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Control-force spectrum for active base-isolated structures with nonlinear viscous dampers using gain-scheduling control strategy

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Active base-isolated structure Nonlinear viscous damper
Control-force spectrum Gain-scheduling

1. Introduction

Response-spectrum-based design method has been expanded to active base-isolated structures with nonlinear viscous dampers (NVDs) by using gain-scheduling control strategy [1-2]. However, there is still a lack of a method to estimate the required maximum control force. To further simplify the design process and clarify the relationship between the control force and design parameters, this paper proposes a control-force spectrum to estimate the required maximum control force for the response-spectrum-based design method of active base-isolated structures with NVDs.

2. Mathematical model

This study uses the SDOF model shown in Fig. 1.

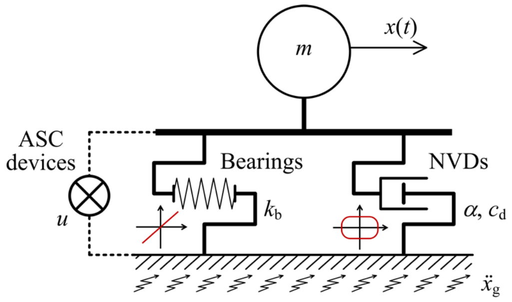

Fig. 1. Structure model

The state-space representation of the system is

$$\dot{z}(t) = Az(t) + Bu(t) + B_{\mathrm{d}} f_{\mathrm{d}}(t) + B_{\mathrm{g}} \ddot{x}_{\mathrm{g}}(t), \qquad (1)$$

where $f_{\mathrm{d}}(t) = c_{\mathrm{d}} \left|\dot{x}(t)\right|^{\alpha} \operatorname{sgn}(\dot{x})$, $z(t) = \begin{bmatrix} x(t) & \dot{x}(t) \end{bmatrix}^{\mathrm{T}}$, $A = \begin{bmatrix} 0 & 1 \\ -m^{-1}k_{\mathrm{b}} & 0 \end{bmatrix}$, $B = B_{\mathrm{d}} = \begin{bmatrix} 0 & -m^{-1} \end{bmatrix}^{\mathrm{T}}$, and $B_{\mathrm{g}} = \begin{bmatrix} 0 & -1 \end{bmatrix}^{\mathrm{T}}$.

For the above equations, t is the time; $z(t)$ is the state vector; $x(t)$, $\dot{x}(t)$ and $\ddot{x}(t)$ are respectively the response displacement, velocity and acceleration; $\ddot{x}_{\mathrm{g}}(t)$ is the ground acceleration; $u(t)$ is the control force; $f_{\mathrm{d}}(t)$ is the damper force of NVDs, where c_{d} is the damping coefficient, α is the velocity exponent ($\alpha \in [0, \ 1]$), and sgn is the sign function; A is the system matrix; B is the input matrix for $u(t)$; B_{d} is the input matrix for $f_{\mathrm{d}}(t)$; B_{g} is the input matrix for $\ddot{x}_{\mathrm{g}}(t)$; m is the mass; k_{b} is the stiffness coefficient provided by bearings. The pseudo LPV system description of Eq .(1) is

$$\dot{z}(t) = A_{\mathrm{TL}}\left(c_{\mathrm{TL}}(t)\right) z(t) + Bu(t) + B_{\mathrm{g}} \ddot{x}_{\mathrm{g}}(t), \qquad (2)$$

where $A_{\mathrm{TL}}\left(c_{\mathrm{TL}}(t)\right) = \begin{bmatrix} 0 & 1 \\ -m^{-1}k_{\mathrm{b}} & -m^{-1}c_{\mathrm{TL}}(t) \end{bmatrix}$ is the time-varying linear system matrix, $c_{\mathrm{TL}}(t)$ is the time-varying linear damping coefficient, defined by

$$c_{\mathrm{TL}}(t) = c_{\mathrm{d}} \left|\dot{x}(t)\right|^{\alpha-1}. \qquad (3)$$

A target equivalent model is constructed to design the maximum response of the system:

$$\dot{z}(t) = A_{\mathrm{tar}} z(t) + B_{\mathrm{g}} \ddot{x}_{\mathrm{g}}(t), \qquad (4)$$

where A_{tar} is the target linear system matrix, $A_{\mathrm{tar}} = \begin{bmatrix} 0 & 1 \\ -m^{-1}k_{\mathrm{tar}} & -m^{-1}c_{\mathrm{tar}} \end{bmatrix}$, k_{tar} is the target equivalent stiffness; c_{tar} is the target equivalent damping coefficient.

