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A prediction method for the total energy dissipation of the VE damper considering the coupling effect by the frame damping

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Viscoelastic damper Fractional derivative Energy dissipation
Wind-induced control High-rise building Frequency-domain method

## 1. Introduction

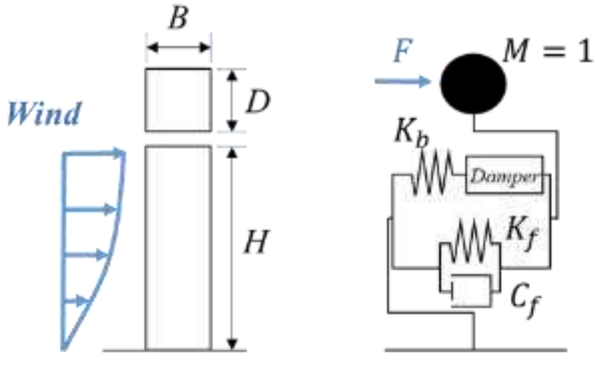
Viscoelastic (VE) damper used in high-rise buildings is one of the well-known passive control methods to reduce excessive vibrations and dissipate energy from wind excitations [1].

Sato et al. (2009) [2] proposed a prediction method for the wind-induced responses of the VE-damped high-rise building considering the effect of the frequency sensitivity of VE dampers. The proposed prediction method can reduce the simulation time for the long-period wind-induced response compared with the time history analysis. However, the prediction method for the energy dissipation of the VE damper was not considered in the said study. The long-term absorbed energy from wind excitation may reduce the performance of the VE damper. In addition, the neglected frame damping in the said study may affect the total energy dissipation of the VE damper.

The aim of this study is to propose a prediction method for the total energy dissipation of the VE damper considering the coupling effect by the frame damping.

## 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 ($\xi'_n(f_n) = 2\%$ without frame damping) are used in this study. 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.




(a) Target building (b)SDOF model
Fig. 1. Target building

$$K_f = M\left(\frac{2\pi}{T_f}\right)^2 = M\omega_f^2 \quad , \quad C_f = 2M\omega_f\xi_f(\omega_f) \qquad (1, 2)$$

## 3. Analytical wind

Fig. (2) 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. (3) shows the 10-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.

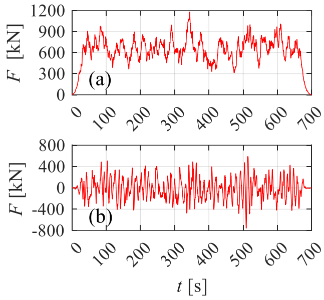



Fig. 2. Time history of wind force (a) along-wind, (b) across-wind

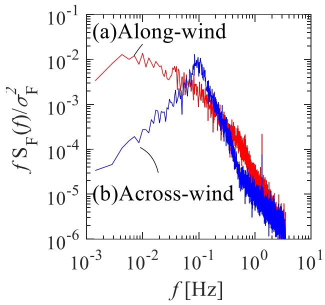



Fig. 3. Normalized PSD of wind force by 10-ensemble-averaging

## 4. Energy dissipation of the VE damper and its prediction method

### 4.1. Time history analysis results

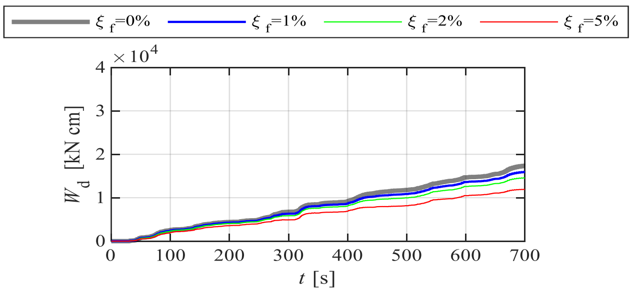
Fig. (4) shows the accumulated energy dissipation of the damper subjected to the (a) along-wind and (b) across-wind by the time history analysis (THA). It expresses that the frame damping has obviously influence on the total energy dissipation ($W_d$) when subjected to the along-wind and across-wind respectively. The equation for the total input energy is given by Eq. (3). Where $t0 = 700$ s of the total simulation time, $F_d$ is the damper force, and $v_d$ is velocity of the damper.

