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著者(和文)	CHANG Ting-Wei, 佐藤 大樹
Authors(English)	Ting-Wei CHANG, Daiki Sato
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COMPARISON IN WIND-INDUCED RESPONSE OF THE SIMPLIFIED VE DAMPERS CONSIDERING FREQUENCY-SENSITIVITY

Ting-Wei CHANG¹⁾, Daiki SATO²⁾

ABSTRACT

This research evaluated the wind-induced response along with the energy dissipation of the simplified VE damper systems considering the influence of frequency-sensitivity. To improve the reliability of the simplified VE damper system subjected to wind excitation. In this paper, some simplified numerical models were used, as the Kelvin model and the Maxwell model, to simulate the Fraction Derivative (FD) model in dynamic analysis. As a result, the comparison of the energy dissipation among the FD system, Kelvin system, and the Maxwell system subjected to the along- and across-wind force was discussed. Then, the aerodynamic feature of the frequency-sensitive VE damped systems can be clearly understood from this study.

Key Words: VE damper, wind excitation, frequency sensitivity

1. INTRODUCTION

Viscoelastic (VE) damper is one kind of passive control system widely used in the high-rise building to dissipate energy from vibration, which is accompanied by the frequency-sensitivity, needs to consider the efficiency of the energy dissipation subjected to the external force. It can reach a hysteresis loop of a tilted ellipse in the $F_d - u_d$ diagram (Fig. (1)) when applying a harmonic wave on the damper, where F_d and u_d are force and displacement of a damper; K'_d and η_d is the storage stiffness and the loss factor of a damper. In addition, the VE damper usually used some simplified numerical models, as the Kelvin model and the Maxwell model, and the Fraction Derivative (FD) model in the dynamic analysis¹⁾ (Fig. (2)).

In the previous papers, the influence on the wind-induced response of the frequency-sensitivity for the VE damper has discussed by Sato et al. (2009)²⁾. However, the analytical wind force by the Auto Regression method²⁾ was used in the previous paper, and the influence on the energy dissipated of the 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 of the frequency-sensitivity on the wind-induced response and the energy dissipation of the VE damper. The analytical wind force came from wind tunnel test³⁾. According to the difference of the frequency sensitivity among VE damped systems, the FD system, Kelvin system, and the Maxwell system, the time history analysis under the along- and across-wind excitation were employed. Finally, this paper discussed the comparison of wind-induced responses and the energy dissipation among the FD system, Kelvin system, and the Maxwell system subjected to the along- and across-wind force.

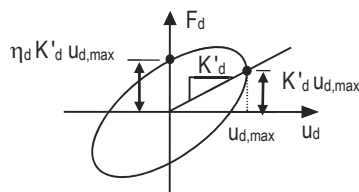


Fig. 1. hysteresis loop of a VE damper

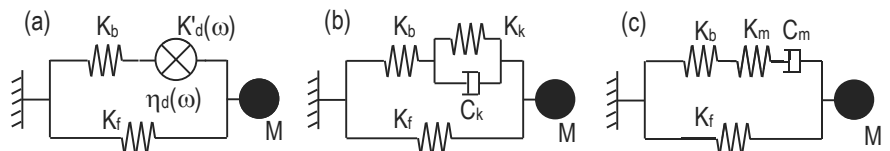


Fig. 2. (a)FD system, (b)Kelvin system, (c)Maxwell system

2. ANALYTICAL WIND

This paper uses along-wind forces with a return period of 500 years. Wind force is determined using wind tunnel tests³⁾. The airflow in the experiment is determined by referring to the building design load in Japan (terrain: III, directional angle: 0 degree)⁴⁾. The target building is a 200 m height with an aspect ratio of 5.0, whose $D=B=40$ m. The design wind velocities of the 500-year-return period is 57.9 m/s. The number of data are 14,000 with the time step $\Delta t = 0.05$ sec, the total time $T_a = 700$ sec. 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. Fig. (3) shows the time history of the 1st mode analytical along- and across-wind forces in the time domain. The along-wind has mean component of the wind force; in contrast, the across-wind does not have the mean component. In addition, Fig. (4) shows the power spectral density (PSD) of the 1st mode analytical

along- and across-wind forces. The across-wind has the peak around 0.1 Hz of the PSD. The PSD of the along-wind leads to a smooth curve. Where S_F is the power spectral of wind force, and σ_F^2 is the variance of wind force.

