Mitigation of Structural Response Due to Near-Field Seismic Ground Motion Using an Optimized Innovative Rotational Inertia Damping Device

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ABSTRACT: This study investigates the use of an innovative light-weight rotational device for the passive protection of structures from the effects of near-field seismic ground motion. A key factor in the effectiveness of these devices is that, through rotation, a relatively small mass can be used to create a device that has a large effective inertial mass. In this work, optimum values of the system are formulated by an exact analytical H2 optimization criteria. The system and optimum values used in this study investigate the response of a structure due to a generalized representation of a near-field seismic ground motion.

INTRODUCTION

Significant investigations have been made into the effectiveness of tuned mass dampers (TMDs) (Figure 1) at protecting structural system subjected to near fault seismic ground motion, with most studies showing that typical TMDs under a short-duration input do not response in time to reduce the peak displacement of the structural system (Sladek and Klingner 1983). While typical TMDs are ineffective at protecting systems from near fault ground motions, large mass ratio TMDs have been shown to be effective under short duration inputs (Matta 2013); however, these systems are not common due to the costs associated with providing this increased TMD mass.

(Ikago, Saito, and Inoue 2012) purposed a new passive control device, shown in Figure 2, which is referred to as a Tuned Viscous mass Damper (TVMD). This device consists of a rotational inertial mass connected to a primary structure with spring and damping elements. The rotational inertial mass converts translational motion into localized rotation of a mass. The effective mass of the TVMD is related to its rotational moment of inertia and the travel distance per rotation of the device; consequently, the TVMD is generally able to provide a rotational inertial mass system with lower dynamic amplification factors while utilizing a smaller physical mass.

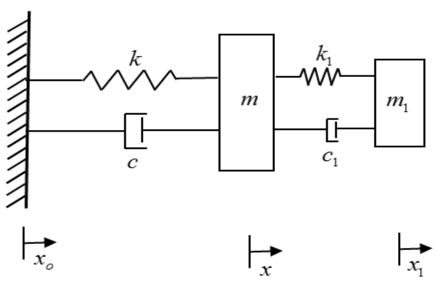

Figure 1. Primary structure with TMD

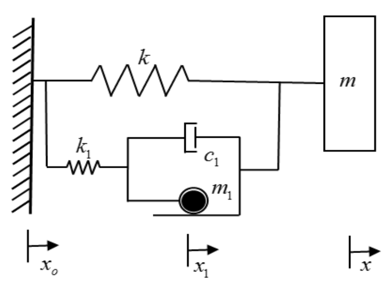

Figure 2. Primary structure with TVMD

The TVMD has been formulated and optimized to minimize the maximum amplification in the frequency domain by (Ikago, Saito, and Inoue 2012) who derived functions for the associated optimal damping and frequency ratio parameters. This optimization of the TVMD was done using the fixed point method, which is an approximate form of H- infinity optimization that has been previously utilized for TMD optimization (Den Hartog 1985). This method optimizes the maximum responses based on two fixed points in the system's frequency domain response curve that are invariant to the damping.

H2 norm, another common optimization criteria, minimizes the square root of the area under the frequency domain response curve (Crandall and Mark 1963). Although the maximum amplitude is generally higher with the H2 criteria compared to the H-infinity criteria, H2 optimization produces a lower response over a broader range of frequencies, which can be more beneficial during random excitations. The H2 criteria has been developed and formulated for different types of traditional and non-traditional TMDs (Cheung and Wong 2011); however, H2 optimization has not been presented for a system utilizing a TVMD.

In this study, a SDOF primary system with an attached TVMD is presented in state space form, then used to obtain the transfer function for the system in the frequency domain. An exact H2 optimization solution for base excitation is formulated and solved. The H2 optimal frequency and damping ratio for the TVMD system are presented and the resulting system response is compared with previously obtained H-infinity optimization results. Additionally, numerical simulations of SDOF structures equipped with H2 and H-infinity optimized TVMDs and a TMD optimized with H2 subjected to near-field seismic ground motion will be compared.

