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Influence of Frame Damping on the VE System and the Wind-Induced Responses

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Viscoelastic, frequency sensitivity, wind-induced response, frame damping, fractional derivative, integer derivative.

1. Introduction

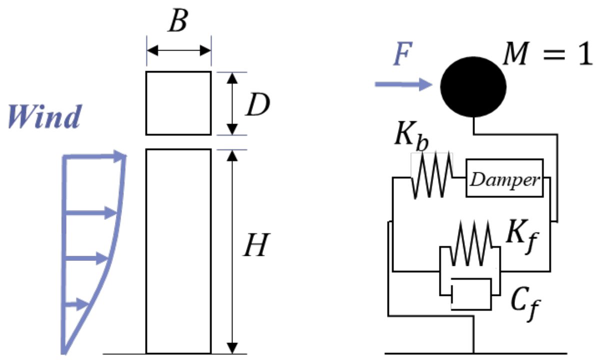
Viscoelastic (VE) damper is one kind of well-known supplemental damping device used in high-rise buildings to reduce excessive vibrations and dissipate energy from wind excitations [1]. Sato et al. (2022) [2] discussed the effects of the frequency sensitivity of the VE damper on the wind-induced responses and the energy dissipation by comparing the complex integer derivative systems with the fractional derivative system. Results indicated that the wind-induced responses and the energy dissipation were dominated by the low frequencies of wind forces, and the frequency sensitivity of the equivalent damping had obvious differences at low frequencies. However, to simplify the initial condition of the VE systems, frame damping was not considered. The aim of this study is to clarify the influence of frame damping on the frequency sensitivity of the VE system and the wind-induced responses.

2. Target building and analytical model

The height of the target building is a $H = 200$ m with an aspect ratio $H/\sqrt{BD} = 4.0$, whose $D = B = 50$ m. Due to the wind-induced response of high-rise buildings is mainly caused by the contribution of the 1st mode [3], the simulation in this study focused on the 1st modal single-degree of freedom (SDOF) model, including the frame with frame damping, the brace, and a VE damper (Fig.(1)). In the simulation, the natural period of frame is set as $T_f = 0.02H$. The 1st modal stiffness of the frame K_f can be obtained by Eq. (1). The soft brace with the stiffness ratio (K_b/K_f) of 3.0, and the weak damper are used in this study. The definition of the soft damper is discussed in Section 3.1. Then, in order to compare the influence of frame damping on the frequency sensitivity of the VE damper and the wind-induced responses, four frame damping coefficient C_f (Eq. (2)) are set to match the frame damping ratio $\xi_f(\omega_f)$ of 0%, 1%, 2%, and 5% at the initial natural frequency.

$$K_f = M\left(\frac{2\pi}{T_f}\right)^2 = M\omega_f^2 \tag{1}$$

$$C_f = 2M\omega_f\xi_f(\omega_f) \tag{2}$$



(a) Target building　　(b)SDOF model

Fig. 1. Target building

3. Fractional derivative (FD) model of the VE system

The FD model is a kind of complex numerical model of the VE damper, which is proposed by Kasai et al. (1993) [4]. The combination of the VE system is a parallel connection of the frame with damping and the added component. The storage stiffness $K'(\omega)$ and the loss factor $\eta(\omega)$ of the system are given by Eq. (3a, b).

$$K'(\omega) = K_f + K'_a(\omega) \tag{3a}$$

$$\eta(\omega) = \frac{\eta_a(\omega)}{1 + K_f/K'_a(\omega)} \tag{3b}$$

where, the added component is a series connection of a brace and a damper. The storage stiffness $K'_a(\omega)$, loss factor $\eta_a(\omega)$, and loss stiffness $K''_a(\omega)$ of the added component are given by Eq. (4a-c).

$$K'_a(\omega) = \frac{\{(1+\eta_d^2(\omega))K'_d(\omega) + K_b\}K'_d(\omega)K_b}{(K'_d(\omega)+K_b)^2 + (\eta_d(\omega)K'_d(\omega))^2} \tag{4a}$$

$$\eta_a(\omega) = \frac{\eta_d(\omega)}{1+(1+\eta_d^2(\omega))K'_d(\omega)/K_b} \tag{4b}$$

$$K''_a(\omega) = K'_a(\omega)\cdot\eta_a(\omega) \tag{4c}$$

Besides, the storage stiffness $K'_d(\omega)$ and loss factor $\eta_d(\omega)$ of the FD model are given by Eq. (5a, b).

