. Passive Control Case: Bridge Deck with Seismic Isolator

If we implement a seismic isolator (isolation bearing) to the bridge deck presented in Fig. 1. The system can be idealized as given in Fig. 2 [16]. c_i and k_i denote the damping and stiffness of the isolation bearing. However, mass of the isolation bearing can be neglected. If we compare the masses of the system and the isolation bearing this assumption is very reasonable.

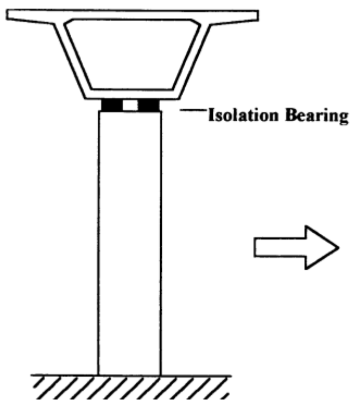

Fig. 2 Bridge deck with isolation bearing dynamic model [16]

The circular frequency ω_{ni} and natural period of motion T_{ni} of the bridge deck with isolation bearing can be expressed as

$$\omega_{ni} = \sqrt{\frac{K}{m_0}} \quad , \quad T_{ni} = 2\pi\sqrt{\frac{m_0}{K}} \tag{4}$$

Hence, the critical damping c_{ci} can be written as

$$c_{ci} = 2\sqrt{m_0 K} \tag{5}$$

In (4) and (5), K is the combined stiffness of the system and can be calculated as [16]

$$K = \frac{k_0 k_i}{k_0 + k_i} \tag{6}$$

The combined stiffness of the system can also be presented as

$$K = 4\pi^2 m_0 / T_{ni}^2 \tag{7}$$

By defining the equation a=K the stiffness of the isolation bearing k_i can be defined as

$$k_i = (a k_0)/(k_0 - a) \tag{8}$$

Dynamic equation of the motion of the bridge deck with isolation bearing Fig. 2, subjected to seismic excitation can be written as

$$m_0\ddot{x} + (c_0 + c_i)\dot{x} + Kx = -m_0\ddot{x}_g \tag{9}$$

III. Formulation of the Semi-Active Controlled Bridge Deck

If we implement a semi active damper to the bridge deck with isolation bearing that is shown in Fig. 2, the dynamic model of the system consisting of bridge deck, isolation bearing, and semi-active damper can be obtained as shown in Fig. 3. The dynamic equation of the motion of the system with semi-active damper can be simply written as [6]. (10) is very similar to (1) and (9); however, there is the semi-active damper force $f_{\dot{x}}$ in the left-hand side of the equation. Semi-active damper force is dependent to the velocity, therefore subscript of $\dot{x}$ is added to *f*.

$$m_0\ddot{x} + (c_0 + c_i)\dot{x} + Kx + f_{\dot{x}} = -m_0\ddot{x}_g \tag{10}$$

In this study, two semi-active control cases are considered for comparing with the passive viscous damping case. As two cases, in the first one we used bang-bang control policy defined in [17] and in the second one we implemented continuous control that was explained in [18].

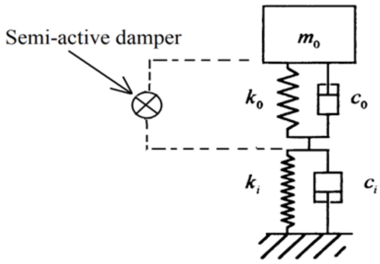

Fig. 3 Dynamic model of the bridge deck with isolation bearing and semi-active damper

A. Bang-Bang Control

For the bang-bang control case, the resulting semi-active damper control force can be written as

$$f_{\dot{x}} = c_d \; v \; \dot{r} \tag{11}$$

Here, the semi-active control force f is changed optimally via the semi active control decision variable or valve variable v. In (10), c_d describes the behavior when the semi-active control decision variable v is 0 and $\dot{r}$ is the relative base velocity of the system. The delayed control decision for the bang-bang control $\dot{v}$ is given by [19]

$$\dot{v} = \left(-1/T_v\right)\left[v - H\left(r\left|\dot{r} + \dot{x}_g\right|\right)\right] \tag{12}$$

where T_v is the response time of the controllable damper, H is the Heaviside step function of the control decision v and r is the base displacement of the system. Because of the Heaviside step function in (12), analytical expressions for the frequency response function cannot be obtained. Frequency response functions for semi-actively controlled structures can however be constructed by numerically integrating the system equations until a harmonic steady state is reached and plotting the ratio of a response amplitude to the excitation amplitude as a function of frequency ratio. Therefore, the relations that will be defined in (14) will be used for performance evaluation of the control methods.