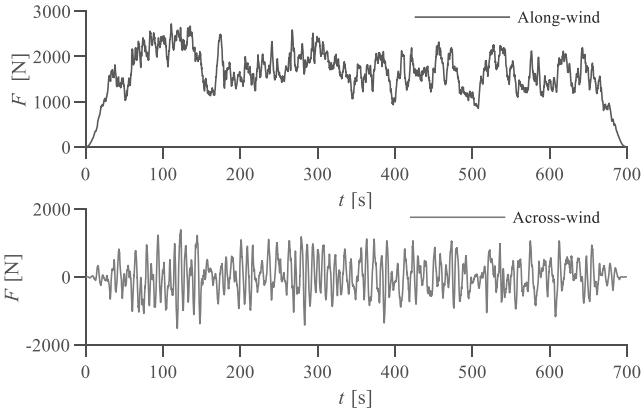


Fig. 3. Time history of the 1st mode analytical wind force

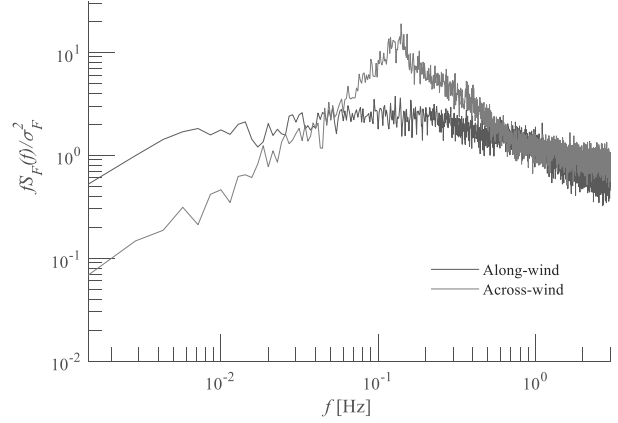


Fig. 4. PSD of the 1st mode analytical wind force

3. VISCOELASTIC (VE) DAMPED SYSTEMS

VE material is a kind of material that performs as elastic behavior within the yield limit and also performs a plastic behavior when out of the yield limit¹⁾. The hysteresis of the VE damper under a harmonic wave tends to a tilt ellipse shape (Fig. (1)). Three kinds of VE damper are discussed in this research. Table.1 indicated 45 models that consist of the fractional derivative (FD) system, Kelvin system, and Maxwell system for the analysis. It can be separated into 3-groups (1H, 2H, and 3H) by natural periods of frame ($T_1 = 2, 4, \text{ and } 6 \text{ sec}$). In addition, there are 3 kinds of damper (hard: ‘H,’ soft: ‘S,’ and weak: ‘W’) and 2 kinds of brace stiffness (hard: ‘H’ and soft: ‘S’) considered.