$$K'_d(\omega)=G\frac{1+ab\omega^{2\alpha}+(a+b)\omega^{\alpha}\cos(\alpha\pi/2)}{1+a^2\omega^{2\alpha}+2a\omega^{\alpha}\cos(\alpha\pi/2)}\frac{A_s}{d} \tag{5a}$$

$$\eta_d(\omega)=\frac{(-a+b)\omega^{\alpha}\sin(\alpha\pi/2)}{1+ab\omega^{2\alpha}+(a+b)\omega^{\alpha}\cos(\alpha\pi/2)} \tag{5b}$$

where, A_s = area of VE material lamination, d = thickness of VE material lamination. In this paper, the 3M material ISD111 is adopted. Then, G = 3.92x10^4, a = 5.6x10^{-5}, b = 2.10, α = 0.558 [4]. The derivation of the A_s/d for the soft damper of the FD model is showed as follows:

Step 1. The stiffness of the frame is selected to calculate the initial natural frequency of the frame ω_f (Eq. (6a)).

Step 2. The loss factor of the damper $\eta_d(\omega_n{}^{(1)})$ is obtained by substituting the initial natural frequency $\omega_n{}^{(1)}$ into Eq. (5b), where superscript (1) means the iteration number.

Step 3. The stiffness of the added component $K'_d(\omega_n{}^{(1)})$ is derived by substituting $K'_d(\omega_n)$ and $\eta_d(\omega_n{}^{(1)})$ into Eq. (4a).

Step 4. Substituting $K'_d(\omega_n)$ into Eq. (3a) resulted in the stiffness of the system $K'(\omega_n{}^{(1)})$.

Step 5. The natural frequency (Eq. (6b)) of the system is obtained by substituting the $K'(\omega_n{}^{(1)})$. Finally, based on the numbers of iteration, the convergence of A_s/d can be achieved.

$$\omega_f=\sqrt{K_f/M}\quad,\ \omega_n^{(1)}=\sqrt{K'(\omega_f)/M} \tag{6a, b}$$

In addition, the natural frequency $f'_n(\omega)$, damping ratio $\xi'_n(\omega)$, are given by Eq. (7a, b).

$$f'_n(\omega)=\frac{1}{2\pi}\sqrt{K'(\omega)/M} \tag{7a}$$

$$\xi'_n(\omega)=\xi_f(\omega)+\frac{\eta(\omega)}{2}\cdot\frac{f'_n(\omega)}{2\pi\omega} \tag{7b}$$

where $$\xi_f(\omega)=\frac{C_f}{2M\omega} \tag{7c}$$

Besides, the damping coefficient $C'_n(\omega)$ of the VE system also have the frequency sensitivity, which is given by Eq. (8).

$$C'_n(\omega)=2M\omega\xi'_n(\omega) \tag{8}$$

4. Features of steady state-response of the VE system

Fig. (2) shows the effect of frame damping on the frequency sensitivity of the VE system. Fig. (2a-c) show that there's no influence of the frame damping on the storage stiffness of the damper K'_d, the loss factor of the damper η_d, and also the natural frequency f'_n. Fig. (2d, e) shows the influence of the frame damping on the frame damping ratio ξ_f and damping ratio of the system ξ'_n. It indicates that ξ'_n and ξ_f are increased as the frame damping increases. However, ξ'_n and ξ_f decreased as frequency increased. Fig. (2f) shows the influence of the frame damping on the damping coefficient C'_n. It indicates that C'_n is increased as the frame damping increases. Besides, C'_n increased as frequency increased. Where f_n is the resonance frequency of the system. $\xi'_n(f_n)$, $\xi_f(f_n)$, and $C'_n(f_n)$ considering their frame damping is indicated in Table 1.

Table 1. frequency sensitivity of parameters at f_n

ξ_f	$\xi'_n(f_n)$	$\xi_f(f_n)$	$C'_n(f_n)$ [kN/m]
0%	0.020	0.000	0.033
1%	0.025	0.010	0.048
2%	0.030	0.019	0.064
5%	0.044	0.048	0.111

5. Analytical wind

Fig. (3) shows examples of the 1st modal analytical wind force in the (a) along-wind and (b) across-wind directions in the time history. For the along-wind force, to avoid the transient response in time-history analysis, the first and last 50 s were modified by envelope. Fig. (4) shows the ten-ensemble-averaging normalized power spectral density (PSD) of the 1st modal analytical wind force, in the along-wind (in red) and across-wind (in blue) directions. The PSD of the along-wind had the high power of a wide band at low frequencies. In contrast, the normalized PSD of the across-wind had a peak close to the frequency of 0.1 Hz.