B. Continuous (Pseudo-Skyhook) Control

The control force of the semi-active damper implemented in the isolation level can be expressed as [20] more information about this control policy can be found in [19]-[21]

$$f_{\dot{x}} = c_d(\dot{r} + \dot{x}_g)H\left[\dot{r}(\dot{r} + \dot{x}_g)\right] \tag{13}$$

IV. Numerical Results

In this study, a simplified single-degree-of-freedom model of an isolated bridge is used. This model is presented in Figs. 2 and 3 [16]. The mass of the bridge deck m_0 is 1065.7 tons, pier stiffness k_0 is 189×10^6 N/m, structural damping coefficient c_0 is 1.42×10^6 N/m/s. Without the isolation bearing, circular frequency of the bridge deck is ω_n=13.32 rad/s, natural vibration period of the bridge deck is T_n=0.47 s and c_0 corresponds to %5 of critical damping, c_c=2.84×10^7 N/m/sec. With the isolation bearing, circular frequency is ω_{ni}=2.51 rad/s and natural vibration period of the bridge becomes T_{ni}=2.5 s. The critical damping for this system is c_{ci}=5.4×10^6 N/m/s.

To compare the performances of the passive damping, bang-bang, and continuous (pseudo-skyhook) control, frequency dependent acceleration, velocity, and displacement response transmissibility ratios $T_a(\omega)$, $T_v(\omega)$, and $T_d(\omega)$ are defined in (14). For each control case, the dynamic analysis is performed for pulse, harmonic, and El Centro 1940 NS (north south) excitation. We generated harmonic excitation using Kanai-Tajimi spectrum that was used in [22] and [23]. More information about this spectrum can be obtained in [22] and [23]. The results and comparison for each control case defined in this paragraph are given in *A*, *B*, and *C* parts of this section.

$$T_a(\omega) = \frac{\max\left|\ddot{x} + \ddot{x}_g\right|}{\max\left|\ddot{x}_g\right|} \quad , \quad T_v(\omega) = \frac{\max\left|\dot{x} + \dot{x}_g\right|}{\max\left|\dot{x}_g\right|}$$
$$T_d(\omega) = \frac{\max\left|x + x_g\right|}{\max\left|x_g\right|} \tag{14}$$

A. Passive Damping Control

Passive damping control in this study is assumed to be achieved by changing c_i, through bearing. To fully investigate the behavior of the structure subjected to the sinusoidal, pulse type, and seismic excitations under different damping levels, damping ratios for c_1 are defined in (15).

$$\zeta_0 = c_1 / c_{ci} = 0.10, 0.20, 0.30, 0.40 \tag{15}$$

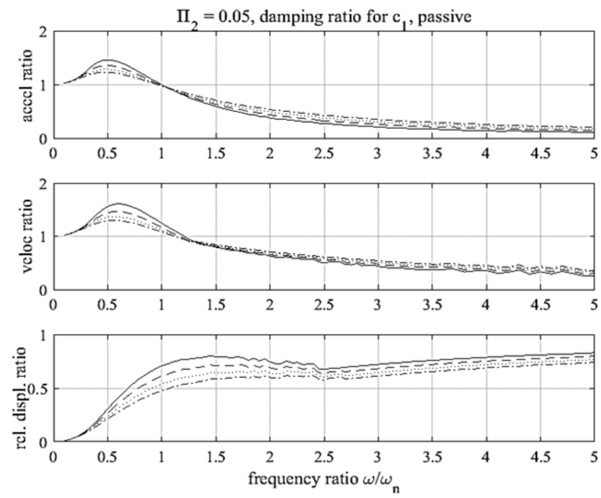

Fig. 4 Transmissibility ratios for passive damping control under pulse excitation

For the bridge deck system with isolation bearing frequency dependent acceleration, velocity, and displacement response transmissibility ratios with respect to frequency ratio ω_n / ω_{ni} are shown in Fig. 4 for pulse excitation and in Fig. 5 for

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harmonic excitation. In Figs. 4 and 5, inside each graphic for acceleration, velocity, and displacement response transmissibility ratios, there are four curves. These curves represent different damping ratios. The solid line represents ζ_0=0.1 whereas the dashed line is ζ_0=0.2, the dotted line denotes ζ_0=0.3, and point dashed line stands for ζ_0=0.4. Π symbol in Fig. 4 is the critical damping ratio and %5.