Table.1. Parameters for the FD system, Kelvin system, and Maxwell system

Group	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)	Maxwell system	K_M (N/m)	C_M (N-s/m)
I	9.870	Hard	Hard	∞	0.311	0.866	F1H-HH	1.1295E-04	K1H-HH	19.74	3.379	M1H-HH	36.87	7.274
				∞	0.126	0.592	F1H-SH	2.6533E-05	K1H-SH	3.948	0.939	M1H-SH	7.038	2.139
		Soft	Soft	29.61	0.121	0.777	F1H-HS	1.1835E-04	K1H-HS	19.74	3.715	M1H-HS	36.40	8.116
				29.61	0.098	0.588	F1H-SS	2.6607E-05	K1H-SS	3.948	0.945	M1H-SS	7.035	2.153
				29.61	0.020	0.512	F1H-WS	3.5422E-06	K1H-WS	0.497	0.134	M1H-WS	0.871	0.312
II	2.467	Hard	Hard	∞	0.281	0.433	F2H-HH	3.7592E-05	K2H-HH	4.934	1.528	M2H-HH	8.437	3.680
				∞	0.112	0.296	F2H-SH	8.6853E-06	K2H-SH	0.987	0.418	M2H-SH	1.599	1.092
		Soft	Soft	7.401	0.113	0.385	F2H-HS	3.9326E-05	K2H-HS	4.934	1.682	M2H-HS	8.289	4.155
				7.401	0.088	0.293	F2H-SS	8.7135E-06	K2H-SS	0.987	0.421	M2H-SS	1.596	1.104
				7.401	0.020	0.257	F2H-WS	1.3182E-06	K2H-WS	0.142	0.067	M2H-WS	0.224	0.182
III	1.097	Hard	Hard	∞	0.261	0.289	F3H-HH	1.9473E-05	K3H-HH	2.193	0.947	M3H-HH	3.541	2.487
				∞	0.103	0.197	F3H-SH	4.4504E-06	K3H-SH	0.439	0.256	M3H-SH	0.668	0.747
		Soft	Soft	3.290	0.107	0.256	F3H-HS	2.0341E-05	K3H-HS	2.193	1.043	M3H-HS	3.476	2.825
				3.290	0.081	0.195	F3H-SS	4.4656E-06	K3H-SS	0.439	0.258	M3H-SS	0.667	0.756
				3.290	0.020	0.172	F3H-WS	7.4038E-07	K3H-WS	0.070	0.045	M3H-WS	0.104	0.138

3.1. FRACTIONAL DERIVATIVE SYSTEM

The FD system of the type ISD 111 (Fig.2a.), which combined with the storage stiffness $K'_d(\omega)$ (Eq.1a) and the loss factor $\eta_d(\omega)$ (Eq.1b), where ω is the circular frequency. The formula of the storage stiffness $K'_d(\omega)$ and loss factor $\eta_d(\omega)$ of the damper proposed by Kasai et al. (2006)⁵⁾. The damping coefficient of the FD system C'_d is given by Eq.(2).

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

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

Where, A_s =laminations of VE damper, d =thickness of VE material lamination, $G=3.92 \times 10^4 \text{ N/m}^2$, $a=5.6 \times 10^{-5}$, $b=2.10$, $\alpha=0.558$. The storage stiffness $K'_d(\omega)$ and the loss factor $\eta_d(\omega)$ of added component are derived by the series connection of the brace and FD damper, which is given by Eq.(3). Where K_b is stiffness of the brace.

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

Then, the storage stiffness $K'(\omega)$ and the loss factor $\eta(\omega)$ of the FD system are derived by the parallel connection of the frame and added component, which is given by Eq.(4). The f_n and ξ_n is given by Eq.(5).

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

$$f_n = \frac{1}{2\pi} \sqrt{K'_d(\omega) / M}, \quad \xi_n = \eta(\omega) / 2. \quad (5a,b)$$

3.2. KELVIN SYSTEM

The Kelvin system (Fig. 2b.) is a system that consists of spring and dash-pot in parallel connection, which has the same dynamic feature (K'_d and η_d) with the FD system while at its natural circular frequency ω_n . The calculation of the storage stiffness of the Kelvin system K_k and damping ratio of Kelvin system C_k come from the derivation of the FD damper, which is given by Eq.(6).

$$K'_d(\omega) = K'_d = K_k, \quad \eta_d(\omega) = C_k \cdot \omega_n / K_k. \quad (6a,b)$$

3.3. MAXWELL SYSTEM

The Maxwell system (Fig.2c) is a system that consists of spring and dash-pot in series connection, which also has the same dynamic feature (K'_d and η_d) with the FD system while at its natural circular frequency ω_n . The calculation of the storage stiffness of the Maxwell system K_m and damping ratio of the Maxwell system C_m came from the derivation of the FD damper, which is given by Eq.(7).

$$K'_d(\omega) = \frac{K_m (C_m \omega)^2}{K_m^2 + (C_m \omega)^2}, \quad \eta_d(\omega) = \frac{K_m^2 C_m \omega}{K_m (C_m \omega)^2} \quad (7a,b)$$

3.4. INFLUENCE OF FREQUENCY-SENSITIVITY

Figure (5) shows the relationship of the dynamic feature (K'_d and η_d) and frequency-sensitivity among three types of the VE damper, the FD, Kelvin, and Maxwell. Here indicates that the storage stiffness of the damper is the same among systems at their natural frequency. However, the increased frequency leads to an increased storage stiffness for the FD and Kelvin systems. In contrast, the lower frequency leads to a massive difference of the storage stiffness among systems. On the other hand, the loss factor of the damper is the same among systems at their natural frequency. However, the loss factor of the Kelvin system has better agreement with the FD system than that of the Maxwell system at lower frequency. In contrast, the higher frequency leads to a massive difference of the loss factor among systems.

