Transactions of the KSNVE. Vol. 14, No. 6, pp. 503~511, 2004.

Maximum Control Force of Velocity-dependent Damping Devices Using Response Estimation Models
응답예측모델을 이용한 속도의존형 감쇠장치의 최대제어력 산정

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(Received February 26, 2004 : Accpeted June 1, 2004)

Key Words : Maximum Control Force(최대제어력), Estimation Models(예측모델), Pseudo-velocity(유사속도), Actual Velocity(실제속도), Damping Ratio(감쇠비)

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 is proposed for estimating actual velocity using pseudo-velocity and this procedure considers the effects of damping ratio increased by the damping device. Time history results indicate that actual velocity should be used for estimating accurate maximum control force of damping device and Newmark design spectrum modified by the proposed equation gives the best estimation results for over all period structures.

요 약

본 연구에서는 푸리에 모델, 확률 모델, 그리고 Newmark 설계 스펙트럼 방법과 같은 응답예측 모델을 사용하여 속도의존형 감쇠장치에 의해 제어되는 구조물의 응답과 제어기의 최대제어력을 예측하였다. 이를 위해, 유사 속도로부터 실제 속도를 예측하는 방법이 제안되었으며, 이 방법은 감쇠장치에 의해 증가되는 감쇠비의 실제속도에 대한 효과를 고려한다. 시간이력해석결과는 정확한 최대제어력을 예측하기 위해서는 실제속도가 사용되어야 하며, 제안된 방법에 의해 수정된 Newmark 설계 스펙트럼이 가장 전 주기구간에 걸쳐 정확한 예측 값을 산정함을 보여준다.

1. 서 론

A well-designed control system utilizing a damping device should consume a reasonable amount of control energy, 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.[1] Also, for comparison and assessment of the performance of damping devices, it is necessary to restrict maximum control force generated by each damping device to the same level, and which enables the designer of controller to select an effective damping device satisfying maximum

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control force limit.

Wu et al. (1996), for the active controller using linear velocity feedback control algorithm, determined the supplemental damping ratio required for obtaining a given response reduction and they evaluated maximum control force to achieve this required damping ratio.[2] Wu et al. estimated the maximum velocity by using 3 estimation models such as global energy bound (GEB) convex model, Fourier envelope (FE) convex model and probability model. The study by Wu et al. showed that GEB convex model gives the highest maximum response estimate, the probability model predicts the lowest response, and FE 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, FE convex model is the best candidate for the evaluation of maximum control force. However, because the procedure proposed by Wu et al. used pseudo-spectral velocity (PSV) instead of the actual spectral velocity (ASV) for determining maximum control force, it causes error when there is large discrepancy between ASV and PSV. It is known that though the ASV of a structure has similar value to PSV only when its fundamental period is in the intermediate range and the discrepancy between ASV and PSV becomes large for long-period or short period structure.[3] Furthermore, this discrepancy increases with increasing damping ratio which may be large when supplemental damping devices are installed.

In this study, for estimating responses of a controlled structure and determining the maximum control force of the controller, Newmark design spectrum as well as the 3 models used by Wu et al. is used. To assess the effectiveness of the estimation methods, the results obtained by using 3 estimation methods are compared with those from seismic analyses. To mitigate the discrepancy between ASV and PSV, a procedure is proposed for estimating ASV using a displacement spectrum given by estimation models.

2. Estimation Models for Response Spectra

2.1 Equation of Motion

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

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

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

2.2 GEB Convex Model

Convex model is developed for the estimation of maximum dynamic response.[4] It defines the uncertainty of earthquake as a function and use the limit value of the function. Since convex model can estimate the maximum seismic responses with little and restricted information about earthquake, it may give conservative estimation results, but it is available in case that there is little information about earthquake.

Maximum displacement, S_x, is given by GEB convex model

$$S_x(\omega_1, \xi_1) = \frac{\sqrt{E_g}}{2\xi_1\omega_1\sqrt{\omega_1}} \tag{2}$$

in which E_g denotes the maximum input energy bound.

