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著者(和文)	李晶, Dave OSABEL, 佐藤大樹, 笠井和彦
Authors(English)	Jing LI, Dave M Osabel, Daiki Sato, Kazuhiko Kasai
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Modified Equivalent Sinusoidal-Deformation to Evaluate Viscoelastic Damper under Long-Duration Wind Loading (Part 1: Background of the Study)

正会員 ○李 晶[*1] 同 OSABEL Dave[*2]
同 佐藤 大樹[*3] 同 笠井 和彦[*4]

Viscoelastic Damper Damper Properties Long-Duration Wind Loading Equivalent Sinusoidal Wave
Frequency Sensitivity

1. INTRODUCTION

1.1 Viscoelastic Damper

Viscoelastic (VE) dampers (e.g., Figure 1) are installed to tall buildings to mitigate structural vibrations induced by earthquake and strong wind. Through the shear deformation of the steel-sandwiched VE material, energy is dissipated and is converted to a small amount of heat within the VE material. For long-duration loading, heat generated from dissipated energy can increase damper temperature significantly. Consequently, changing the VE damper dynamic properties (i.e., damping and stiffness).

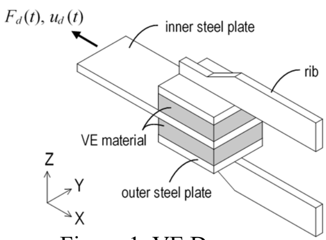

Figure 1. VE Damper

1.2 Dynamic Properties of VE Dampers

It is a customary practice to evaluate dynamic properties of VE dampers from the hysteretic relationship of the damper force F_d and deformation u_d (Figure 2a), or of the shear stress τ and strain γ (Figure 2b) obtained from harmonic loading. Here, the following are defined:

F_d' and F_d'' = forces are at maximum deformation u_{d0} and zero deformations, respectively;
K_d' and K_d'' = storage stiffness and loss stiffness, respectively;
W_d = energy dissipated for one cycle which is equal to the area of the inclined ellipse;
G' and G'' = storage modulus and loss modulus, respectively;
η = loss factor.

Among many factors that affects the VE material behavior, structural engineers are mostly concern with the significant effect of frequency and temperature at which the VE damper operates. At low frequency and high temperature, a VE damper has low dynamic properties. On the other hand, at high frequency and low temperature, a VE damper has high dynamic properties [1].

1.3 Evaluating VE Properties for Random Loading

As mentioned in Section 1.2, VE properties are easily evaluated by considering a harmonic loading. In real world scenario, however, exciting forces such earthquakes and strong wind act in randomly. Consequently, VE dampers deform in random manner (e.g., Figure 3a). Damper forces have similar wave pattern with damper deformation (Figure 3b).

Under random loading, the VE damper force-deformation hysteresis curves (Figure 3c) are not the typical elliptical curves shown in Figure 2. As such, it is quite difficult to grasp the properties of VE dampers.

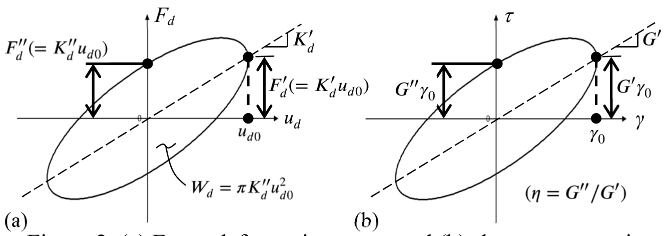

Figure 2. (a) Force-deformation curve and (b) shear stress-strain curve obtained from harmonic loading.

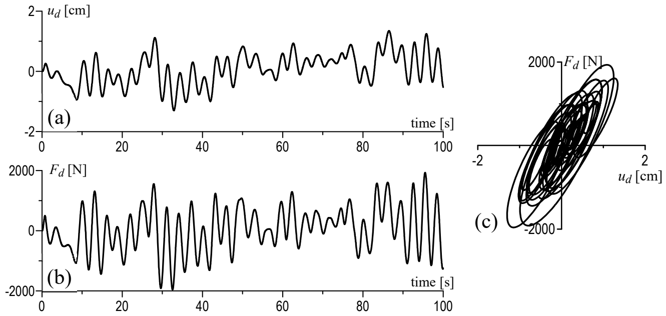

Figure 3. Example of (a) damper deformation and (b) damper force from random excitation, and (c) their F_d-u_d curve.