Figure (6) shows the hysteresis loops of the harmonic response, whose (a) means the harmonic wave of $f = 0.5f_n$ applying on systems, (b) means the harmonic wave of $f = f_n$ applying on systems, and (c) means the harmonic wave of $f = 2f_n$ applying on systems. In addition, Fig. (6) also indicates the hysteresis loops have a great agreement among systems when the frequency of the sinusoidal wave is equal to the natural frequency of the system. When applying the harmonic wave at lower frequency, the area of the hysteresis of the Maxwell system is bigger than the FD system, and also bigger than the Kelvin system. In contrast, when applying the sinusoidal wave higher frequency, the area of the hysteresis of the Maxwell system is less than the FD system, and less than the Kelvin system.

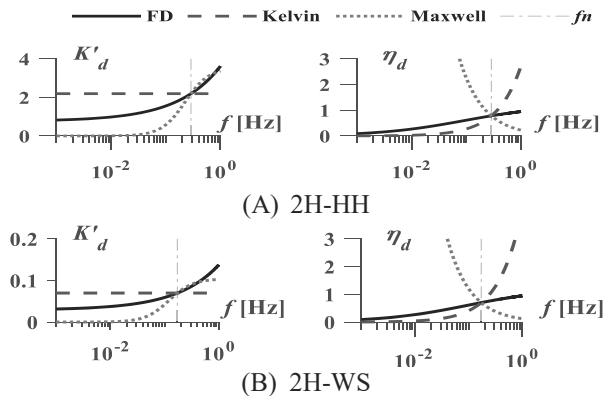


Fig.5. Frequency-Sensitivity of 2H-HH Systems

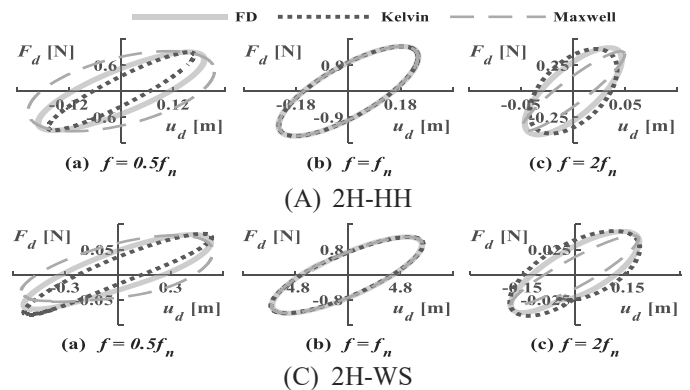


Fig.6. Hysteresis loops of the harmonic wave response

4. RESULTS

4.1. WIND-INDUCED RESPONSE OF THE FRACTIONAL DERIVATIVE SYSTEM

Figure (7) shows the dimensionless PSD of along-wind response of displacement, velocity, and acceleration of the F2H-HH and F2H-WS system. The high system damping leads to low power at the natural frequency of the displacement. Besides, there is a peak at the natural frequency of the velocity and acceleration. The peak of the F2H-WS system is sharper than that of the F2H-HH system. Then, Fig. (8) shows the dimensionless PSD of across-wind response. The high system damping leads to low power at the natural frequency of the displacement. Besides, there is a peak with a narrow band at the natural frequency of the velocity and acceleration. The peak of the F2H-WS system is sharper than that of the F2H-HH system. Where, σ_D^2 , σ_V^2 , σ_A^2 is the variance of the displacement, velocity, acceleration, and the broken line is the natural frequency of systems.