2.3 FE Convex Model

FE convex model bounds 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.[5] For a transient earthquake input $\ddot{x}_g(t)$, its Fourier transform is determined by

$$F_{\ddot{x}_g}(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\ddot{x}_g(t)e^{-j\omega t}dt \quad (3)$$

The greatest relative displacement is found to be

$$S_x(\omega_1,\xi_1)=\int_{-\infty}^{\infty}|H(\omega,t)|F_{\ddot{x}_g}(\omega)d\omega \quad . \quad (4)$$

where the asymptotic value for is

$$|H(\omega,\infty)|^2=\frac{1}{\left(\omega_1^2-\omega^2\right)^2+4\xi_1^2\omega_1^2\omega^2} \quad (5)$$

2.4 Probability Model

Kiureghian (1980) derived a following equation for maximum response by using the formula proposed by Venmark and modifying the peak factor proposed by Davenport.[6]

$$S_x=\gamma_p\sigma_x \quad (6)$$

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

$$\gamma_p=\sqrt{2\ln v_e t_s}+\frac{0.5772}{\sqrt{2\ln v_e t_s}} \quad (7)$$

in which t_s is strong motion period of earthquake, and the simplified equation for v_e is

$$v_e=\begin{cases} v, & \xi_1\le 0.54 \\ (1.90\xi_1^{0.15}-0.73)v, & \xi_1>0.54 \end{cases} \quad (8)$$

$$v=\frac{\omega_1}{\pi} \quad (9)$$

Transfer function of displacement response of SDOF system is

$$x(i\omega)=H(i\omega)\ddot{x}_g(i\omega) \quad (10)$$

$$H(i\omega)=\frac{1}{\omega_1^2-\omega^2+2\xi_1\omega\omega_1 i} \quad (11)$$

Power spectral density function (PSDF) of displacement is

$$S_x(\omega)=|H(i\omega)|^2 S_{\ddot{x}_g}(\omega) \quad (12)$$

PSDF of ground acceleration is given by

$$S_{\ddot{x}_g}(\omega)=\left[\frac{1+4\xi_g^2(\omega/\omega_g)^2}{\left(1-(\omega/\omega_g)^2\right)^2+4\xi_g^2(\omega/\omega_g)^2}\right]S_o \quad (13)$$

Equeation (13) is Kanai-Tajimi spectrum 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

$$\sigma_x^2=\frac{1}{2\pi}\int_{-\infty}^{\infty}S_x(\omega)d\omega \quad (14)$$

2.5 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 for estimation of maximum seismic response of structure. Newmark and Hall developed procedures to construct such design spectra from ground motion parameters,[3] and it is used as an estimation model in this study.

2.6 Parameters for Input Earthquake Data

A procedure[2] which Wu et al proposed for the comparison between estimation methods is used in this study for the same purpose. 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 accelerationis $a_{\max}$ is given by

$$\sigma_{\ddot{x}_o} = 220(a_{\max})^{0.87} \tag{15}$$

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.

$$t_s = 30\exp\left[-3.254(a_{\max})^{0.35}\right] \tag{16}$$

For the GEB convex model, is given by mean-value homology.

$$E_g = E\left[\int_0^{t_s} \ddot{x}_g^2(\tau)d\tau\right] = \sigma_{\ddot{x}_g}^2 t_s \tag{17}$$

For the FE convex and probability models, the spectral density, S_o, is given by

$$S_o = \frac{2\xi_g \sigma_{\ddot{x}_g}^2}{\pi\omega_g(1+4\xi_g^2)} \tag{18}$$

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

$$F_o(\omega) = E\left[\left|F_{\ddot{x}_g}(\omega)\right|\right] = \sqrt{\frac{t_s S_{\ddot{x}_g}(\omega)}{2}} \tag{19}$$

The normalized pseudo-acceleration spectrum is chosen as the quantity of comparison, i.e.

$$PSA(\omega_1,\xi_1) = \frac{\omega_1^2 S(\omega_1,\xi_1)}{a_{\max}} \tag{20}$$

Four earthquake records which are listed in table 1, are used for earthquake response spectrum. GEB convex model, FE convex model, probablity model and Newmark design spectrum are used to predict maximum responses. PRB model represents probabilistic model. Soil parameters are selected for rock sites which represents the soil condition of four earthquake records: w_g = 26.7, ξ_g =0.35, and the peak ground acceleration of earthquake records are scaled to 0.4 g. Figure 1 illustrates the pseudo-acceleration spectra with various damping ratios. Spectra are modified when T 〈 0.5 s so that it doesn't exceed the spectral ordinate of T=0.5 s.