The control force, $u(t)$, is generated by state-feedback:

$$u(t) = Kz(t) = \begin{bmatrix} K_{\mathrm{D}} & K_{\mathrm{V}} \end{bmatrix} \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix} = K_{\mathrm{D}} x(t) + K_{\mathrm{V}} \dot{x}(t), \qquad (5)$$

where $K = \begin{bmatrix} K_{\mathrm{D}} & K_{\mathrm{V}} \end{bmatrix}$ is the gain of the controller, K_{D} and K_{V} are the displacement feedback gain and the velocity feedback gain, respectively. In this study, the gains are calculated by the following gain-scheduling strategy [1]:

$$K_{\mathrm{D}} = k_{\mathrm{tar}} - k_{\mathrm{b}} \qquad (6)$$

$$K_{\mathrm{V}}(t) = \begin{cases} c_{\mathrm{tar}} - c_{\mathrm{TL}}(t), & \left|\dot{x}(t)\right| > \left|\dot{x}\right|_{\mathrm{sw}}, \\ 0, & \left|\dot{x}(t)\right| \le \left|\dot{x}\right|_{\mathrm{sw}}. \end{cases} \qquad (7)$$

where $\left|\dot{x}\right|_{\mathrm{sw}}$ is the switching velocity, satisfying

$$c_{\mathrm{tar}} = c_{\mathrm{TL}}\left(\left|\dot{x}\right|_{\mathrm{sw}}\right) = c_{\mathrm{d}} \left|\dot{x}\right|_{\mathrm{sw}}^{\alpha-1} \qquad (8)$$

3. Control-force spectrum

We denote the control force from K_{V} as $u_{\mathrm{V}}(t)$, and denote the control force from K_{D} as $u_{\mathrm{D}}(t)$:

$$u_{\mathrm{V}}(t) = \left[c_{\mathrm{tar}} - c_{\mathrm{TL}}(t)\right] \dot{x}(t) \qquad (9)$$

$$u_{\mathrm{D}}(t) = \left(k_{\mathrm{tar}} - k_{\mathrm{b}}\right) x(t) \qquad (10)$$

The shear-force coefficient of the control force from K, K_{V}, and K_{D} are respectively defined as

$$C_u(t) = \frac{u(t)}{mg}, \quad C_{u,\mathrm{D}}(t) = \frac{u_{\mathrm{D}}(t)}{mg}, \quad C_{u,\mathrm{V}}(t) = \frac{u_{\mathrm{V}}(t)}{mg}. \qquad (11)$$

From Eq. (10), the control force spectrum of $C_{u,\mathrm{D}}(t)$, denoted as $S_{\mathrm{C,D}}$, can be simply derived as

$$S_{\mathrm{C,D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}},T_{\mathrm{b}}\right)=\frac{4\pi^2}{g}\left|\frac{1}{T_{\mathrm{tar}}^2}-\frac{1}{T_{\mathrm{b}}^2}\right|S_{\mathrm{D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right). \quad (12)$$

where T_{tar} is the target period, ζ_{tar} is the target damping ratio, T_{b} is the period of bearings, $S_{\mathrm{D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)$ is the displacement spectrum of the target equivalent model.

For $|\dot{x}(t)|>|\dot{x}|_{\mathrm{sw}}$, from Eq. (7), $C_{u,\mathrm{V}}(t)$ can be simply deduced as

$$C_{u,\mathrm{V}}(t)=\frac{\left[c_{\mathrm{tar}}-c_{\mathrm{TL}}(t)\right]\dot{x}(t)}{mg}=\frac{\left[c_{\mathrm{tar}}|\dot{x}(t)|-c_{\mathrm{d}}|\dot{x}(t)|^{\alpha}\right]\mathrm{sgn}(\dot{x})}{mg}. \quad (13)$$