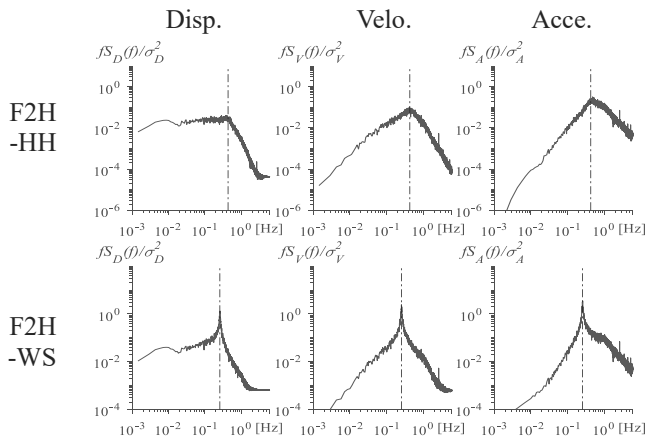


Fig.7. PSD of along-wind response of FD Systems

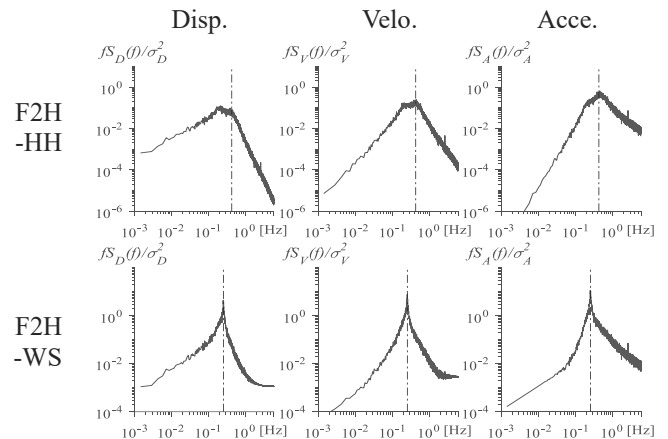


Fig.8. PSD of across-wind response of FD Systems

4.2. COMPARISON IN ALONG-WIND-INDUCED RESPONSE

Figure (9) shows the hysteresis loop of the damper with a high damping ratio in (a) FD system (F2H-HH), (b) Kelvin system (K2H-HH), and (c) Maxwell system (M2H-HH), which indicates that when the natural frequency of the system is high, the area of the hysteresis loop of the Kelvin model is less than that of the FD model. In contrast, the area of the hysteresis loop of the Maxwell model is larger than that of the FD model. Besides, Fig. (10) shows the hysteresis loop of the damper with a low damping ratio in (a) FD system (F2H-WS), (b) Kelvin system (K2H-WS), and (c) Maxwell system (M2H-WS), which indicates that when the natural frequency of the system is low, the area of the hysteresis loop of the Kelvin model is close to that of the FD model and that of the Maxwell model.

Figure (11) shows the comparison of the along-wind response in (a) displacement, (b) velocity, and (c) acceleration between the Kelvin system and the FD system. The maximum value, standard deviation σ , mean value μ , and the peak factor (PF=Maximum value/ Standard deviation) and considered in the analysis, whose Fig. (11a) shows that the high natural frequency of the system leading to a massive difference of the maximum displacement and the average displacement between the Kelvin system and the FD system. Also, the standard deviation of the displacement of the Kelvin system is smaller than that of the FD system. The difference of the peak factor between the Kelvin system and the FD system is less than 20%. Fig. (11b, c) shows that 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%.

Figure (12) shows the comparison of the along-wind response in (a) displacement, (b) velocity, and (c) acceleration between the Maxwell system and the FD system. Fig. (12a) shows that the high natural frequency of the system leading to a massive difference of the maximum displacement and the average displacement between the Maxwell system and the FD system, which is also bigger than that of Kelvin system. However, the standard deviation of the displacement of the Maxwell system is bigger than that of the FD system. The difference of the peak factor between the Kelvin system and the FD system is also less than 20%. Fig. (12b, c) shows that as the natural frequency is lower, the difference of the maximum value, standard deviation, and the peak factor of the velocity and acceleration are small, which is less than 20%. The along-wind responses also have the same trend as results from Sato et al. (2009)².