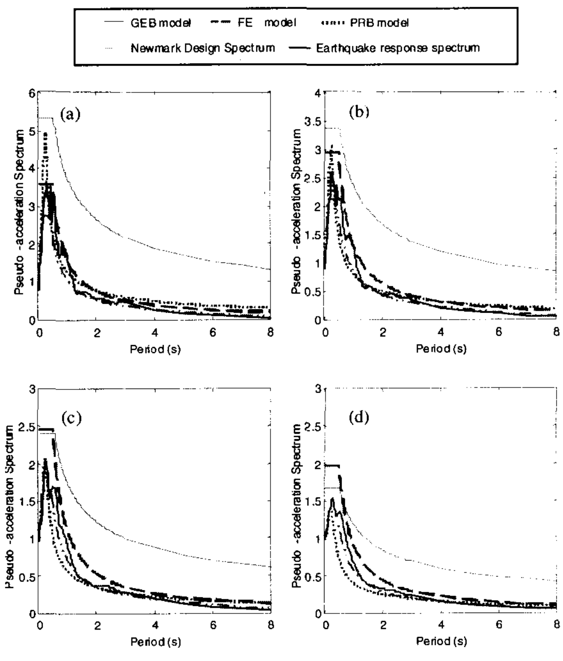

Fig. 1 Response spectra by various estimation method: (a) $\xi_1=0.02$ (b) $\xi_1=0.05$ (c) $\xi_1=0.10$ (d) $\xi_1=0.20$

Figure 1 clearly shows that the GEB convex model gives the highest maximum response estimate for all damping ratios. Newmark design spectrum predicts the lowest response and the probability model and FE convex model usually provides an intermediate estimate when $\xi_1 = 0.02$. With increasing damping ratio, Newmark design spectrum provides an intermediate estimate, and probability model predicts the lowest response.

3. Maximum Control Force 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

$$\ddot{x}(t) + 2\xi_o\omega_1\dot{x}(t) + \omega_1^2 x(t) = u(t) - \ddot{x}_g(t) \quad (21)$$

Control force generated by the damping device is mass normalized and ξ_o denotes the damping ratio of uncontrolled system. 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

$$u(t) = -g_v\dot{x}(t) \quad (22)$$

in which is control gain for velocity of structure.

Substituting Eq. (22) into Eq. (21), the equation of motion becomes

$$\ddot{x}(t) + 2(\xi_o + \xi_a)\omega_1\dot{x}(t) + \omega_1^2 x(t) = -\ddot{x}_g(t) \quad (23)$$

where $\xi_a = g_v / 2w_1$.

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 the estimation models.

Maximum control force to obtain the desired damping ratio is[2]

$$S_u(\omega_1, \xi_1) = g_v S_{\dot{x}}(\omega_1, \xi_1) \quad (24)$$

in which, $\xi_1 = \xi_o + \xi_a$

If the motion of multi degree of freedom (MDOF) system is governed by a fundamental mode and the effect of a damping device can be substituted by equivalent damping ratio, the procedure developed for SDOF system controlled by linear velocity feedback algorithm can be applied for the MDOF system equipped with other types of damping devices.

3.2 Estimation of the Velocity Spectrum from a Given Displacement Spectrum

ASV, $S_{\dot{x}}$, of a structure with controller should be known for the estimation of maximum control force. When earthquake motion data are given, the procedure for obtaining the ASV is straight forward. For practical application, however, only design displacement spectrum is given while ASV is not. Gupta[7] proposed the procedure for estimating the ASV from a given displacement spectrum.

Figure 2 shows, Vr, the ratio of ASV to PSV 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 PSV is higher in the higher frequency range, and the ASV is higher in the lower frequency range.

Gupta obtained the relationship between the PSV and ASV velocity spectrum. In the low frequency range, the relationship is

$$\frac{S_A^v}{S_A^d} = \frac{\dot{u}_{g\max}}{\omega u_{g\max}} = \frac{\omega^L}{\omega} \quad (25)$$

and in the high frequency range

$$\frac{S_A^v}{S_A^d}=\frac{\ddot{u}_{g\max}}{\omega\ddot{u}_{g\max}}=\frac{\omega^H}{\omega} \quad (26)$$

Also

$$f^L=\frac{S_{v\max}^d}{2\pi S_{D\max}^d},\quad f^H=4.3\frac{S_{A\max}^d}{2\pi S_{v\max}^d} \quad (27)$$

