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Influence of Frequency-Sensitive VE Damper on Wind-Induced Energy Dissipated

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Wind excitation, Viscoelastic damper,

Kelvin system, Fractional derivative system,

1. Introduction

Equipping the high-rise building with viscoelastic (VE) dampers can be considered as an effective solution for the vibration control to reduce not only the wind response but also the seismic response. The function of the VE damper works is to dissipate the input energy for the building. Also, it can not only reduce the displacement response of a building but also ensure the comfort and safety of residents in the building.

Compare with all types among the dampers, the characteristic of VE damper is seen as a viscous damper with the storage stiffness that accompanied by frequency sensitivity. Besides, it can get the hysteresis loop of a tilted ellipse (Fig. 1.) when applying a sinusoidal wave on the damper. The influence on the wind response of frequency sensitivity for the VE damper proposed by Sato et al. (2009) [1]. However, the influence on the energy dissipated of frequency sensitivity of the VE damper didn't be discussed in the previous researches yet.

The purpose of this paper is to clarify the influence on the energy dissipated of the frequency sensitivity of the VE damper subjected to wind force. Based on the VE system with different frequency sensitivity, the fractional derivative (FD) system and Kelvin system were adopted to conduct the time history analysis under the across- and along-wind excitation. Finally, this paper emphasized the comparison of the energy dissipated between the FD system and Kelvin system under the across- and along-wind excitation.

2. Analytical Model

2.1. Building Model

The analytical model of the high rise building is a 10-degree-of-freedom model with the height $H_b = 200$ m, the width of the base, $B = D = 50$m with the density $\rho_s = 175\ \mathrm{kg/m^3}$.

Besides, there are 15 frames of 5 setups with 3-types (I, II, and III) of natural periods ($T_1 = 2, 4,$ and 6 sec) for the Kelvin and FD system. The first alphabet in the name of the frame is 'F' or 'K' that means the system belongs to 'FD system' or 'Kelvin system'; the number '1', '2', and '3' means 'Type I', 'Type II', and 'Type III'. The third alphabet of the setup is that the 'H' means 'Hard,' the 'S' means 'Soft,' and the 'W' means 'Weak' for the stiffness of the damper; the last alphabet of the setup is that the 'H' means 'Hard,' and the 'S' means 'Soft,' for the stiffness of the brace, which plots in Table. 1.

In this paper, the single degree-of-freedom models were conducted at condition of the 1st mode because of the response mainly based on the contribution in the 1st mode. Hence, the generalized mass ($M = 1$ kg), generalized stiffness of frame K_f were used.

2.2. Fractional Derivative System

The fractional derivative (FD) system of the type ISD 111 (Fig.2a.), which is mainly constructed by the storage stiffness $K'_d(\omega)$ (Eq.1a) and the loss factor $\eta_d(\omega)$ (Eq.1b), where ω is the circular frequency of a sinusoidal wave. The formula of the storage stiffness $K'_d(\omega)$ and loss factor $\eta_d(\omega)$ proposed by Kasai et al. (2006)[2]. The damping coefficient of the FD system C'_d shows in Eq.(2).

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

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

$$C'_d(\omega) = \frac{K'_d(\omega)\eta_d(\omega)}{\omega}. \tag{2}$$

Where, A_s = laminations of VE damper, d = thickness of VE material lamination, $G = 3.92 \times 10^4\ \mathrm{N/m^2}$, $a = 5.6 \times 10^{-5}$, $b = 2.10$, $\alpha = 0.558$.