In 2015, Sato et al. [2] addressed the aforementioned matter by proposing the use of equivalent sinusoidal deformation. They calculated the frequency f_r and amplitude A_r of the equivalent sinusoidal deformation as:

$$f_r = N_0^+ / t_a \text{ , and } A_r = \sigma_u \sqrt{2} \text{ .} \quad (1a, b)$$

Here, N_0^+ = number of positively sloped x-intercept, t_a = duration of random loading, and σ_u = standard deviation of the random deformation. Figure 4 shows an example of the random deformation and its equivalent sinusoidal deformation.

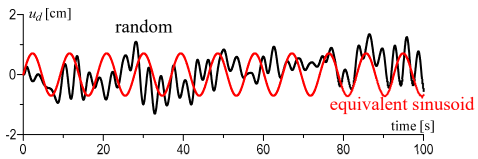

Figure 4. An example of a random deformation vs. equivalent sinusoidal deformation [2].

1.4 Problem Statement and Objectives

However, as will be discussed later, it was found that there is a noticeable difference between the cumulative energy dissipated W_d of the original random deformation and equivalent sinusoidal loading. It is, therefore, the goal of this study to introduce a modified equivalent sinusoidal deformation for the analysis of VE dampers. Part 1 discusses the overview of the previous method by presenting example from the previous study, and Part 2 discusses the proposed modification.

2. BEHAVIOR OF A VISCOELASTIC DAMPER UNDER LONG-DURATION WIND LOADING

2.1 VE Damper Details

This study utilizes the VE damper (Figure 5) used by Sato et al. [2]. Due to page limitation, material properties of the VE damper are not enumerated in this report. Please refer to Ref [2] for the details.

Ambient temperature θ_0 = 24°C was used in the study [2].

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of three-dimensional heat transfer analysis and static analysis using common finite element model of the damper. Using the equivalent-sinusoidal deformations (Section 2.2.2), the first model was used to estimate the heat transfer coefficient α_c of the VE damper. The results were validated with test.

The second model [3] is a combination of one-dimensional (1D) heat transfer analysis and viscoelastic constitutive rule using the fractional-derivatives of stress and strain. This model can carry out time-history analysis of VE damper. Conveniently, it is referred as long-duration (LD) model as it can accurately simulate VE damper under long-duration loading. The equivalent 1D heat transfer coefficients $\alpha_{c,out}$ and $\alpha_{c,in}$ for the outer and inner plates, respectively, used for the second model were determined from the α_c values estimated from the first model.

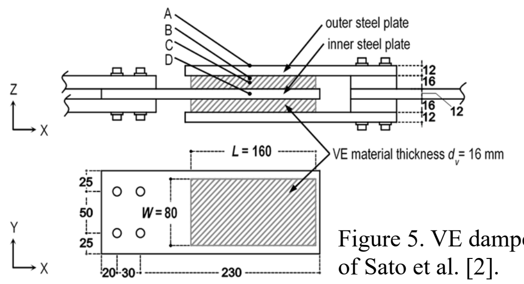

Figure 5. VE damper in the study of Sato et al. [2].

2.2 Displacement-Controlled Random Loading

2.2.1 Random Loading

Random deformation time-histories used in the analysis of VE damper are shown in Figure 6. These were determined from the time-history analysis of a building with natural period T_n = 3 seconds (or natural frequency f_n = 0.333 Hz) and damping ratio h = 2% subjected to long-duration wind loading. Note that these deformations were normalized such that their root-mean square (RMS) values were the same. This normalization was done in order to eliminate the effect of strain level at which the VE damper deforms, thus, enabling to better grasp the effect of frequency content of the response. This concept will be clarified in the calculation equivalent sinusoidal deformations.