The two frequencies, f^L and f^H, vary depending upon the frequency content and distribution of actual ground motion. The two frequencies can be obtained from a given displacement spectrum by using the following equations:

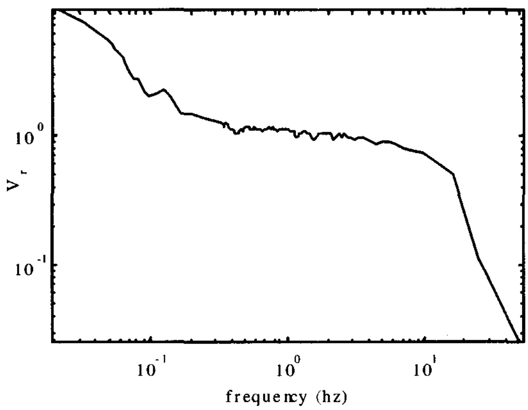

Fig. 2 The ratio of actual velocity spectrum to pseudo-velocity spectrum

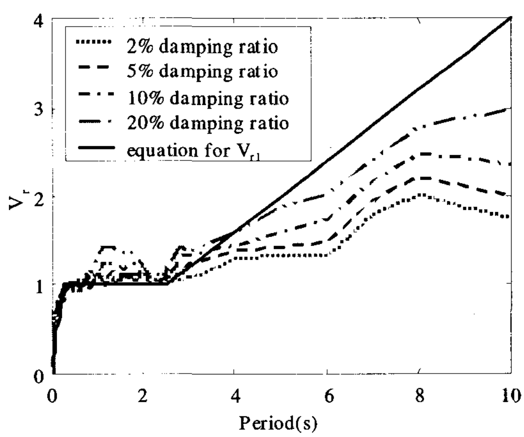

Fig. 3 V_{r1} and V_r

$$f^L=\frac{S_{v\max}^d}{2\pi S_{D\max}^d},\quad f^H=4.3\frac{S_{A\max}^d}{2\pi S_{v\max}^d} \quad (28)$$

For, $f\le f^L$, Eq. (25) holds; for $f^L < f < f^H$, $S^v = S^d$, and for $f\ge f^H$ Eq. (26) holds.

$$V_{r1}=\frac{S_V^v}{S_V^d}=\begin{bmatrix} f^L/f\ ; & f<f^L \\ 1\ ; & f^L\le f<f^H \\ f^H/f\ ; & f\ge f^H \end{bmatrix} \quad (29)$$

Figure 3 shows the V_{r1} and V_r, which are, respectively, obtained by the Eq. (29) and by the seismic analyses of a structure with 2 %, 5 %, 10 % and 20 % damping ratio. It is observed that Eq. (29) can reproduce the variation trend of V_r. Eq. (29), however, cannot consider the effect of damping ratio and gives larger values than deterministic records. To consider the effect of damping ratio, the following equation for V_{r2} is proposed

$$V_{r2}=V_{r1}^{\sqrt{3\xi}} \quad (30)$$

Equeation (30) and are plotted for comparison in Fig. 4. The variation tendency of is approximately described by Eq. (30). Though the Eq. (30) 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}.

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 5 illustrates the comparison between ASV by seismic analyses and the S_v^d estimated by FE convex model, probability model, and

Newmark design spectrum. GEB convex model is excluded since it provides too much overestimated values Seismic analyses are performed for 4 earthquake records and spectral velocity is obtained by taking mean value of results from 4 seismic analyses. Newmark design spectrum are constructed by using two amplification factors for two different non-exceedance probabilities, 50 % and 84.1 %. The 50 % non-exceedance probability represents the median value of the spectral ordinates and the 84.1 % represents the median-plus-one-standard-deviation value assuming log-normal probability distribution for the spectral ordinates.