Moreover, the storage stiffness $K'_a(\omega)$ and the loss factor $\eta_a(\omega)$ of added component is derived by the series connection of the brace and FD damper, which shows in Eq.(3).

$$K'_a(\omega) = \frac{\{(1+\eta_d^2(\omega))K'_d(\omega)+K_b\}K'_d(\omega)K_b}{(K'_d(\omega)+K_b)^2+(\eta_d(\omega)K'_d(\omega))^2}, \tag{3a}$$

$$\eta_a(\omega) = \frac{\eta_d(\omega)}{1+(1+\eta_d^2(\omega))K'_d(\omega)/K_b}. \tag{3b}$$

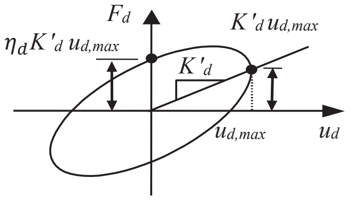
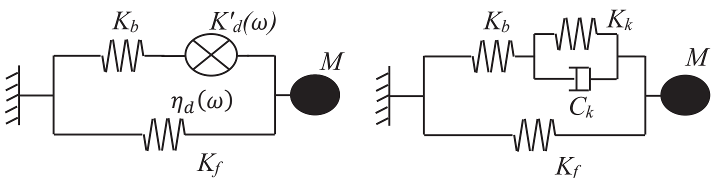


Fig.1. Hysteresis loop of a VE damper



(a) FD system　　(b) Kelvin system

Fig.2. (a) FD system and (b) Kelvin system

Table.1. Parameters in the Viscoelastic Damper

Type	K_f (N/m)	Damper	Brace	K_b (N/m)	ξ_n	f_n (Hz)	FD system	A_s/d (m)	Kelvin system	K_k (N/m)	C_k (N-s/m)
I	9.870	Hard	Hard	∞	0.311	0.866	F1-HH	1.1295E-04	K1-HH	19.74	3.379
		Soft			0.126	0.592	F1-SH	2.6533E-05	K1-SH	3.948	0.939
		Hard	Soft	29.61	0.121	0.777	F1-HS	1.1835E-04	K1-HS	19.74	3.715
		Soft			0.098	0.588	F1-SS	2.6607E-05	K1-SS	3.948	0.945
		Weak			0.020	0.512	F1-WS	3.5422E-06	K1-WS	0.497	0.134
II	2.467	Hard	Hard	∞	0.281	0.433	F2-HH	3.7592E-05	K2-HH	4.934	1.528
		Soft			0.112	0.296	F2-SH	8.6853E-06	K2-SH	0.987	0.418
		Hard	Soft	7.401	0.113	0.385	F2-HS	3.9326E-05	K2-HS	4.934	1.682
		Soft			0.088	0.293	F2-SS	8.7135E-06	K2-SS	0.987	0.421
		Weak			0.020	0.257	F2-WS	1.3182E-06	K2-WS	0.142	0.067
III	1.097	Hard	Hard	∞	0.261	0.289	F3-HH	1.9473E-05	K3-HH	2.193	0.947
		Soft			0.103	0.197	F3-SH	4.4504E-06	K3-SH	0.439	0.256
		Hard	Soft	3.290	0.107	0.256	F3-HS	2.0341E-05	K3-HS	2.193	1.043
		Soft			0.081	0.195	F3-SS	4.4656E-06	K3-SS	0.439	0.258
		Weak			0.020	0.172	F3-WS	7.4038E-07	K3-WS	0.070	0.045

Then, the storage stiffness $K'(\omega)$ and the loss factor $\eta(\omega)$ of the FD system is derived by the parallel connection of the frame and added component, which shows in Eq.(4).

$$K'(\omega)=K_f+K'_a(\omega) \quad , \quad \eta(\omega)=\frac{\eta_a(\omega)}{1+K_f/K'_a(\omega)} . \qquad (4a,b)$$

Besides, the natural circular frequency ω_n of the system can be obtained as Eq.(5). Then, the damping ratio ξ_n come out by Eq.(6).

$$\omega_n=2\pi f_n=\sqrt{K'(\omega_n)/M} \quad , \quad \xi_n=\eta(\omega_n)/2 . \qquad (5,6)$$

