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Frequency-domain Method for VE Systems with Frequency Sensitivity Subjected to Along-wind without Mean Component

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Frequency-Domain Method, Power Spectral, Fourier Transform,
Frequency Sensitivity, Viscoelastic, Fractional Derivative.

1. Introduction

Time-domain method (TDM) of the dynamic analysis on viscoelastic (VE) systems is a stable and reliable method to obtain the response in the time domain. However, compared with frequency-domain method (FDM), time-domain method is complicated and costs time because it bases on the convolution of the function of external force and the equation of motion of the system [1]. In addition, VE system needs to consider its frequency sensitivity [2]. And, the along-wind excitation includes a wide range of frequency contents [3]. However, the research on frequency-domain method of the dynamic analysis on the frequency-sensitive VE systems is limited in the seismic response. Therefore, the purpose of this paper is to evaluate the wind-induced response subjected to the along-wind without mean component by FDM. The results compared the frequency-domain method and the time-domain method of single-degree-of-freedom (SDOF) models of fractional derivative (FD) model (Fig.1a), 4-Element model (Fig.1b), and 6-Element model (Fig.1c).

2. Frequency-domain method

Frequency-domain method of the dynamic analysis is a fast calculation method, which makes an inner product between Fourier spectral of wind and transfer function of the system in the frequency domain. Fourier spectral of the 1st modal displacement response of the system is given by Eq. (1).

$$X(i\omega) = H(i\omega) \cdot P(i\omega) \tag{1}$$

Where, transfer function of displacement $H(i\omega)$ is given by Eq. (2).

$$H(i\omega) = \frac{1}{1-\left(\dfrac{\omega}{\omega_0}\right)^2 + \dfrac{K'_a(\omega)}{K_f} + i\left(2\xi_0\dfrac{\omega}{\omega_0} + \dfrac{K''_a(\omega)}{K_f}\right)} \cdot \frac{1}{K_f} \tag{2}$$

$P(i\omega)$= Fourier spectral of the 1st modal wind force.

The response in the time domain obtained by inverse Fourier transform of Fourier spectral of the 1st modal displacement $x(t)$ response of the system, which is given by Eq. (3).

$$x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)e^{i\omega t}d\omega \tag{3}$$

3. VE systems

Storage stiffness K'_a, loss factor η'_a, and loss stiffness K''_a of the added component are given by Eq. (4a, b, c), which is composed of a series connection of damper and brace stiffness K_b. However, storage stiffness K'_d and loss factor η_d of damper are different caused by different VE models, which are discussed from Section 3.1 to Section 3.3.

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

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

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

3.1. FD model

Storage stiffness $K'_d(\omega)$ and loss factor $\eta_d(\omega)$ of FD model (Fig. 1a) in the frequency domain 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 damper, 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.

3.2. 4-Element model [3]

Storage stiffness $K'_d(\omega)$ and loss factor $\eta_d(\omega)$ of 4-Element system (Fig. 1b) in the frequency domain are given by Eq. (6a, b, c).

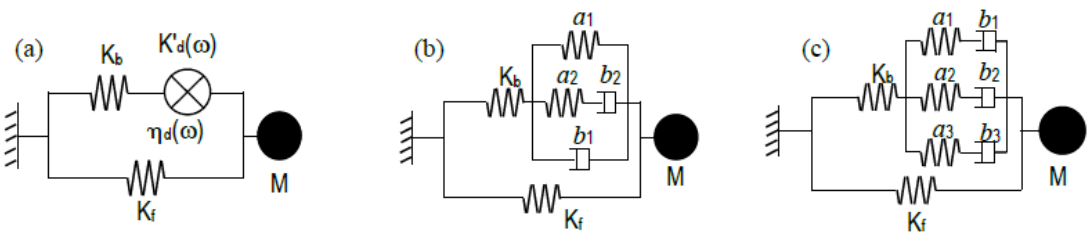

Fig. 1. Viscoelastic systems: (a) FD system, (b) 4-Element system, (c) 6-Element system

$$K'_d = \frac{A_s}{d}\left[a_1 + \frac{a_2(b_2\omega)^2}{a_2^2+(b_2\omega)^2}\right] \tag{6a}$$

$$K''_d = \frac{A_s}{d}\left[\frac{b_1\left\{a_2^2+(b_2\omega)^2\right\}\omega + a_2^2(b_2\omega)}{a_2^2+(b_2\omega)^2}\right] \tag{6b}$$

$$\eta_d(\omega) = \frac{K''_d(\omega)}{K'_d(\omega)} \tag{6c}$$

3.3. 6-Element model [3]