$$W_{d,THA} = \int_{t=0}^{t0} F_d(t)v_d(t)dt \qquad (3)$$

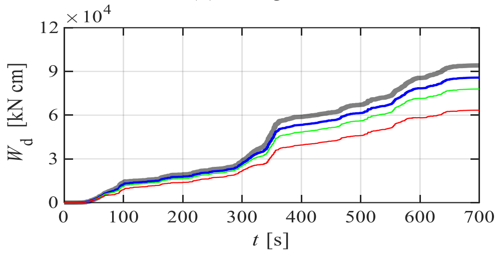
### 4.2. Prediction method

On the other hand, the equation for the total input energy of Eq. (3) can be rewritten into Eq. (4). Based on Eq. (4), the total energy dissipation of the damper ($W_d$) equals to total input energy ($E_{input}$) minus total energy dissipation of frame damping ($W_{fd}$). The prediction method of the total energy dissipation transferring into frequency domain of the damper is given by Eq. (5).

$$W_d = E_{input} - W_{fd} = \int_{t=0}^{t0} F(t)v(t)dt - C_f\int_{t=0}^{t0} v^2(t)dt \qquad (4)$$




(a) along-wind




(b) across-wind

Fig. 4. Energy dissipation of the damper

$$W_{\mathrm{d,Predi}} = t_0 \int_0^{\infty} Re[\dot{H}(n)]\widetilde{S_F}(n)dn - C_f \int_0^{\infty} \widetilde{S_V}(n)dn \tag{5}$$

where $\dot{H}^*(n)$ is conjugation of $\dot{H}(n)$, $n = \omega/2\pi$; $\widetilde{S_F}(n)$ is the 10-ensemble-averaging PSD of the 1st modal wind force, and the PSD of the 1st modal velocity response of the FD system is given by Eq. (6).

$$\widetilde{S_V}(n) = |\dot{H}(n)|^2\, \widetilde{S_F}(n) \tag{6}$$

In addition, the transfer function of displacement and velocity are given by Eq. (7) and Eq. (8).

$$H(n) = \frac{1}{1-\left(\frac{n}{f_n}\right)^2 + \frac{K'_a(n)}{K_f} + i\left(2\xi_f(n)\frac{n}{f_n} + \frac{K''_a(n)}{K_f}\right)}\frac{1}{K_f} \tag{7}$$

$$\dot{H}(n) = i2\pi\omega H(n) \tag{8}$$

where $f_n = \omega_n/2\pi$.

In Eq. (7), the storage stiffness $K'_a(n)$, loss factor $\eta_a(n)$, and loss stiffness $K''_a(n)$ of the added component are given by Eq. (9a-c).

$$K'_a(n) = \frac{\{(1+\eta_d^2(n))K'_d(n) + K_b\}K'_d(n)K_b}{(K'_d(n)+K_b)^2 + (\eta_d(n)K'_d(n))^2} \tag{9a}$$

$$\eta_a(n) = \frac{\eta_d(n)}{1+(1+\eta_d^2(n))K'_d(n)/K_b} \tag{9b}$$

$$K''_a(n) = K'_a(n)\cdot\eta_a(n) \tag{9c}$$

The storage stiffness $K'_d(n)$ and loss factor $\eta_d(n)$ of the FD model of the VE damper are given by Eq. (10a, b).

$$K'_d(n) = G\frac{1+abn^{2\alpha}+(a+b)n^{\alpha}\cos(\alpha\pi/2)}{1+a^2n^{2\alpha}+2an^{\alpha}\cos(\alpha\pi/2)}\frac{A_s}{d} \tag{10a}$$

$$\eta_d(n) = \frac{(-a+b)n^{\alpha}\sin(\alpha\pi/2)}{1+abn^{2\alpha}+(a+b)n^{\alpha}\cos(\alpha\pi/2)} \tag{10b}$$

where, $A_s$ = area of VE material lamination, $d$ = thickness of VE material lamination. In this paper, the 3M material ISD111 is adopted: $G = 3.92\times10^4$, $a = 5.6\times10^{-5}$, $b = 2.10$, $\alpha = 0.558$ [4].

Fig. (5) shows the accuracy of the prediction method of the energy dissipation of the VE damper. It indicates that the error of the prediction of the energy dissipation of the damper is less than 2 % in both along-wind and across-wind.

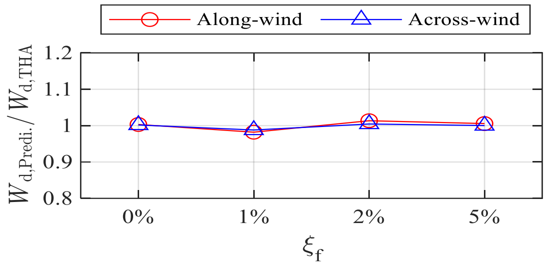



Fig. 5. Accuracy of prediction method

## 6. Conclusions

This study proposed a prediction method of the total energy dissipation of the VE damper with the influence of the frame damping. The proposed prediction method of the total energy dissipation has high accuracy within 2% error. The future work is to extend the range of this prediction method to the VE dampers with higher storage stiffness.

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