The derivation of the A_s/d of the FD system showed as follows. First, the stiffness of the frame was selected to calculate the initial natural frequency (Eq.7a). Then, the loss factor of a damper $\eta_d(\omega_n{}^{(1)})$ obtained by substituting the initial natural frequency $\omega_n{}^{(1)}$ into Eq.(1b), which the superscript (1) means the iteration number. Next, the stiffness of the added component $K'_a(\omega_n{}^{(1)})$ derived by substituting $K'_d(\omega_n)$ and $\eta_d(\omega_n{}^{(1)})$ into Eq.(3a). Also, by substituting $K'_a(\omega_n)$ into Eq.(4a) resulted in the stiffness of the system $K'(\omega_n{}^{(1)})$. Then, the natural frequency (Eq.7b) of the system obtained by substituting the $K'(\omega_n{}^{(1)})$. Finally, based on the numbers of iteration, the convergence of A_s/d can be achieved.

$$\omega_0=\sqrt{K_f/M} \quad , \quad \omega_n^{(1)}=\sqrt{K'(\omega_0)/M} . \qquad (7a,b)$$

2.3. Kelvin System

The Kelvin system (Fig. 2b.) is a system that combined with stiffness and damper in parallel connection, which has the same dynamic feature with the FD system while at its natural circular frequency ω_n. Therefore, the calculation of the storage stiffness of Kelvin system K_k and damping ratio of Kelvin system C_k came from the derivation of the FD damper, which shows in Eq.(8) and Eq.(9). Detail of parameters in the Kelvin system and FD system shows in Table.1.

$$K_k=K'_d=K'_d(\omega_n) \quad , \quad C_k=\eta_d(\omega_n)\cdot\omega_n/K_k . \qquad (8,9)$$

3. Comparison of the Frequency Sensitivity

Based on the previous sections 2.2 and 2.3, the FD system and Kelvin system were derived by equations clearly. It can be observed that the FD system with high-frequency sensitivity because of the derivation of the FD system contents frequency component (Eq. (2) ~Eq. (6)). According to Eq. (8) and Eq. (9), however, the Kelvin system has the same storage stiffness and damping with the FD system while at its natural frequency. That is, the Kelvin system has the same response as the FD system at its natural frequency of the system.

Therefore, to clarify the influence of frequency sensitivity of the FD and Kelvin system, the verification was conducted by applying sinusoidal waves at three different frequencies of natural frequency f_n, low frequency $0.5f_n$, and the high frequency $2f_n$ in the simulation.

As a result of the simulation, it emphasized that the fact of hysteresis loop under a sinusoidal wave at its natural frequency has good agreement in the FD and Kelvin system, which show in Fig.3. On the other hand, when applying a sinusoidal wave in lower frequency, the area of energy dissipated in a Kelvin system is less than the FD system. In contrast, when applying a sinusoidal wave in higher frequency, the area of energy dissipated in a Kelvin system is larger than the FD system.