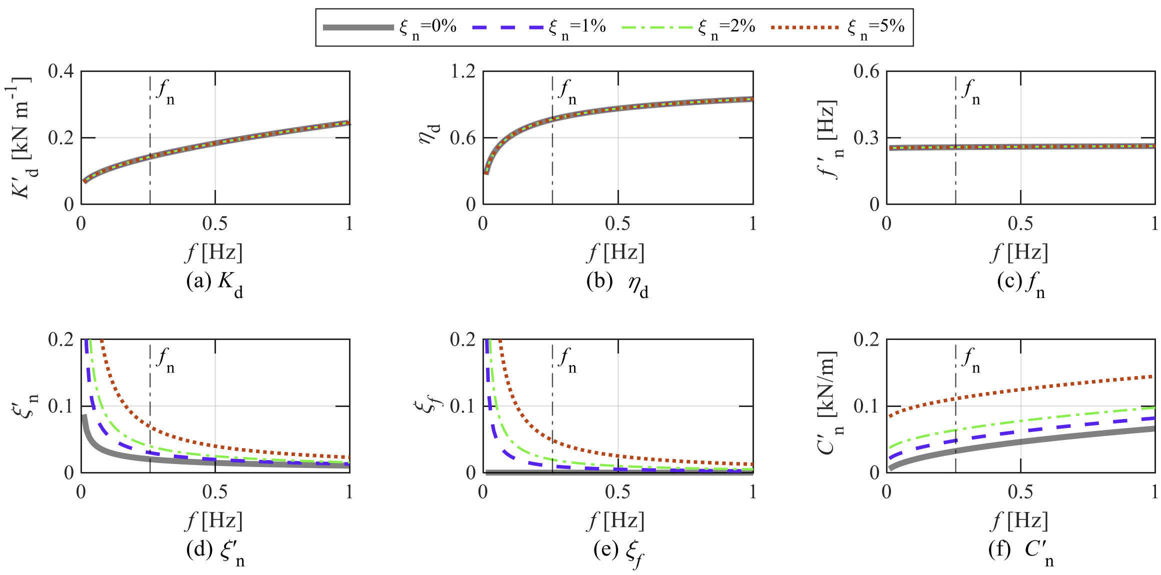


Fig. 2. Effect of frame damping on the frequency sensitivity of the VE system

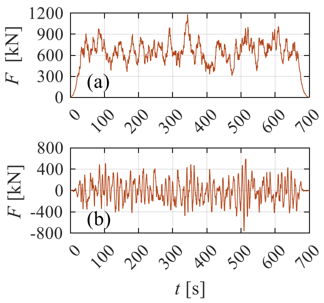


Fig. 3. Time history of wind force (a) along-wind, (b) across-wind

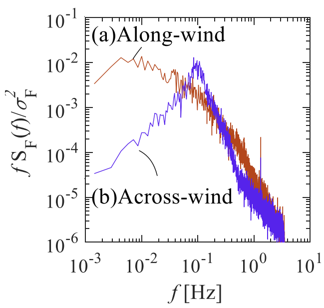
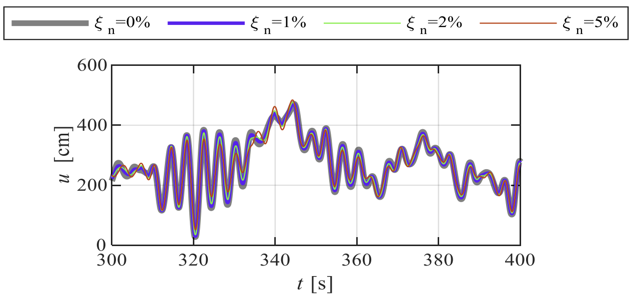


Fig. 4. Normalized PSD of wind force

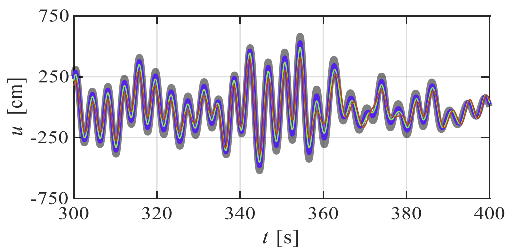
6. Effect of frame damping on wind-induced responses

6.1. Displacement, velocity, and acceleration

Fig. (5) shows wind-induced displacement subjected to the (a) along-wind and (b) across-wind. In the along-wind, the frame damping has a minor effect on the maximum displacement, but it has an obvious effect on the shape of the time history of the displacement. In contrast in the across-wind, the amplitude of the displacement is significantly affected by the frame damping.



