APPLICABILITY OF SEMI-ACTIVE CONTROL FOR SEISMIC PROTECTION OF ELEVATED BRIDGES

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1. Introduction

Passive control devices have been shown to protect bridges under seismic excitation. A typical elevated bridge consists a substructure and a superstructure connected by bearing where passive devices are installed. In this study optimal design of passive control devices are discussed. It is shown that passive control has theoretical limitation in reducing both superstructure and substructure responses simultaneously. Semi-active control using magnetorheological (MR) damper is studied to overcome this difficulty. Numerical simulations show that semi-active control improves passive one considerably and has comparable performance to the fully active system. A method is proposed for the design of MR damper also.

2. Optimal Design Parameters for Passive Control

Bridge deck-bearing-pier system is modeled as a two-degree-of freedom system as shown in Figure 1. m_1, m_2 denote pier and deck masses, respectively. k_1, c_1, ξ_1, ω_1, T_1 are stiffness, damping constant, damping ratio, natural frequency, and natural period of pier, respectively. k_2, c_2, ξ_2, ω_2, T_2 are stiffness, damping constant, damping ratio, natural frequency, and natural period of bearing, respectively. The energy-dissipating device for passive control is assumed to be an elastomeric bearing with linear damping and linear stiffness. Abe and Fujino (1998) showed that mean square response of the system could be obtained by normalizing the solution of the following equation

$$\mathbf{FZ} + \mathbf{ZF}^T = -\mathbf{G}Q\mathbf{G}^T \qquad (1)$$

where

$$\mathbf{Z} = E[\mathbf{zz}^T], \mathbf{z} = \begin{bmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \mathbf{G} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{r} \end{bmatrix}, \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \mathbf{M} = \begin{bmatrix} m_1 & 0 \\ m_2 & m_2 \end{bmatrix}, \mathbf{C} = \begin{bmatrix} c_1 & -c_2 \\ 0 & c_2 \end{bmatrix}, \mathbf{K} = \begin{bmatrix} k_1 & -k_2 \\ 0 & k_2 \end{bmatrix}, r = \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \qquad (2)$$

where x_1 is the displacement of the pier relative to the ground and x_2 is the displacement of the deck relative to the pier. Abe and Fujino, (1998) showed that maximum mean responses estimated by Equation 2 are in good agreement with simulations based on actual earthquake ground motions. ξ_1, T_1 and m_2/m_1 are set to 5 %, 0.5 sec and 5, respectively, which represent typical values for elevated highway bridges. Figure 2 gives the relation between maximum mean responses, ξ_2 and k_2 for m_1 = 1 kg. Observing that increase in k_2 and ξ_2 results increase in the response of pier and deck respectively and considering bearing stiffness requirement of Japanese code in service condition, ω_2/ω_1 is set to 0.2, which results k_2 to be 31.58 N/m (Japan Road Association, 1996). Observing Figure 3, optimum value of ξ_2 is taken as 0.5. The parameters of the final system for analysis are obtained in terms of m_1 and as follows:

$$m_2 = 5m_1,\ k_1 = 157.91m_1,\ k_2 = 31.58m_1,\ c_1 = 1.256m_1,\ c_2 = 12.56m_1 \qquad (3)$$

2. Semi-Active Control

Clipped-optimal control algorithm is reported to be effective for semi-active control using MR damper (Dyke, et. al., 1998). In this study an experimentally verified MR damper model (Spencer, et. al., 1996) is used to supply an optimal control force determined by an LQR algorithm utilizing clipped optimal control algorithm setting m_1 = 10 tons. Since the model proposed uses parameters for simulating the behavior of a prototype version of MR damper, it cannot be used directly for this problem. A design method for MR damper is proposed with the use of clipped optimal algorithm assuming, MR damper behaves optimally if the maximum damper force that can be produced by the damper is same as the maximum optimal control force during an earthquake and maximum damper force occurs when the damper velocity and voltage are maximum. A probabilistic study should be carried out to determine a realistic value for maximum optimal control force and damper velocity. In this paper, however, these values of the TDOF system are obtained for the NS component of El Centro 1940 earthquake. Assuming that newly produced MR damper behavior will be a scaled version of the behavior of the prototype, the original model is modified to give the desired force levels (Figure 4). Figure 5 shows responses of the passive, active and semi-active systems and optimal control force and damper force under NS component of El Centro 1940 earthquake. As can be observed, response of the semi-active system is very similar to the active one. The reason for this is the success of the semi-active system in obtaining the optimal control force.

3. Discussions and Recommendations for Future Study

In this study semi-active control is used utilizing a modified version of MR damper. The original version is scaled to obtain desired maximum force. However a damper, which will be produced to give the desired maximum force, may not have a

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behavior similar to the prototype damper. Moreover, since the stochastic nature of earthquake motions, an optimal value for the maximum optimal control force should be determined after probabilistic studies. Trial simulations gave unrealistic results for the cases

$$max(F_d)^{v=0V} << max(F_c) << max(F_d)^{v=v(max)},\ \ max(F_c) << max(F_d)^{v=0V},\ max(F_d)^{v=v(max)} << max(F_c) \qquad (4)$$

where F_d is damper force and F_c is the optimal control force and v is the current voltage(not presented). Hence the performance of the semi-active control is highly affected by the difference between maximum damper force and maximum optimal control force. To eliminate this problem partially, clipped optimal control algorithm should allow to apply not only v = 0V and v = v(max) but also any values between these values. It should be noted that, a further study on the active control design would yield an increase in semi-active control performance. The performance of passive and active control should be studied for multi-degree-of-freedom model of the bridge also.