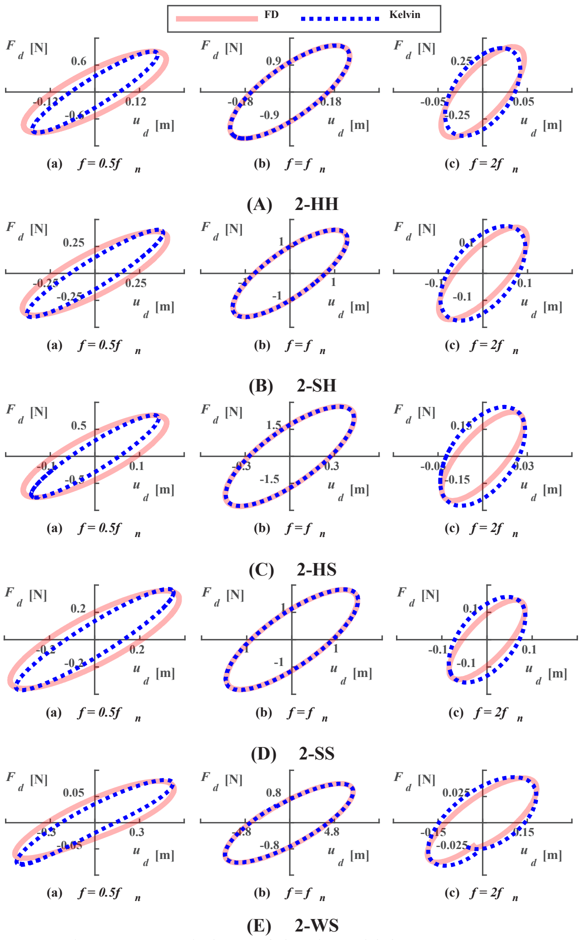


Fig.3. Hysteresis loop of the sinusoidal wave response

4. Wind Response

4.1. Analytical Wind Force

Based on the AIJ recommendations for Loads on Buildings (2015) [3], the wind tunnel experiment determines the analytical wind excitation, in which the terrain categories of the building set as III, and design the wind velocity of the 500-year return period. The envelopes adopt in the first 50 seconds and the end of 50 seconds to avoid the influence of transient response under the along-wind. Moreover, the analysis of this paper adopts wind data between 50 s to 650 s to obtain the responses of each model. The time history of the 1st mode along- and across-wind force shows in Fig. 4.

In addition, to observe the frequency component of the wind force, based on Fig.5, that can find the across-wind of its 1st mode with a peak of the power spectrum concentrated density close to its natural frequency. In contrast, the along-wind of its 1st mode has broadband in the power spectrum density.

4.2. Responses in the Along-Wind Force

Based on the simulations, the following are the results: Fig. 6 shows the hysteresis loop of the damper with a high damping ratio in (a) Kelvin system (K2-HH) and (b) FD system (F2-HH),

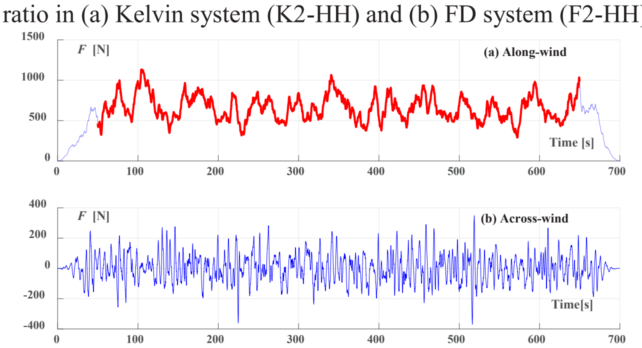


Fig.4. Time-history of wind force

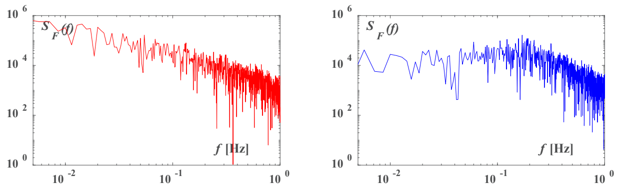


Fig.5. Power spectrum density of wind force

respectively. It shows that when the natural frequency of the system is high, the average displacement of the Kelvin system is less than that of the FD system because of the influence of the mean component in the along-wind force. In contrast, Fig.7 shows the hysteresis loop of the damper with a low damping ratio in (a) Kelvin system (K2-WS) and (b) FD system (F2-WS). It shows that when the natural frequency of the system is low, the average displacement of the Kelvin system is close to that of the FD system.

Fig.8 compares the maximum value, standard deviation σ, and the peak factor (PF=Maximum value/ Standard deviation) of the (a) displacement, (b) velocity, and (c) acceleration responses of the Kelvin and the FD systems. Based on Fig.8a, it shows that the higher the natural frequency of the system is, the more significant the difference of the maximum displacement between the Kelvin system and the FD system. Besides, the standard deviation of the displacement of the Kelvin system is smaller than which of the FD system; for example, the standard deviation of the displacement of the K1-HH model is about 0.52 times as the F1-HH model. However, the difference of the peak factor between the Kelvin system and the FD system is less than 20%.