According to the differentiation of Eq. (13), the absolute value of $C_{u,\mathrm{V}}(t)$, $|C_{u,\mathrm{V}}(t)|$, increases monotonically with the increase of $|\dot{x}(t)|$ from $|\dot{x}|_{\mathrm{sw}}$. Therefore, the maximum absolute value of $C_{u,\mathrm{V}}(t)$, $|C_{u,\mathrm{V}}|_{\mathrm{max}}$, corresponds to the maximum velocity, $|\dot{x}|_{\mathrm{max}}$, and can be derived as

$$\left|C_{u,\mathrm{V}}\right|_{\mathrm{max}}=\frac{c_{\mathrm{tar}}|\dot{x}|_{\mathrm{max}}-c_{\mathrm{d}}|\dot{x}|_{\mathrm{max}}^{\alpha}}{mg}\cong\frac{c_{\mathrm{tar}}S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)-c_{\mathrm{d}}S_{\mathrm{V}}^{\alpha}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)}{mg}$$
$$=\frac{4\pi\zeta_{\mathrm{tar}}\left[S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)-|\dot{x}|_{\mathrm{sw}}^{1-\alpha}S_{\mathrm{V}}^{\alpha}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)\right]}{T_{\mathrm{tar}}g}, \quad (14)$$

where $S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)$ is the velocity spectrum of the target equivalent model. Since Eq. (14) can be used to estimate the required maximum control force under an earthquake directly, we define Eq. (14) as the control-force spectrum using switching velocity, $S_{\mathrm{C,D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}},\alpha,|\dot{x}|_{\mathrm{sw}}\right)$. Note that if $S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)\le|\dot{x}|_{\mathrm{sw}}$, the maximum control force is expected to approach zero. Thus, we express the complete form of $S_{\mathrm{C,D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}},\alpha,|\dot{x}|_{\mathrm{sw}}\right)$ as

$$S_{\mathrm{C,D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}},\alpha,|\dot{x}|_{\mathrm{sw}}\right)=\begin{cases}\dfrac{4\pi\zeta_{\mathrm{tar}}\left[S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)-|\dot{x}|_{\mathrm{sw}}^{1-\alpha}S_{\mathrm{V}}^{\alpha}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)\right]}{T_{\mathrm{tar}}g}, & S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)>|\dot{x}|_{\mathrm{sw}},\\ 0, & S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)\le|\dot{x}|_{\mathrm{sw}},\end{cases} \quad (15)$$

The control force spectrum of $C_u(t)$, denoted as S_{C}, is estimated by the SRSS of $S_{\mathrm{C,D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}},T_{\mathrm{b}}\right)$ and $S_{\mathrm{C,D}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}},\alpha,|\dot{x}|_{\mathrm{sw}}\right)$:

$$S_{\mathrm{C}}=\sqrt{S_{\mathrm{C,V}}^2+S_{\mathrm{C,D}}^2}. \quad (16)$$

4. Accuracy verification

We use 44 far-field ground motion records from FEMA P695 [3] to show the estimation accuracy of the control force spectrum, Eq. (16). the parameters are shown in Table 1. The results are shown in Fig. 2, where R_{sw} is the switching velocity ratio, defined as

$$R_{\mathrm{sw}}=\frac{|\dot{x}|_{\mathrm{sw}}}{S_{\mathrm{V}}\left(T_{\mathrm{tar}},\zeta_{\mathrm{tar}}\right)}. \quad (17)$$

As shown, the error is basically within the range of ±20%, indicating a good estimation accuracy.

Table 1. Parameters

α	0.3
T_{b}[s]	4
T_{tar}[s]	2 ~ 8, per 0.5
ζ_{tar}	0.2, 0.4
R_{sw}	0.3, 0.6

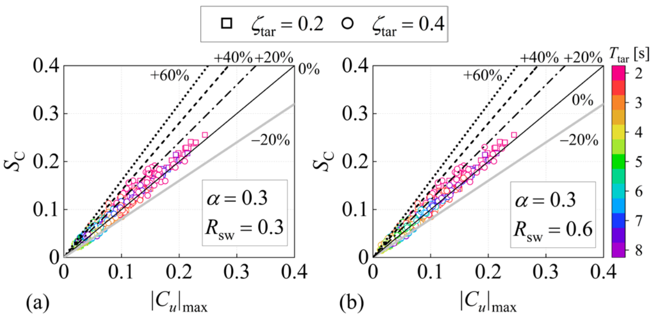

Fig. 2. Comparison of spectra and simulation results ($\alpha=0.3$): (a) $R_{\mathrm{sw}}=0.3$ and (b) $R_{\mathrm{sw}}=0.6$

5. Summary

This paper proposed a control-force spectrum to estimate the maximum required control force for the response-spectrum-based design method of active base-isolated structures with NVDs using gain scheduling control strategy. The estimation accuracy of the control-force spectrum was verified by 44 far-field ground motion records. The results showed a good accuracy level, which indicates the feasibility of the spectrum.

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