Storage stiffness K'_d (ω) and loss factor η_d (ω) of 6-Element system (Fig. 1c) in the frequency domain are given by Eq. (7a, b, c).

$$K'_d = \frac{A_s}{d}\left[\sum_i^3 \frac{a_i(b_i\omega)^2}{a_i^2+(b_i\omega)^2}\right] \tag{7a}$$

$$K''_d = \frac{A_s}{d}\left[\sum_i^3 \frac{a_i^2(b_i\omega)}{a_i^2+(b_i\omega)^2}\right] \tag{7b}$$

$$\eta_d(\omega) = \frac{K''_d(\omega)}{K'_d(\omega)} \tag{7c}$$

4. Analytical wind

This paper employed wind forces with a return period of 500 years. Wind force was determined by using a wind tunnel test [4]. The airflow in the experiment was determined by referring to the building design load in Japan [5] (terrain: III, directional angle: 0 degree). The design wind velocities of the 100-year-return period is 57.9 m/s.

Fig. 2 shows power spectral density (PSD) of 1st modal along-wind force obtained by 10 waves-ensemble average. Where $S_F(f)$= power spectral of the 1st modal wind force. σ_F= standard deviation of the 1st modal wind force.

Fig. 3 shows one example of the 1st modal along-wind force (600 s) without the mean component in the time domain. To eliminate the extra transient response, the wind force (700 s) was modified in the first 50 s and the end 50 s by envelope, and add zeros of 150 s before the start and after the end (a total analytical time = 1000 s). Thus, the response only 600 s considered in each case.

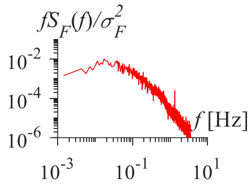

Fig. 2. PSD of along-wind

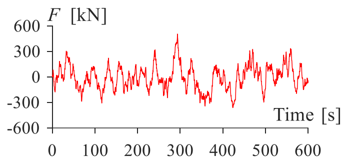

Fig. 3. Time history of the along-wind without mean component

5. Displacement response (along-wind without mean)

The 2H-HH system (K_f = 2.467 [kN m^{-1}], $K_b/K_f = \infty$, $K_d/K_f = 2.0$) and 2H-WS system (K_f = 2.467 [kN m^{-1}], $K_b/K_f = 3.0$, damping ratio = 2%) were employed in the analysis. Fig. 4 and Fig. 5 show that displacement response of 2H-HH systems and 2H-WS systems caused by frequency-domain method has good agreements with that by time-domain method. The error of the maximum response and standard deviation is less than 1%.

6. Conclusions

This paper presented the displacement response among FD system, 4-Element system, and 6-Element, by frequency-domain method has good agreement with that by time-domain method, subjected to the along-wind force without mean component.

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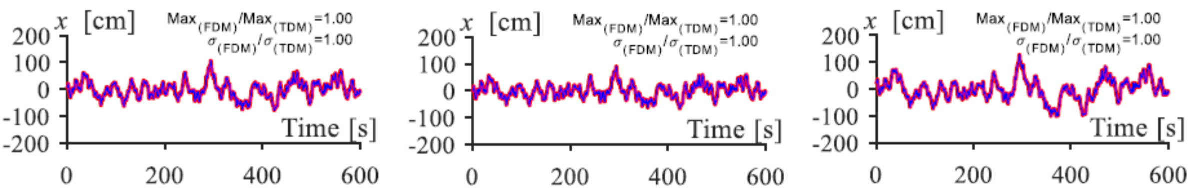
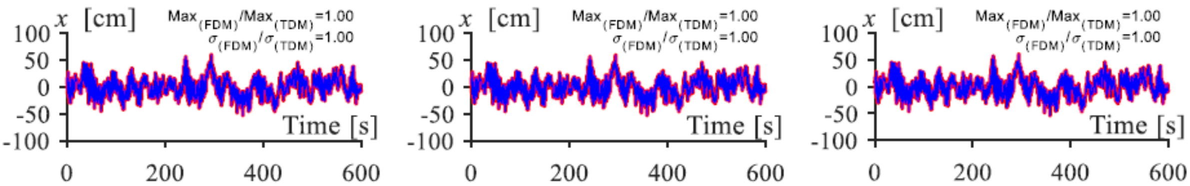


(a) FD system (b) 4-Element (c) 6-Element

Fig. 4. Comparison of the wind-induced displacement in the time domain (2H-HH) (TDM FDM)



(a) FD system (b) 4-Element (c) 6-Element

Fig. 5. Comparison of the wind-induced displacement in the time domain (2H-WS) (TDM FDM)

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