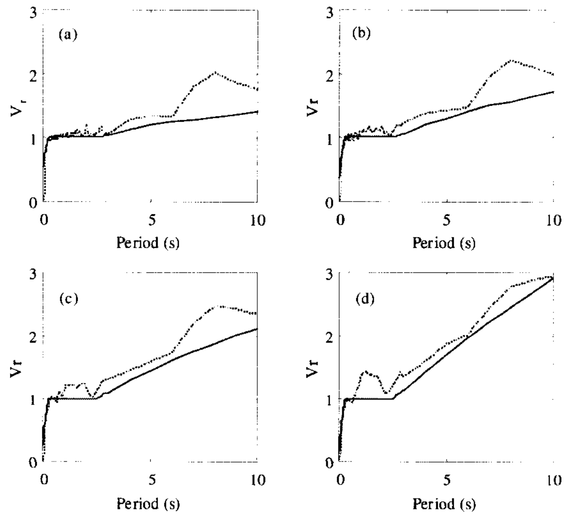

Fig. 4 Comparison between V_{r2} and V_r: (a) 2 %: (b) 5 %: (c) 10 %: (d) 20 % (---: V_r, —: V_{r2})

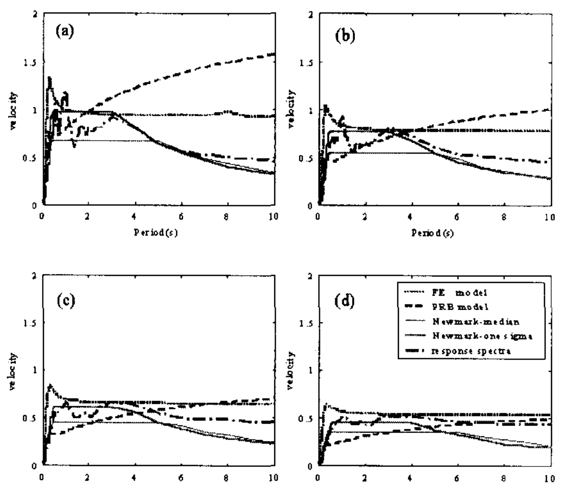

Fig. 5 Spectral velocity by estimation models: (a) $\xi_1 = 0.02$; (b) $\xi_1 = 0.05$; (c) $\xi_1 = 0.1$: (d) $\xi_1 = 0.2$

PSV by FE model is generally larger than S_v over all period ranges. For medium period structure, PSV by FE model is almost the same with the deterministic results, and for structures having period longer than 4s or shorter than 0.5s, it gives overestimated result. For longer period structure, the discrepancy between S_v and PSV by FE model decreases with increasing damping ratio. However, it should be noted that this is not because FE model can reflect the dynamic characteristic of longer period structure, but because S_v has increased with increasing damping ratio, and thus the discrepancy between S_v and overestimated velocity by FE model is mitigated. Consequently, it cannot be concluded that PSV by FE model can describe the variation trend of S_v with respect to structural period and damping ratio.

PSV by probability model shows monotonic increase with period and the effect of increased damping ratio on response reduction is overestimated. For structure with period longer than 2s and 2 % damping ratio, probability model gives the largest PSV, but with increasing damping ratio, the reduction of response becomes so large that PSV of a structure with 20 % damping ratio by probability model is smaller than deterministic results over all periods. Since probability model underestimates the velocity especially for a shorter period structure, probability model may induce unsafe design, as mentioned in Wu's study.

It is observed that Newmark design spectrum reflects well the variation trend of S_v with respect to period and damping ratio. For medium period structure, estimations by median give lower values than by deterministic records, and those by one-sigma give almost exact values. Therefore, for safe design method adopting one-sigma should be used. Though the discrepancy becomes large for longer period structure with large damping ratio, this is due to the difference between PSV and S_v, which can be compensated by using Eq. (30).

The estimated spectral velocities, which are obtained by multiplying PSV (plotted in Fig. 5) by V_{r2}, are compared with S_v in Fig. 6.

For Newmark design spectrum, the difference between PSV and S_v, which is distinct in a longer period structure, is so reduced that Newmark design spectrum can give accurate estimation of S_v over all periods. In contrast, the errors in FE model and probability model are larger than the results shown in Fig. 5. This is because PSV by FE model or probability model is larger than S_v. Therefore, it is reasonable for FE model and probability model that PSV rather than equation modified by V_{r2} should be used for the estimation of maximum control force.

Figure 7 shows the maximum control force by time history analysis along with ones by FE model, probability model and Newmark design spectrum for a structure of which motion is governed by Eq. (21). 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. FE 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). probability model gives so small esti- mation value that it may induce unsafe design of control system.