Fig.13 shows that the accumulated energy-dissipated of the Kelvin system is under-evaluated than which of FD system; in contrast, the accumulated energy-dissipated of the Maxwell system is over-evaluated than which of FD system. For 2H-WS models, it had a high agreement of accumulated energy dissipated among these three damper systems. Fig.14 shows that the total energy-dissipated of the Kelvin system matches well to the FD system. However, the total energy-dissipated of the Maxwell system relies on its frequency-sensitivity. If the natural frequency of the system is higher, the energy-dissipated of the Maxwell system is over-evaluated.

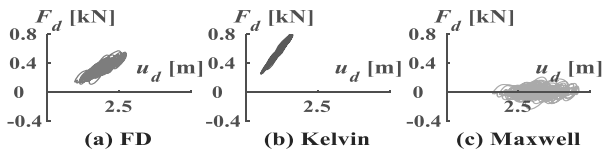


Fig.9. Hysteresis loop of along-wind response (2H-HH)

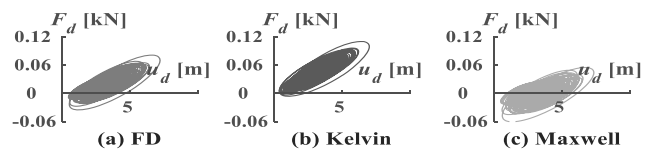


Fig.10. Hysteresis loop of along-wind response (2H-WS)

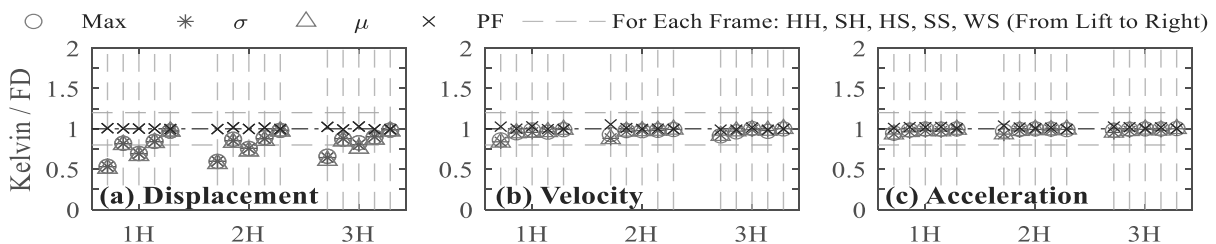


Fig.11. Comparison in along-wind response of the FD system and Kelvin system

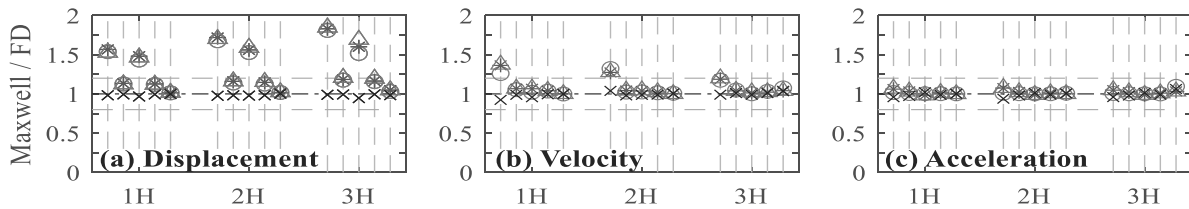


Fig.12. Comparison in along-wind response of the FD system and Maxwell system

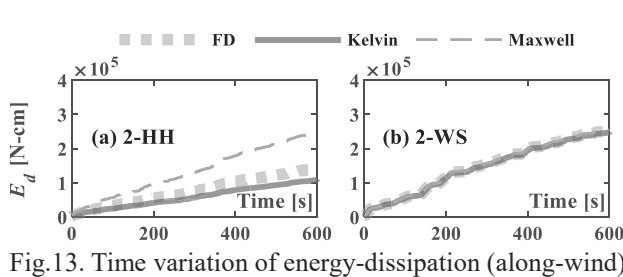


Fig.13. Time variation of energy-dissipation (along-wind)