OPTIMIZATION

The equations of motion of the TVMD system are

$$m\ddot{x}+kx+k_1(x-x_1)=-m\ddot{x}_o; \quad m_1\ddot{x}_1+c_1\dot{x}_1-k_1(x-x_1)=0 \tag{1}$$

where:

m = main mass; m_1 = TVMD mass; k = primary structure stiffness; k_1 = tunning stiffness;
c_1 = TVMD damping coeffeicent; x = main mass disp.; x_1 = secondary mass disp.; x_0 = ground motion

The Eq. (1) can be written in the state space form with the displacement of the main mass as the output:

$$\dot{\mathrm{q}}(t)=\mathrm{Aq}(t)+\mathrm{B}u(t); \quad y(t)=\mathrm{Cq}(t)+Du(t) \tag{2}$$

Using the system stiffness, mass, and damping matrices, the states and state space matrices are

$$\mathrm{q}=[\mathrm{x}\ \dot{\mathrm{x}}];\ \ \mathrm{x}=[x \quad x_1];\ \ \mathrm{A}=\begin{bmatrix} I & 0 \\ -M^{-1}K & -M^{-1}\tilde{C}\end{bmatrix};\ \ \mathrm{B}=\begin{bmatrix}0 & 0 & -1 & 0\end{bmatrix}^T;\ \ C=[1 \quad 0 \quad 0 \quad 0];\ \ D=[0] \tag{3}$$

For H2 Optimization, the dimensionless transfer function in frequency domain is

$$H(i\omega)=C(i\omega I-A)^{-1}B$$
$$H(i\lambda)=\frac{\beta^2-\gamma^2+\beta\lambda\gamma i}{\omega^2{}_n\left[\left(1-\gamma^2\right)\left(\beta^2-\gamma^2\right)-\mu\beta^2\gamma^2+\left(1+\mu\beta^2-\gamma^2\right)i\beta\lambda\gamma\right]} \tag{4}$$
$$\mu=\frac{m_1}{m};\omega_n{}^2=\frac{k}{m};\omega_1{}^2=\frac{k_1}{m_1};\beta=\frac{\omega_1}{\omega_n},\gamma=\frac{c}{m_1\omega};\lambda=\frac{\omega}{\omega_n}$$

Considering S_0 as the spectral density, the variance of the output is

$$\sigma^2{}_x=S_0\int_{-\infty}^{\infty}\left|H(i\omega)\right|^2 d\omega=S_0\omega_n\int_{-\infty}^{\infty}\left|H(i\lambda)\right|^2 d\lambda \tag{5}$$

Utilizing integration tables (Gradshteyn and Ryzhik 1994), the result of this expression is

$$\sigma^2{}_x=\tfrac{1}{\beta^5\gamma\mu}\left(\pi(\beta^4+\beta^2\gamma^2+\beta^2\mu-2\beta^2+1)\right) \tag{6}$$

The H2 optimum tuning frequency ratio and damping are the solution of Eq. (7).

$$\partial\sigma^2{}_x/\partial\beta=0; \quad \partial\sigma^2{}_x/\partial\gamma=0 \tag{7}$$

Solving Eq. (7) leads to functions for the H2 optimum tuning and damping ratio for shown in Eq. (8).

$$\beta = \frac{1}{2}\sqrt{-3\mu + 6 + \sqrt{9\mu^2 - 36\mu + 4}}; \qquad \gamma = \frac{1}{\beta}\sqrt{1 + \beta^4 + (\mu - 2)\beta^2} \tag{8}$$

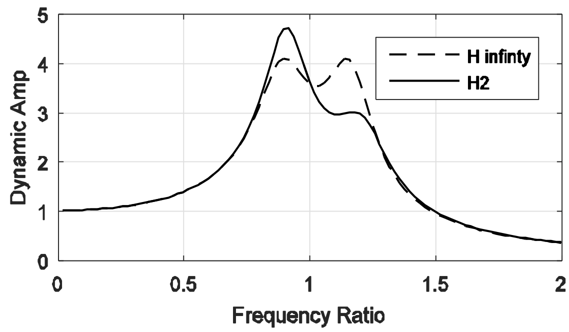

Figure 3. TVMD H2 and H-infinity Optimization Response

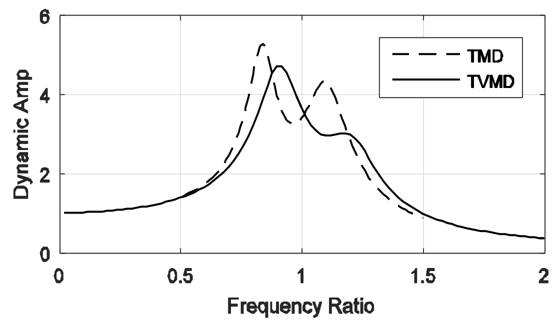

Figure 4. H2 Optimization of TMD and TVMD Response

The system frequency responses considering a 10% effective mass ratio are presented in Figure 3 for the H2 optimized TVMD and the H-infinity optimized TVMD (Ikago, Saito, and Inoue 2012) and in Figure 4 for the H2 optimized TVMD and H2 optimized TMD (Warburton 1982) .