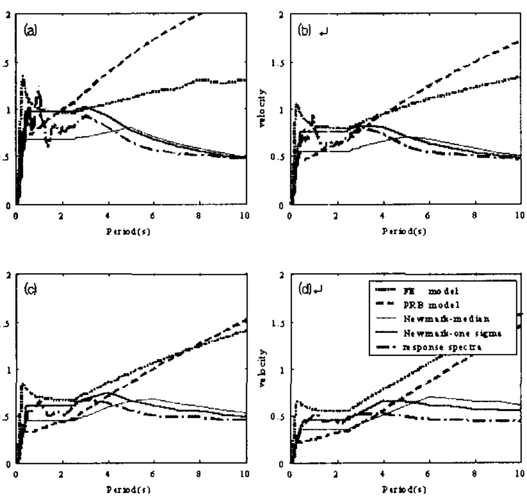

Fig. 6 Spectral velocity by estimation models modified by V_{r2}:
(a) $\xi_1=0.02$; (b) $\xi_1=0.05$;
(c) $\xi_1=0.1$; (d) $\xi_1=0.2$

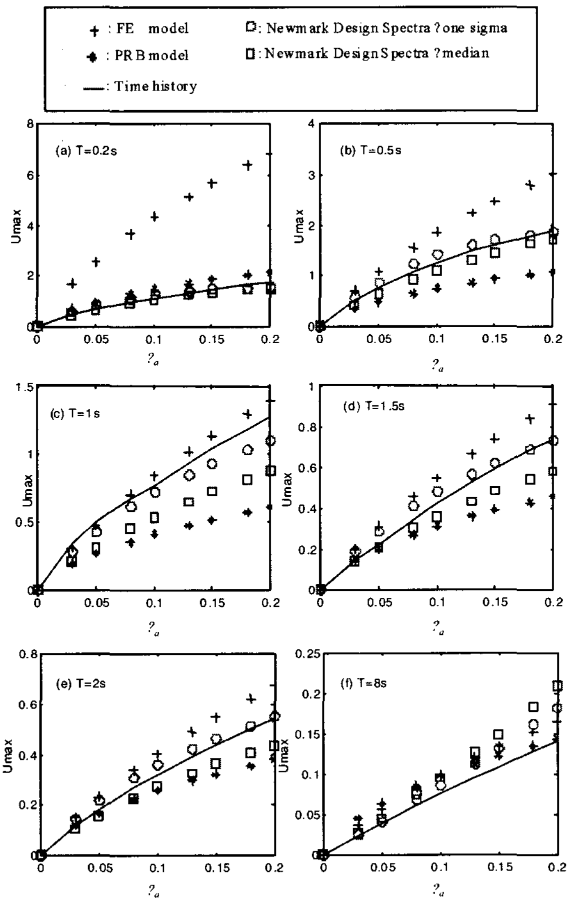

Fig. 7 Estimated maximum control forces

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.

Acknowledgement

The authors would like to acknowledge the financial support from Korea Science and Engineering Foundation (KOSEF, Project No. R01-2003-000-11584-0), and Korea Institute of Construction & Transportation Technology Evaluation and Plan (KICTTEP, Project No. 03 Industry and University Cooperative Research C 103A200 0010-03A0200-01010).

Reference

(1) Ben-Haim, Y., Chen, G., Wu et al., T. T., 1996, "Maximum Structural Response Using Convex Model," Journal of Engineering Mechanics, ASCE, Vol. 122, No. 4, pp. 325~333.

(2) Cai, G.Q., Huang, J., Sun, F. and Wang, C, 2000, "Modified Sliding-Modė Bang-Bang Control For Seismically Excited Linear Structures," Earthquake Engineering and Structural Dynamics, Vol. 29, pp. 1647~1657.

(3) Chopra, A. K., 1995, "Dynamics of Structures: Theory and Applications to Earthquake Engineering," Prentice Hall, New Jersey, p. 729

(4) Kiureghian, A. D., 1980, "Structural Response to Stationary Excitation," Journal of Engineering Mechanics Division, ASCE, Vol. 106, No. EM6, pp. 1195~1213.

(5) Shinozuka, M., 1970, "Maximum Structural Response to Seismic Excitations," Journal of Engineering Mechanics, Vol. 96, pp. 729~738.

(6) Wu, Z., Wu et al., T.T., 1996, "Design Spectra for Actively Controlled Structures Based on Convex Models," Journal of Engineering Structures, ASCE, Vol. 18, No. 5, pp. 341~350.

(7) Gupta, A. K., 1990, "Response Spectrum Method: in seismic analysis and design of structures," CRC Press Inc., p. 170