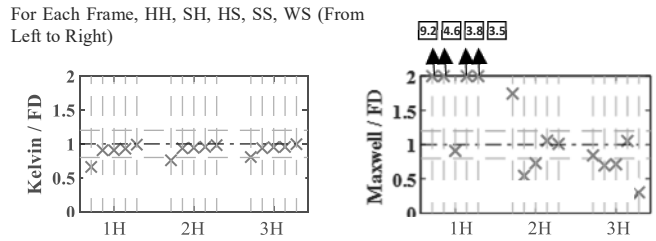


Fig.14. Comparison in total energy-dissipation (along-wind)

4.3. COMPARISON IN ACROSS-WIND-INDUCED RESPONSE

Figure (15) shows the hysteresis loop of the damper with a high damping ratio in (a) FD system (F2H-HH), (b) Kelvin system (K2H-HH), and (c) Maxwell system (M2H-HH), which indicates that when the natural frequency of the system is high, the area of the hysteresis loop of the Kelvin model is less than that of the FD model. In contrast, the area of the hysteresis loop of the Maxwell model is larger than that of the FD model. Besides, Fig. (16) shows the hysteresis loop of the damper with a low damping ratio in (a) FD system (F2H-WS), (b) Kelvin system (K2H-WS), and (c) Maxwell system (M2H-WS), which indicates that when the natural frequency of the system is low, the area of the hysteresis loop of the Kelvin model is matching to that of the FD model and that of the Maxwell model.

Figure (17) shows the comparison of the across-wind response in (a) displacement, (b) velocity, and (c) acceleration between the Kelvin system and the FD system. The maximum value, standard deviation σ , and the peak factor (PF=Maximum value/ Standard deviation) and considered in the analysis, whose Fig. (17a) shows that the high natural frequency of the system leading to a massive difference of the maximum displacement between the Kelvin system and the FD system. Also, the standard deviation of the displacement of the Kelvin system is smaller than that of the FD system. The difference of the peak factor between the Kelvin system and the FD system is less than 20%. Fig. (17b, c) shows that 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%.

Figure (18) shows the comparison of the across-wind response in (a) displacement, (b) velocity, and (c) acceleration between the Maxwell system and the FD system. Fig. (18a) shows that the high natural frequency of the system leading to a massive difference of the maximum displacement between the Maxwell system and the FD system, which is also bigger than that of Kelvin system. However, the standard deviation of the displacement of the Maxwell system is bigger than that of the FD system. The difference of the peak factor between the Kelvin system and the FD system is also less than 20%. Fig. (18b, c) shows that as the natural frequency is lower, the difference of the maximum value, standard deviation, and the peak factor of the velocity and acceleration are small, which is less than 20%. The across-wind responses also have the same trend as results from Sato et al. (2009)².

Fig.(19) shows that the accumulated energy-dissipated of the Kelvin system is under-evaluated than which of FD system; in contrast, the accumulated energy-dissipated of the Maxwell system is over-evaluated than which of FD system. For 2H-WS models, it had a high agreement of accumulated energy dissipated among these three damper systems. Fig. (20) shows that the total energy-dissipated of the Kelvin system matches well to the FD system. However, the total energy-dissipated of the Maxwell system relies on its frequency-sensitivity. If the natural frequency of the system is higher, the energy-dissipated of the Maxwell system is over-evaluated.

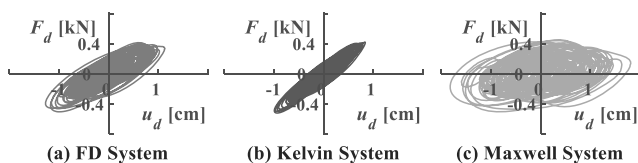


Fig.15. Hysteresis loop of across-wind response (2H-HH)

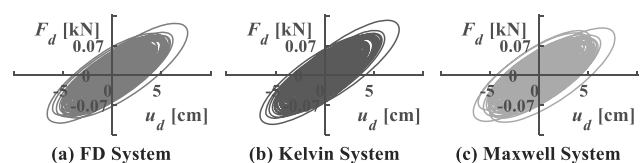


Fig.16. Hysteresis loop of across-wind response (2H-WS)

