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응답예측모델을 이용한 속도의존형 감쇠장치의 최대제어력 산정

Maximum Force Limit of Velocity-dependent Damping Devices Using Response Estimation Models

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ABSTRACT

In this study, for estimating responses of a controlled structure and determining the maximum control force of velocity-dependent damping devices, three estimation models such as Fourier envelope convex model, probability model, and Newmark design spectrum are used. For this purpose, a procedure proposed by Gupta (1990) for estimating spectral velocity using pseudo-spectral velocity which is given by the estimation models is used and modified to consider the effects of increased damping ratio by the damping device. Time history results indicate that Newmark design spectrum gives the best estimation of maximum control force for over all period structures.

1. Introduction

A well-designed control system should use a reasonable amount of control, that is, maintain the control inputs at sufficiently small levels that the actuators are not saturated and do not utilize excessive amounts of energy, fuel, and so on. Also, for the comparison and assessment of performance of proposed control algorithms, it is necessary to restrict maximum control force generated by each control algorithm to the same level. This enables the designer of controller to select control algorithm which makes most of control force under the same maximum control force limit.

Soong(1996), for the active controller using linear velocity feedback, determined the amount of supplemental damping ratio necessary for obtaining a given reduction of structural responses and evaluated maximum control force to achieve this required damping ratio. Soong estimated the maximum velocity by using 3 estimation models such as global energy bound convex model, Fourier envelope convex model and probability model. The study by Soong showed that global energy bound convex model gives the highest maximum response estimate, the probability model predicts the lowest response, and Fourier envelope convex model usually provides an intermediate estimate. Compared with the results from deterministic simulation for a six-storey framed building of which the fundamental period is about 1.0s, Fourier envelope convex model is the best candidate for the evaluation of maximum control force. However, in this procedure for a determination of maximum control force, pseudo-spectral velocity is used instead of spectral velocity and which may generate error if there is a large discrepancy between velocity and pseudo-velocity. It is known that though the spectral velocity of a structure of which fundamental period is in the intermediate range have similar value to pseudo-spectral velocity, the discrepancy between velocity and pseudo-velocity become large for long-period or short period structure (Chopra, 1995). Furthermore, this discrepancy increases with increasing damping ratio.

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In this study, for estimating responses of a controlled structure and determining the maximum control force of controller, in addition to Fourier envelope convex model and probability model which are used by Soong for the same purpose, Newmark design spectrum are used. To assess the effectiveness of estimation methods, the results obtained from 3 estimation methods are compared with those from seismic analyses. Also, to mitigate the discrepancy between pseudo-spectral velocity and spectral velocity, velocity spectrum is estimated from a displacement spectrum given by 3 estimation model. For this purpose, the procedure proposed by Gupta (1990) is adopted and modified to consider the effects of damping ratio.

2. Methods for the Estimation of Response Spectra

2.1 Equation of motion

The equation of motion of a single degree of freedom (SDOF) system with is

$$\ddot{x} + 2\xi_1\omega_1\dot{x} + \omega_1^2 x = -\ddot{x}_g \qquad (1)$$

in which, ω_1, ξ_1, x, $\ddot{x}_g$ are natural frequency, damping ratio, relative displacement and ground acceleration, respectively.

2.2 Fourier Envelope Convex Model

In this model, the bound is applied to the Fourier transform of the uncertain seismic input. Shinozuka (1970) used a constraint of this kind in an early study of structural response to unknown earthquake excitations. For a transient earthquake input $\ddot{x}_g(t)$, its Fourier transform is determined by

$$F_{\ddot{x}_g}(\Omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \ddot{x}_g(t)e^{-j\Omega t}dt \qquad (2)$$

The greatest relative displacement is found to be

$$S_v(\omega_1, \xi_1) = \max[x(t)] = \int_{-\infty}^{\infty} |H(\Omega,t)| F_g(\Omega)d\Omega \qquad (3\text{-a})$$

where the asymptotic value for $t \to \infty$ is

$$|H(\Omega,\infty)|^2 = \frac{1}{(\omega_1^2 - \Omega^2)^2 + 4\xi_1^2\omega_1^2\Omega^2} \qquad (3\text{-b})$$

Therefore, equation (3-a) provides maximum response information once $F_o(\Omega)$ is known.