Based on Fig.8b and Fig.8c, no matter the natural frequency is high or low, the difference of the maximum value, standard deviation, and the peak factor of the velocity and acceleration are less than 20%.

4.3. Responses in the Across-Wind Force

Based on the simulation subjected to the across-wind force, the analysis results show as follows: Fig.9 and Fig.10 show a good agreement in hysteresis loop between the Kelvin system and the FD system due to the frequency component in the across-wind force concentrated on the natural frequency of the system (0.2~0.9 Hz).

In Fig.11a, it shows that the higher the natural frequency of the system is, the more significant the difference of the maximum displacement and the standard deviation of the displacement between the Kelvin system and the FD system. Besides, Fig.11b and Fig.11c shows that no matter the natural frequency is high or low, the error of the maximum value, standard deviation, and the peak factor of the velocity and acceleration are less than 20%.

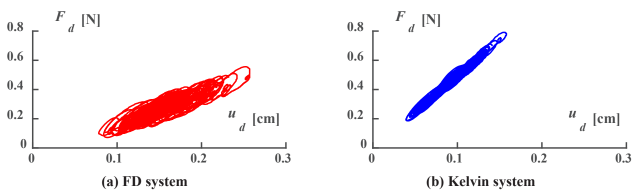


Fig.6. Hysteresis loop of the along-wind response (2-HH)

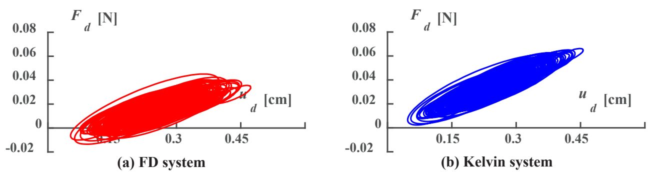


Fig.7. Hysteresis loop of the along-wind response (2-WS)

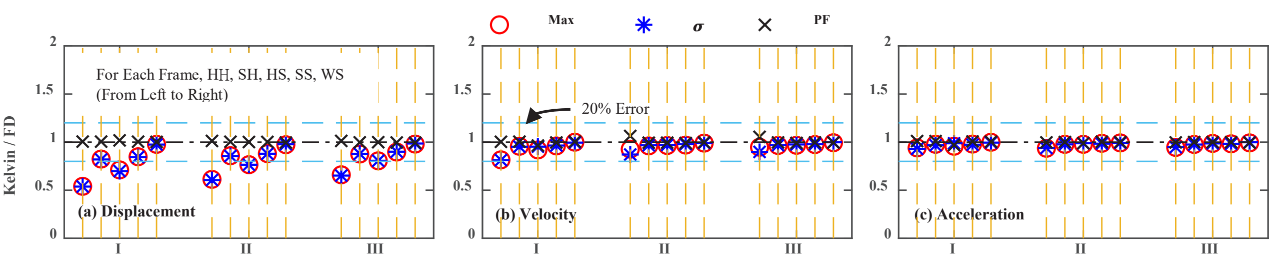


Fig.8. Comparison in response of the FD system and Kevin system (Along-wind)

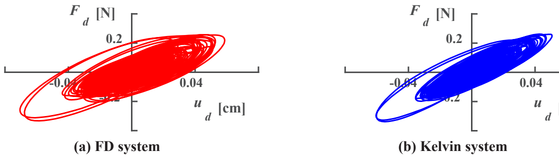


Fig.9. Hysteresis loop of the across-wind response (2-HH)

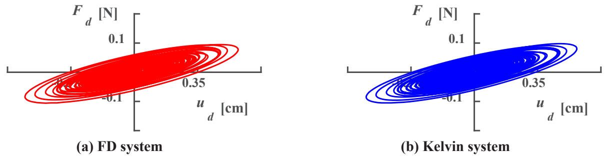


Fig.10. Hysteresis loop of the across-wind response (2-WS)