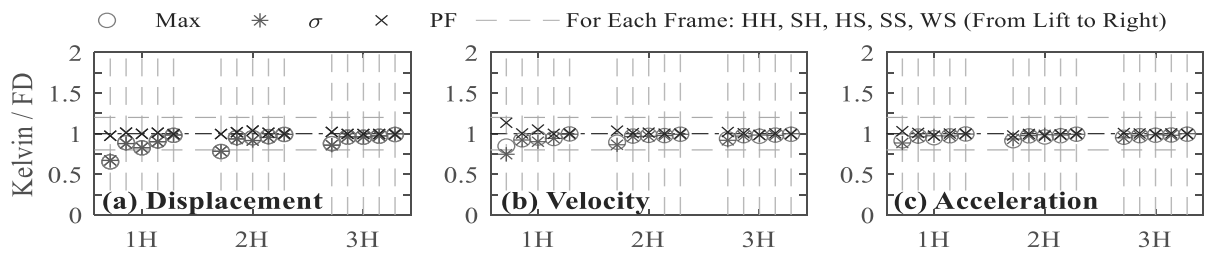


Fig.17. Comparison in across-wind response of the FD system and Kelvin system

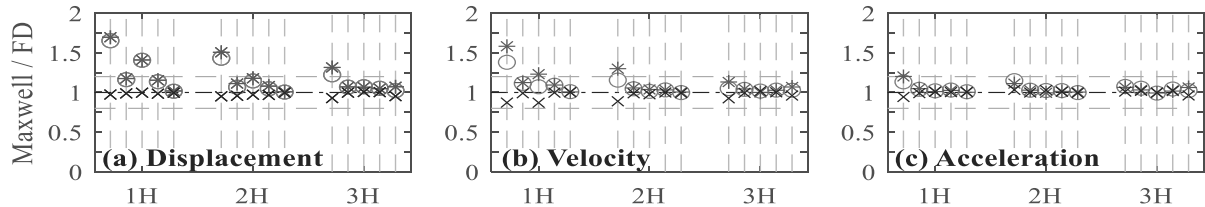


Fig.18. Comparison in across-wind response of the FD system and Maxwell system

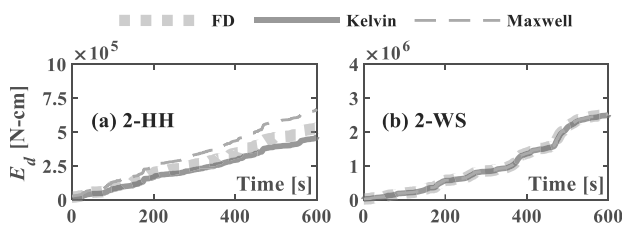


Fig.19. Time variation of energy-dissipation (across-wind)

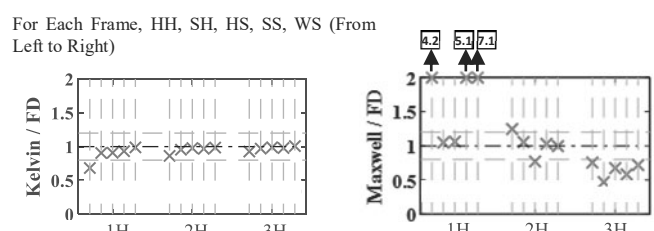


Fig.20. Comparison in total energy-dissipation (across-wind)

5. CONCLUSIONS

This paper presented the dynamic features of wind-induced response among the FD, Kelvin, and Maxwell, considering the frequency-sensitivity of the VE damped system. There are four points emphasized in conclusions:

- (1) The hysteresis loops have a great agreement among systems, as the FD system, Kelvin system, and the Maxwell system when the frequency of the harmonic wave is equal to the natural frequency of the system.
- (2) When the natural frequency of system is lower, the difference of the maximum value, standard deviation, and the peak factor of the displacement, velocity, and acceleration are small, which is also less than 20%.
- (3) The accumulated energy dissipation of the Kelvin system is less than the FD system when the natural frequency of the system is high, which also matches well between the Kelvin system and the FD system when the system with the low natural frequency.
- (4) The total energy-dissipated of the Maxwell system relies on its frequency-sensitivity. That is, the total energy-dissipated of the Maxwell system is under-evaluated with a low natural frequency.

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¹⁾ Graduate Student, Dept. Architecture and Building Engineering, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, Japan.

²⁾ Associate Professor, Laboratory for Future Interdisciplinary Research of Science and Technology (FIRST), Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, Japan.