2.3 Probability Theory

Kiureghian (1980) derived a following equation for maximum response by using the formula proposed by Venmark and modifying the peak factor proposed by Davenport.

$$S_x = \gamma_p \sigma_x \qquad (4)$$

where, σ_x is the root-mean-square response of the structure, and γ_p is a peak factor which can be determined by

$$\gamma_p = \sqrt{2\ln \nu_e t_s} + \frac{0.5772}{\sqrt{2\ln \nu_e t_s}} \qquad (5)$$

in which t_s is strong motion period of earthquake Simplified equation for ν_e is

$$\nu_e = \begin{cases} \nu, \ \xi_1 \le 0.54 \\ (1.90\xi_1^{0.15} - 0.73)\nu, \ \xi_1 > 0.54 \end{cases} \qquad (6)$$

$$\nu = \frac{\omega_1}{\pi} \qquad (7)$$

Transfer function of displacement response of SDOF system is

$$x(i\omega) = H(i\omega)\ddot{x}_g(i\omega) \qquad (8)$$

$$H(i\omega) = \frac{1}{\omega_1^2 - \omega^2 + 2\xi_1\omega\omega_1 i} \qquad (9)$$

Power spectral density function (PSDF) of displacement is

$$S_x(\omega) = |H(i\omega)|^2 S_{\ddot{x}_g}(\omega) \qquad (10)$$

PSDF of ground acceleration is given by

$$S_{\ddot{x}_g}(\omega) = \left[\frac{1 + 4\xi_g^2(\omega/\omega_g)^2}{[1-(\omega/\omega_g)^2]^2 + 4\xi_g^2(\omega/\omega_g)^2} \right] S_w \qquad (11)$$

Equation (11) is so called Kanai-Tajimi spectrum and ω_g and ξ_g are, respectively, the natural frequency and damping ratio of the oscillator determined by the characteristics of the local earth surface layer. Mean values of ω_g and ξ_g for rock site, are 26.7 and 0.35, and ones for soil sites are 19.1 and 0.32, respectively. RMS values of displacement is obtained by

$$\sigma_x^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_x(\omega) d\omega \qquad (12)$$

2.4 Newmark Design Spectrum

The design spectrum is based on statistical analysis of the response spectra for the ensemble of ground motions. Therefore, design spectrum can be used as a method for estimation of maximum seismic response of structure. Newmark and Hall developed procedures to construct such design spectra from ground motion parameters [Chopra, 1995].

2.5 Parameters for input earthquake data

A procedure which Soong (1996) used for the comparison between estimation methods is adopted. To obtain maximum response by the models described above, power spectral density, and strong-motion period should be given.

The correlations between RMS acceleration $\sigma_{\ddot{x}_g}$ and peak acceleration a_{max} is given by

$$\sigma_{\ddot{x}_o} = 220(a_{max})^{0.87} \qquad (13)$$

where $\sigma_{\ddot{x}_g}$ and a_{max} have units of cm/s^2 and g, respectively. Also, for strong-motion period t_s, the following regression equation has been suggested.

$$t_s = 30\exp\left[-3.254(a_{max})^{0.35}\right] \qquad (14)$$

For the FEB and PRB model, the spectral density, S_w, is given by

$$S_w = \frac{2\xi_g \sigma_{\ddot{x}_g}^2}{\pi\omega_g(1+4\xi_g^2)} \qquad (15)$$

Similarly, mean-value homology for the FEB model can be approximated by

$$F_o(\Omega) = E\left[\left|F_{\ddot{x}_g}(\Omega)\right|\right] = \sqrt{\frac{t_s G_{\ddot{x}_g}(\Omega)}{2}} \qquad (16)$$

3. Force Limit of Damping Device

3.1 Equation of Motion of Structure with Damping Device

The equation of motion of a SDOF system with damping device is

$$\ddot{x}(t) + 2\xi_o\omega_o\dot{x}(t) + \omega_o^2 x(t) = u(t) - \ddot{x}_g(t) \qquad (17)$$

Control force $u(t)$ is mass normalized. If control force is determined by linear velocity feedback control, the variation of damping ratio caused by control force can be easily calculated. The control force is

$$u(t) = -g_v\dot{x}(t) \qquad (18)$$

in which g_v is control gain for velocity of structure.