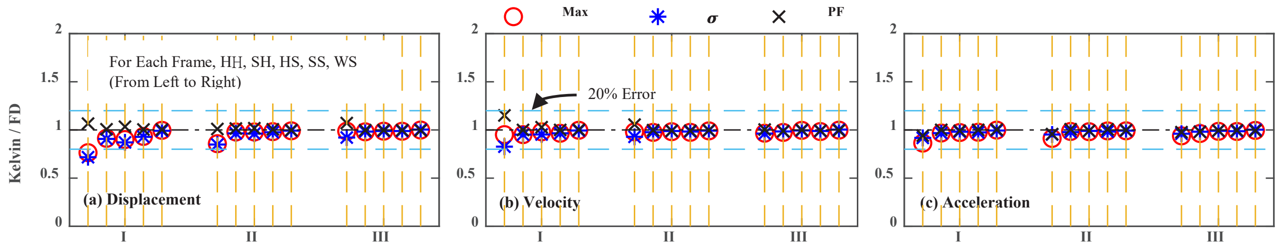


Fig.11. Comparison in response of the FD system and Kevin system (Across-wind)

4.4. Energy Dissipated

Fig.12 shows that the time variation of energy dissipated E_d subjected to wind force (along-wind and the across-wind). It can observe that when the natural frequency of the system is high, the accumulated energy dissipated of the Kevin system is less than the FD system. On the other hand, when the natural frequency of the system is low, the accumulated energy dissipated matches well between the Kevin system and the FD system. Based on Fig.13, when the system with the high natural frequency which subjected to the along-wind force, the energy dissipated efficiency of the Kelvin system is about 0.7~0.8 times to the FD system. However, the lower the natural frequency is, the better the accumulated energy dissipated matches between the Kevin system and the FD system.

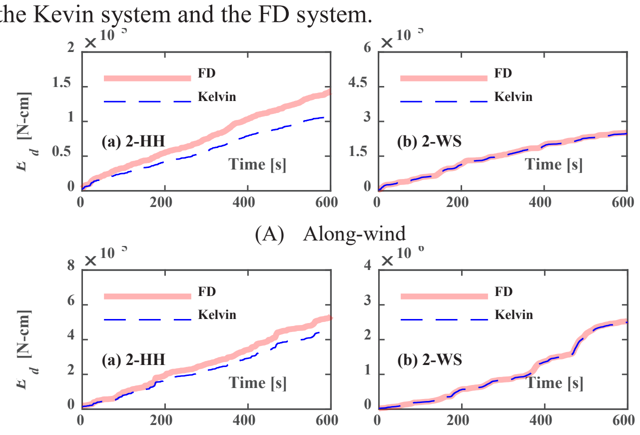


Fig.12. Time variation of energy dissipated

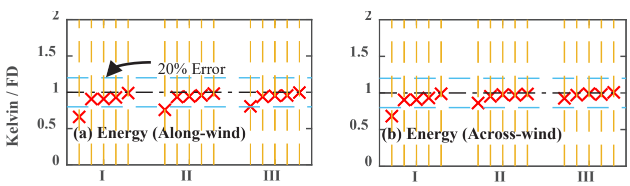


Fig.13. Comparison in total energy dissipated

5. Conclusions

This paper presented the comparison of wind response between the FD system and the Kelvin system. Due to the frequency sensitivity is a significant characteristic in an FD system, some simulations were conducted to clarify the influence of frequency sensitivity. This paper emphasized four points as follows:

(1) The average displacement of the Kelvin system is less than that of the FD system because of the influence of the mean component in the along-wind force when the natural frequency of the system is high.

(2) The hysteresis loop has a good agreement between the Kelvin system and FD system under the across-wind because the frequency component of the across-wind is concentrated on the natural frequency of the system.

(3) The accumulated energy dissipated of the Kevin system is less than the FD system when the natural frequency of the system is high.

(4) The accumulated energy dissipated matches well between the Kevin system and the FD system when the system with the low natural frequency which subjected to the along-wind force.

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