(a) along-wind



(b) across-wind

Fig. 5. Wind-induced displacement (300-400s)

Fig. (6) indicates that there's no influence of frame damping on the mean displacement when subjected to the along-wind. Where, $\bar{u}_{,\mathrm{FD0}}$ is the mean displacement without frame damping. Fig. (7) and Fig. (8) express that the effect of frame damping on the standard deviation of the along- and across-wind displacement is minor, but it affects the standard deviation of velocity and acceleration obviously.

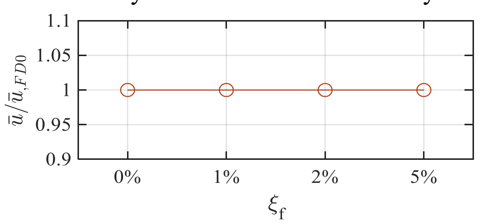


Fig. 6. Effect of frame damping on mean displacement (Along-wind)

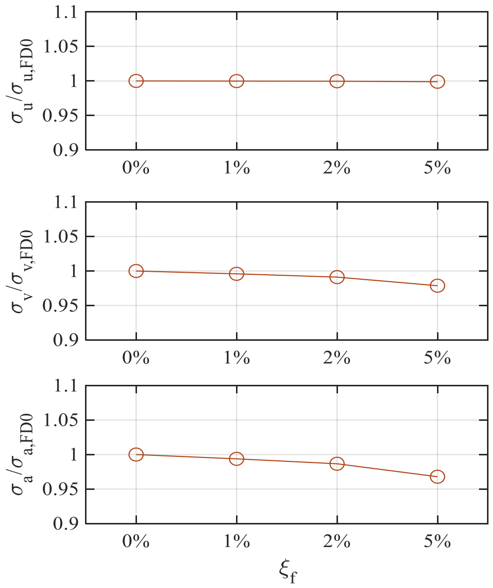


Fig. 7. Effect of frame damping on standard deviation (Along-wind)

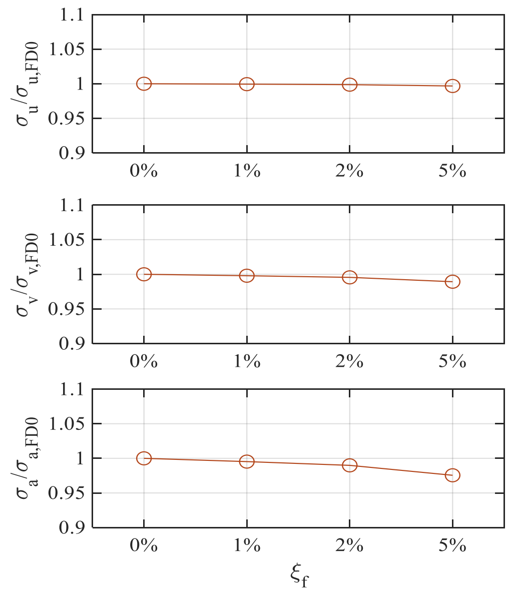


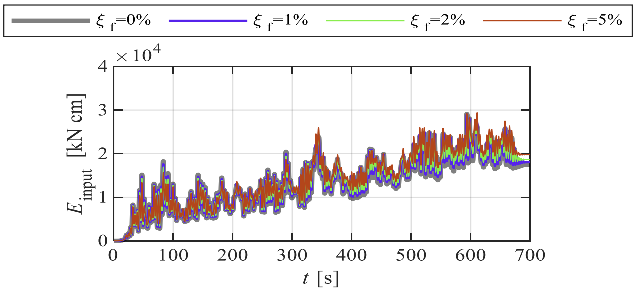
Fig. 8. Effect of frame damping on standard deviation (Across-wind)