4. References

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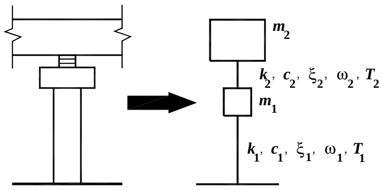

Figure 1. TDOF model of bridge.

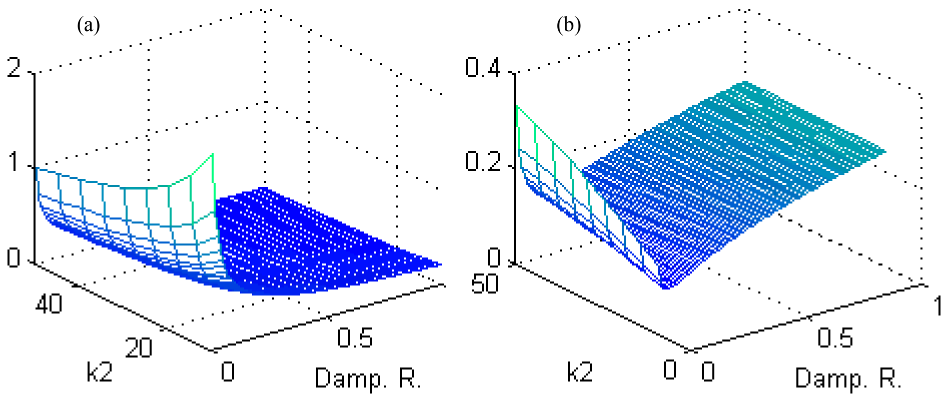

Figure 2. Max. mean response of (a) deck and (b) pier.

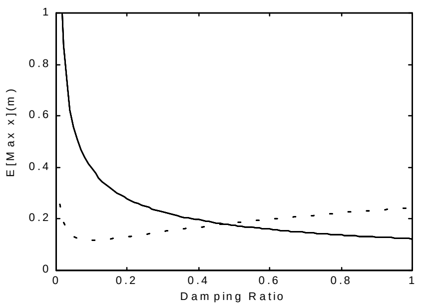

Figure 3. Max. mean response of (__) deck and (…) pier for k_2 = 31.58N/m.

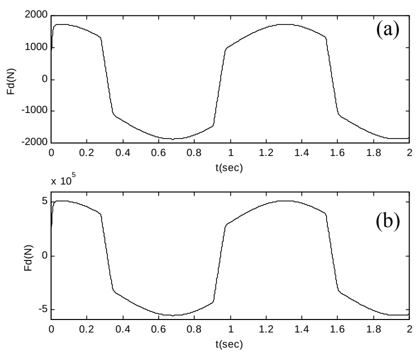

Figure 4. Damper behavior, (a) original (b) modified.

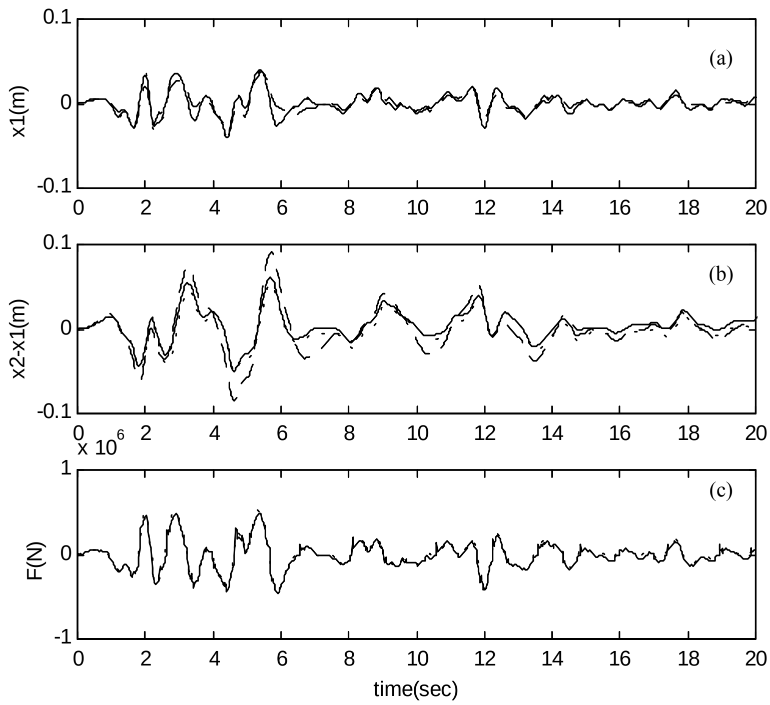

Figure 5. Responses of (a) pier and (b) deck and (c) damper and optimal control forces ((- -) passive, (…) active, (__) semi-active).