GROUND MOTION RESPONSE

To investigate the system's time-history response, a pulse loading can be numerical applied to the system. The analytical ground motion model proposed by (He and Agrawal 2008) is utilized for this investigation. The time-history of this ground motion model is

$$\ddot{x}_p(t) = Ct^n e^{-at}\left[(n/t - a)\sin(\omega t + v) + \omega\cos(\omega t + v)\right]; \quad t \geq t_0 \tag{9}$$

in which ω is the dominate pulse frequency, C is the amplitude scaling factor, n is the parameter controlling the skewness the pulse (speed of the buildup of pulse amplitude), a is the pulse decay factor, v is phase angle of the sinusoidal component, and t_0 is the beginning time of the pulse. The acceleration time-history utilized in this analysis is presented in Figure 5 and was produced with the parameters $\omega = 2\pi$, $n = 1$, $a = 2.51$, and $C = 7.17$ (Xu et al. 2007). This ground motion has a peak pulse velocity of 1 m/s and peak acceleration of 0.6g.

Figure 6 shows the time-history responses of system subjected to the pulse shown in Figure 5 with 10% mass ratio TVMDs with parameters from the H2 and H infinity optimizations. Figure 7 shows the pulse response of the uncontrolled system, the H2 optimized TMD, and the H2 optimized TVMD. Furthermore, the peak displacement of the structure with H2 and H-infinity optimized TVMDs in response the ground motion with varied dominate pulse frequency is shown in Figure 8.

CONCLUSION

The H2 optimization of the tuned viscous mass damper (TVMD) is performed in this paper and close-formed expressions for the optimum parameters to minimize the area under the random excitation frequency response curve are derived. The results of this optimization show that the TMVD leads to a system with an overall lower frequency response than a system with a TMD of the same effective mass.

The behavior of the optimum system was also investigated using numerical simulations of the response of the system to a pulse model of a near fault ground motion. This analysis demonstrated that the TVMD system had a superior time-history response compared to the TMD system. Additionally, the H2 optimized TVMD system had slightly slower pulse response attenuation compared to the H-infinity optimized TVMD, but the H2 optimized system demonstrated superior peak displacement reduction when the dominate frequency of the pulse input was varied (Figure 8).

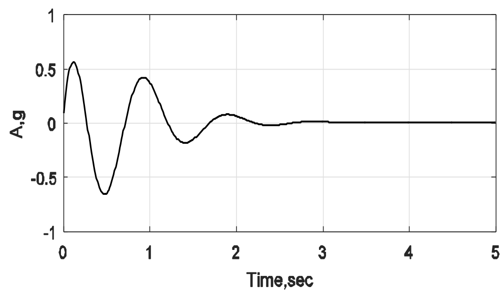

Figure 5. Ground motion pulse model representation

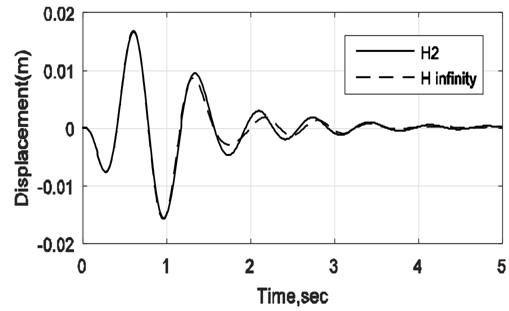

Figure 6. Time history response of TVMD H2 and H infinity optimum values

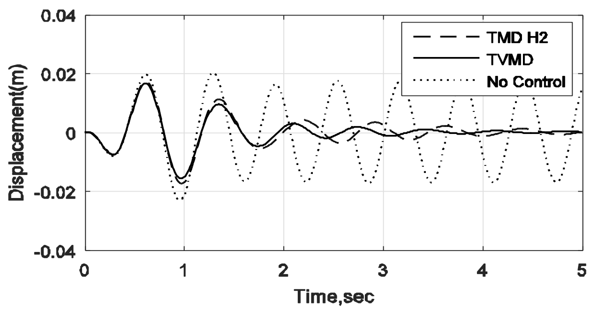

Figure 7. H2 Optimized TMD , TVMD and No Control SDOF response.

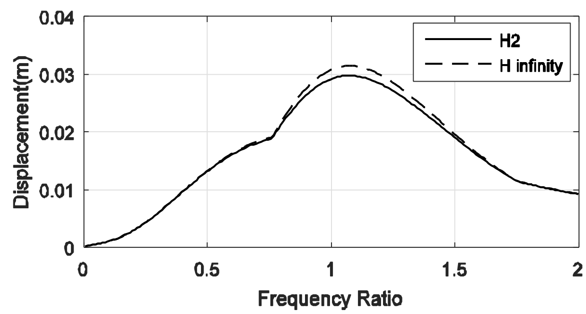

Figure 8. Frequency response of H2 and H infinty of TVMD under pulse load.

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