Substituting equation (18) into equation (17), the equation of motion becomes

$$\ddot{x}(t) + 2\omega_o\left(\xi_o + \xi_a\right)\dot{x}(t) + \omega_o^2 x(t) = -\ddot{x}_g(t) \quad (19)$$

where $\xi_a = g_v / 2m\omega$.

Since the equation of motion is expressed in terms of damping ratio and natural frequency, the maximum response of controlled structures can be calculated using response spectrum as in the uncontrolled cases.

Maximum control force to obtain the desired damping ratio is

$$S_u(T,\xi_c) = g_v S_{\dot{x}}(T,\xi_c) \quad (20)$$

in which, $\xi_c = \xi_o + \xi_a$

3.2 Estimation of the Velocity Spectrum from a Given Displacement Spectrum

For the estimation of maximum control force, spectral velocity $S_{\dot{x}}$ of a structure with controller should be known. For a given earthquake motion history, the procedure for obtaining the velocity response spectrum is straight forward. For design purposes, the displacement spectrum is specified, while the velocity spectrum is not. Gupta proposed the procedure for estimating the velocity spectrum from a given displacement spectrum.

Figure 1 shows the displacement and the velocity spectra of a SDOF system with 5% damping ratio for an ensemble of 4 ground motions on firm ground. Two spectra are approximately equal in the intermediate frequency range. The displacement spectrum is higher in the higher frequency range, and the velocity spectrum is higher in the lower frequency range.

Gupta (1990) obtained the relationship between the displacement and the velocity spectrum. In the low frequency range, the relationship is

$$\frac{S_A^v}{S_A^d} = \frac{\dot{u}_{g\max}}{\omega u_{g\max}} = \frac{\omega^L}{\omega} \quad (21)$$

and in the high frequency range

$$\frac{S_A^v}{S_A^d} = \frac{\dddot{u}_{g\max}}{\omega \ddot{u}_{g\max}} = \frac{\omega^H}{\omega} \quad (22)$$

Also

$$f^L = \frac{\omega^L}{2\pi}\text{(Hz)},\ f^H = \frac{\omega^H}{2\pi}\text{(Hz)} \quad (23)$$

The two frequencies, f^L and f^H, vary depending upon the frequency content and distribution of actual ground motion. If an actual ground motion is known one need not estimate these frequencies or the velocity response spectrum. Both the displacement and the velocity spectra can be determined directly from the ground motion record. For design purposes, the two frequencies can be obtained from a given displacement spectrum by using the following equations:

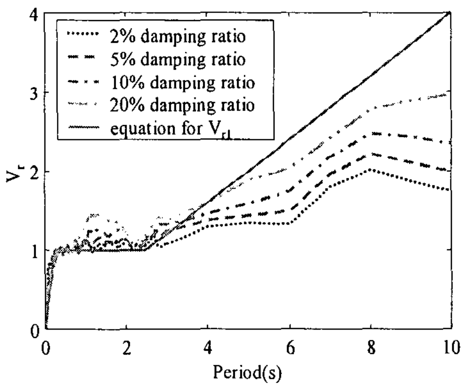

Figure 1. V_{rl} and V_r

Now, consider the effect of damping ratio on V_r especially in the region of period less than 10s to which typical building structures belong. The following figure shows the ratio of spectral velocity to pseudo-spectral velocity which is obtained by equation (25) and by seismic analyses of a structure with 2%, 5%, 10% and 20% damping ratio.

$$f^L = \frac{S_{v\max}^d}{2\pi S_{D\max}^d},\ f^H = 4.3\frac{S_{A\max}^d}{2\pi S_{v\max}^d} \quad (24)$$

For $f \le f^L$, equation (21) holds; for $f^L < f < f^H$, $S^v = S^d$, and for $f \ge f^H$ equation (22) holds.

$$V_{r1} = \frac{S_V^v}{S_V^d} = \begin{cases} f^L / f \; ; & f < f^L \\ 1 \; ; & f^L \le f < f^H \\ f^H / f \; ; & f \ge f^H \end{cases} \qquad (25)$$

Figure 1 shows that the differences between the displacement and the velocity spectra, as indicated by how much the value of V_r differs from unity, increase with damping and over the medium-period range V_r is approximately equal to unity. It should be noted that equation (25) cannot consider the effect of damping ratio and gives larger values than deterministic records. To compensate this and to consider the effect of damping ratio, the following equation for V_{r2} is proposed

$$V_{r2} = V_{r1}^{\sqrt{3\xi}} \qquad (26)$$

Equation (26) and V_r are plotted for comparison in figure 2. The variation tendency of V_r is approximately described by equation (26). Though equation (26) gives smaller values than deterministic data, it can consider the effects of damping ratio and the global discrepancy decreases compared with that by V_{r1}.