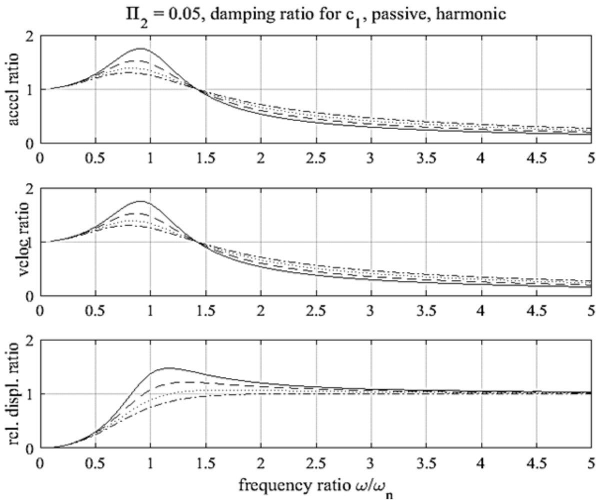

Fig. 5 Transmissibility ratios for passive damping control under harmonic excitation

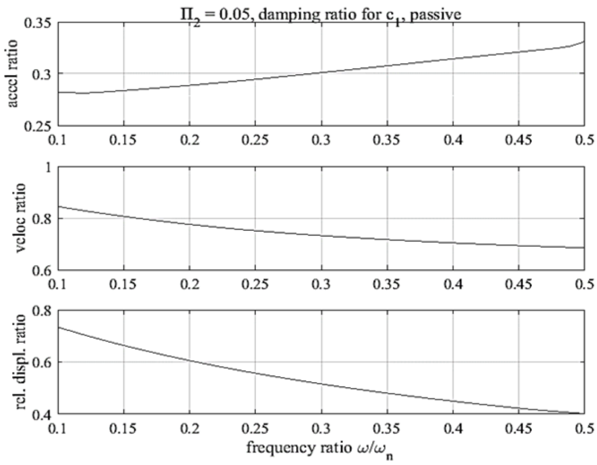

Fig. 6 Transmissibility ratios for passive damping control under El Centro North-South excitation

Earthquake response of the passive damping control is also observed. The dynamic analysis of the bridge deck system with isolation bearing is performed under the effect of El Centro 1940 earthquake NS component. The transmissibility and the frequency ratios ω_n / ω_{ni} for El Centro earthquake are presented in Fig. 6. For El Centro NS component, the transmissibility and the frequency ratios are obtained for a single damping level. The comments and conclusions that are obtained from all the curves presented in this section are given in conclusion section of this paper.