6.2. Input energy

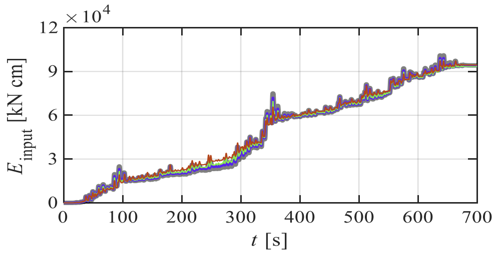
Fig. (9) shows the input energy subjected to the (a) along-wind and (b) across-wind. It expresses that the frame damping has obviously influence on the total input energy (E_{input}) when subjected to the along-wind. In contrast, it has minor influence on the total input energy when subjected to the across-wind. The equation for the total input energy is given by Eq. (9). Where $t0 = 700$ s of the total simulation time.

$$E_{\mathrm{input}} = \int_{t=0}^{t0} F(t)v(t)dt \tag{9}$$

Fig. (10) shows the effect of frame damping on input energy. It indicates that the total input energy increased as the frame damping increased when subjected to the along-wind, but there's no influence of frame damping on the total input energy when subjected to the across-wind.

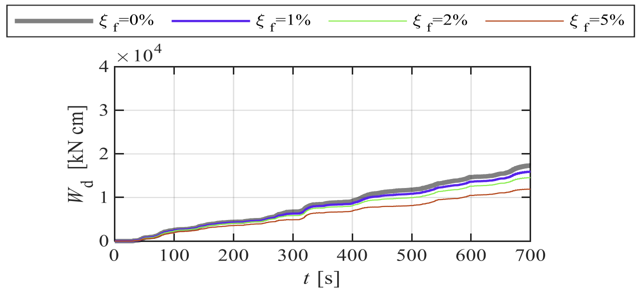


(a) along-wind

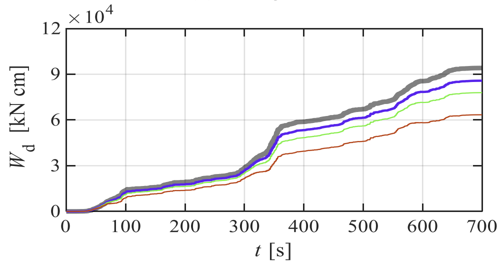


(b) across-wind

Fig. 9. Input energy



(a) along-wind



(b) across-wind

Fig. 11. Energy dissipation of the damper

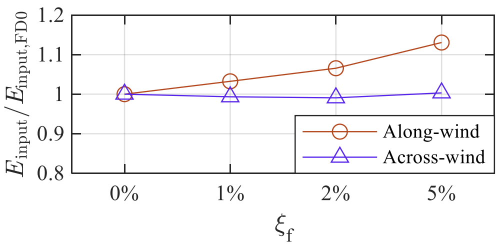


Fig. 10. Effect of frame damping on input energy

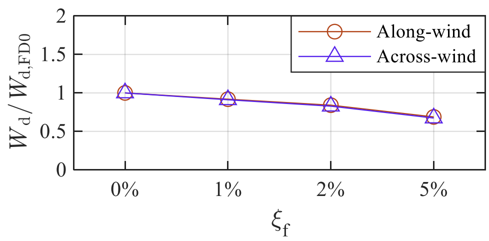


Fig. 12. Effect of frame damping on input energy

6.3. Energy dissipation of the damper

Fig. (11) shows the energy dissipation of the damper subjected to the (a) along-wind and (b) across-wind. It expresses that the frame damping has obviously influence on the total energy dissipation (W_{d}) when subjected to the along-wind and across-wind respectively. The equation for the total input energy is given by Eq. (10). Where $t0 = 700$ s of the total simulation time, F_d is the damper force, and v_d is velocity of the damper.

$$W_{\mathrm{d}} = \int_{t=0}^{t0} F_d(t) v_d(t) dt \tag{10}$$

Fig. (12) shows the effect of frame damping on input energy. It indicates that the total energy dissipation of the damper decreased as the frame damping increased when subjected to the along-wind and across-wind respectively.

7. Conclusions

This study compared the different frame damping to clarify the influence of frame damping on the frequency sensitivity and the wind-induced responses.

Results indicate that the frame damping influenced the velocity and acceleration responses obviously. In addition, input energy and energy dissipation are affected by the frame damping significantly.

Acknowledgement

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