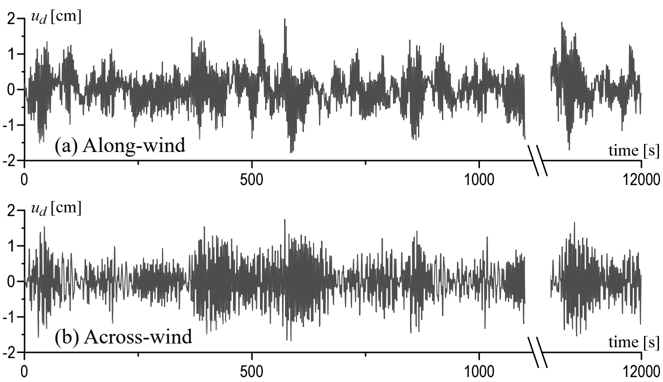

Figure 6. Damper deformation time-history.

Figure 7 shows the power spectral density (PSD) plots of the along- and across-wind damper deformations (Figure 6). Both PSD plots are peaking at natural frequency f_n. However, the along-wind deformation contains more low-frequency vibration than in across-wind deformation.

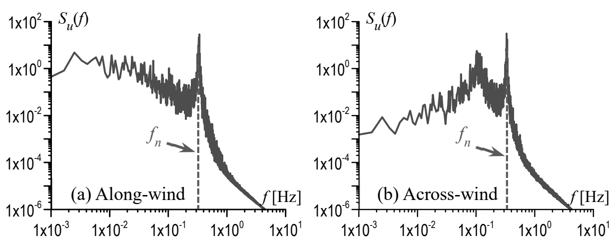

Figure 7. Power spectral density of damper deformation.

2.2.2 Equivalent-Sinusoidal Deformation

For the along-wind VE damper random deformation, N_0^+ = 3452 and σ_u = 0.50 cm. For the across-wind VE damper random deformation, N_0^+ = 3460 and σ_u = 0.50 cm. For both wind directions, t_a = 12000 s. By Equation (1), the equivalent-sinusoidal deformations in the along- and across-wind directions are the similar with f_r = 0.288 Hz and A_r = 0.707 cm.

2.3 VE Damper Analyses

The two prediction models proposed by Kasai et al. [3] were used in the analyses of the VE damper. The first model is a combination

3. RESULTS AND DISCUSSION

Although not shown here due to page limitation, the results (e.g., temperature, storage stiffness and loss stiffness) from the LD model analysis of VE damper with the equivalent-sinusoidal deformation appear to be similar to those from the original random loading.

However, upon closer look into the cumulative energy dissipated W_d, significant variation can be in the along-wind direction, as in Figure 8. The W_d obtained from the equivalent-sinusoidal deformation is higher than those from the original random deformation. This variation is inherently attributed to using only one equivalent-sinusoid, thereby neglecting the significant contribution of the low-frequency broad-band content of the along-wind random deformation.

Since VE damper performance decreases with temperature rise, and temperature increase is directly linked to the amount of energy dissipated, it is therefore imperative to modify the equivalent-sinusoidal deformation to better evaluate VE damper under long-duration wind loading. A good agreement of energy dissipated is a strong indicator that the random deformation is well represented.

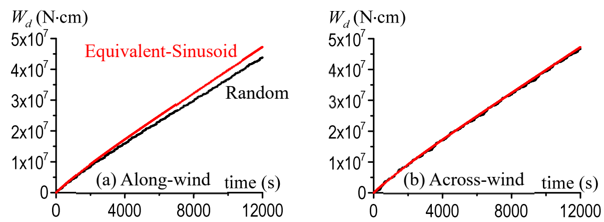

Figure 8. Cumulative energy dissipated: random vs. equivalent-sinusoidal of damper deformation.

4. CONCLUSION

This paper gave the overview of how the equivalent-sinusoidal deformation was used to evaluate the characteristics of VE dampers subjected to long-duration wind loadings. However, when the cumulative dissipated of the VE damper under the equivalent-sinusoidal deformation and the original random deformation are compared, significant error was found. As such, modification is proposed and is reported in the succeeding paper.

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*1 東京工業大学 研究生

*2 東京工業大学 大学院生

*3 東京工業大学 准教授・博士（工学）

*4 東京工業大学 教授　Ph.D.

*1 Research Student, Tokyo Institute of Technology

*2 Graduate Student, Tokyo Institute of Technology

*3 Assoc. Prof., Tokyo Institute of Technology, Dr. Eng.

*4 Professor, Tokyo Institute of Technology, Ph.D.