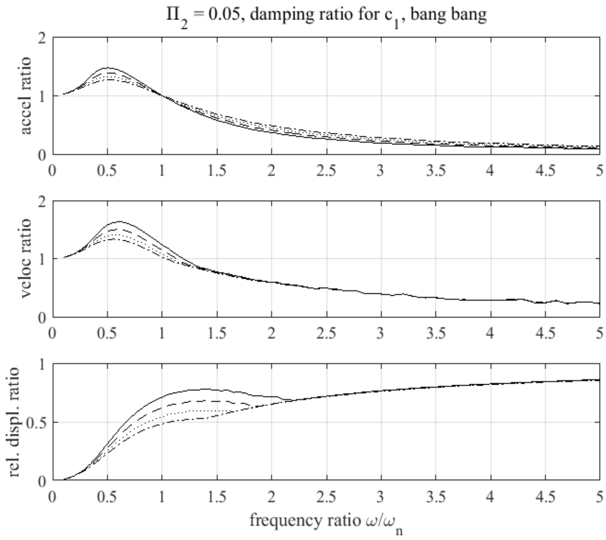

Fig. 7 Transmissibility ratios for bang-bang control under pulse excitation

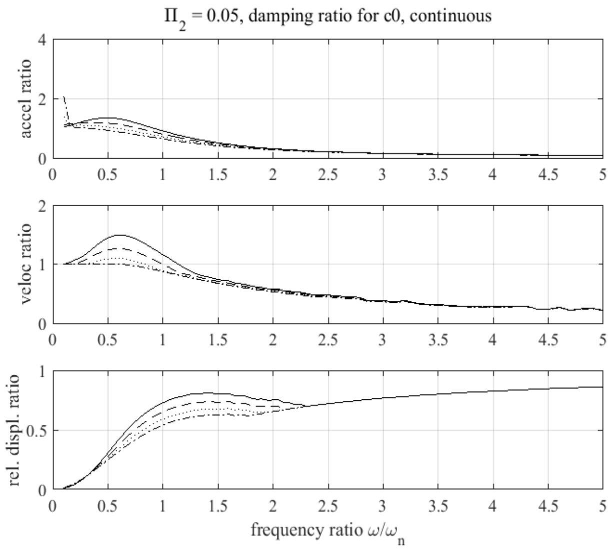

Fig. 8 Transmissibility ratios for continuous control under pulse excitation

B. Semi-Active Control Bang-Bang Type

The control policy of bang-bang control is given with (11) and (12). The same bridge deck system presented in Figs. 2 and 3 is used. Dynamic analysis for the semi-active control cases is performed by using pulse excitation. The transmissibility ratios for pulse excitation for bang-bang control case are shown in Fig. 7.

C. Semi-Active Continuous (Pseudo-Skyhook) Control

The semi-active resulting control equation of continuous control is given with (13). In this semi-active control case, the dynamic analysis is performed under the effect of pulse, harmonic and El Centro NS excitations. The transmissibility ratios for pulse excitation are given in Fig. 8, whereas for harmonic and El Centro NS excitations these ratios are shown in Figs. 9 and 10, respectively.

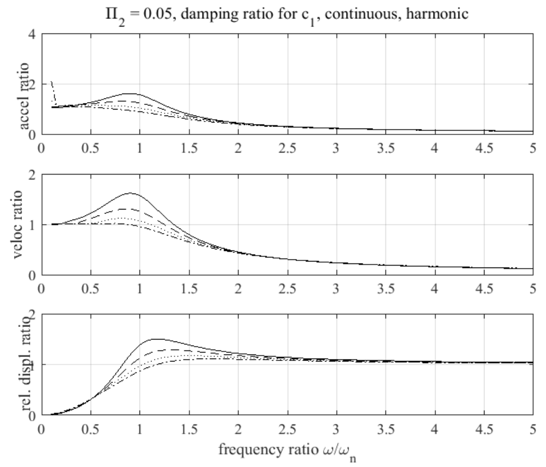

Fig. 9 Transmissibility ratios for continuous control under harmonic excitation

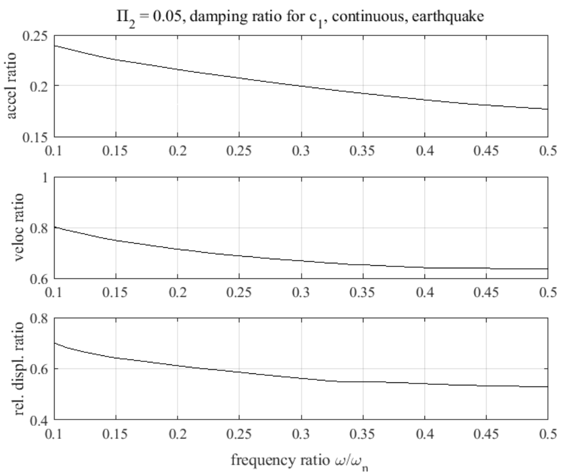

Fig. 10 Transmissibility ratios for continuous control under harmonic excitation

V. CONCLUSION

In this research, it has been observed that in comparison with passive damping control, bang-bang control was not very effective in reducing the bridge deck responses. The comparisons of the transmissibility ratios for the semi-active continuous control with passive damping control cases showed that, for both pulse and harmonic type excitations, continuous control was superior to the passive damping control in reducing the bridge deck responses. In conclusion, by implementing semi-active damper to the structure, better seismic performance than passive damping control can be achieved even by a small battery as power source of the semi-active device.

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