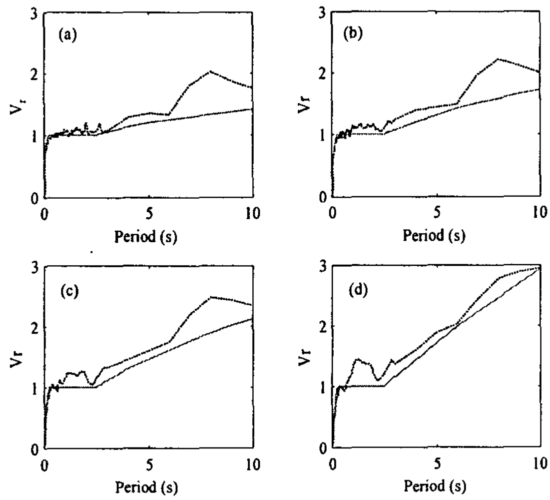

Figure 2. Comparison between V_{r2} and V_r:

(a) 2%; (b) 5%; (c) 10%; (d) 20% (---: V_r, —: V_{r2})

The fact that V_{r2} is smaller than deterministic results may cause the designer to estimate the maximum control force smaller than actual state, which results in unsafe design of control systems. This problem can be solved by overestimating the spectral displacement using a conservative estimation method

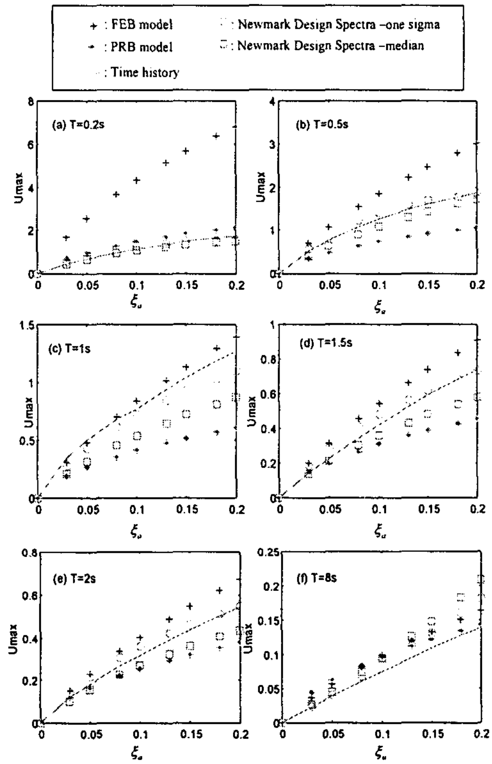

Figure 3. Maximum Control Forces by Estimation Models and Time History Analysis

Figure 3 shows the maximum control force by time history analysis along with ones by FEB model, PRB model and Newmark design spectrum for a structure of which motion is governed by equation (19). Control gain is determined to get desired damping ratio and the variation of maximum control force is plotted against damping ratio. Numerical analyses are performed on SDOF system with period 0.2s, 0.5s, 1.0s, 1.5s, 2.0s, and 8s.

Newmark design spectrum gives the best estimation of maximum control force for over all period structures. FEB model generally predicts the largest maximum control force except for a 8.0s period structure and the error is relatively large for short periods(0.2s and 0.5s) structures but small for medium and longer period (more than 1s). PRB model gives so small estimation value that it may induce unsafe design of control system.

4. Conclusions

In this study, for estimating responses of a controlled structure and determining the maximum control force of controller, three estimation models such as Fourier envelope convex model, probability model, and Newmark design spectrum are used. To mitigate the discrepancy between pseudo-spectral velocity and spectral velocity, velocity spectrum is estimated from a displacement spectrum given by the estimation models. For this purpose, the procedure proposed by Gupta (1990) is adopted and modified to consider the effects of damping ratio. Time history results indicate that Newmark design spectrum gives the best estimation of maximum control force for over all period structures

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