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Validation of mechanical admittance functions of high-rise buildings

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ABSTRACT

High-rise buildings experience various wind events, including daily winds and typhoons. During these events, buildings move laterally to dissipate energy, which should be properly controlled to prevent a degradation of structural stability and serviceability. In particular, the resonance effect of wind loads and building structure might cause serious structural damage to the building. Therefore, in usual cases, building codes provide a displacement spectrum to ensure that the design phase of the building avoids adverse situations where the natural frequency of the building and the frequency band of the wind load itself match.

Based on the fact that the behavior of the building due to the wind load is dominated by the first mode, the displacement spectrum is estimated by assuming the building as a single degree of freedom. However, completely neglecting the effects of other modes might lead to distorted results of calculating the displacement smaller than the lateral displacement of the actual building. Therefore, in this study, the displacement spectrum is calculated using the results of measuring the natural frequency and mode damping ratio of a 282.3 m high-rise RC shear frame building actually built in Japan.

In this study, theoretical background of spectrum method is revisited. In other words, from wind load to wind response, the relationships existing in the meantime are elaborated based on KBC 2016. Then, the displacement spectrum of the shear building with three degrees of freedom was theoretically derived and compared with the case of the single degree of freedom (code provision). Furthermore, time history data of the wind load regenerated by the time history regeneration method were converted into the displacement spectrum that can be obtained by interpreting the Newmark-beta method, and compared with the displacement spectrum of the 3-degree shear building.

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1. INTRODUCTION

In order to estimate the wind speed for building design, KBC 2016 utilizes the 10-minute mean wind speed as the standard. Here, it can be figured out that the fluctuating component of wind speed must be considered for 10-minute mean wind speed in order to consider the natural characteristics in which the mean and fluctuating components coexist. Therefore, the concept of the gust factor, which is the ratio of the maximum displacement and the average displacement of a building, is introduced to express the effect caused by the fluctuating wind speed of the natural wind. The gust factor G_Y is defined as in Eq. (1). In the equation, g_Y, σ_Y, γ, B, *and* R indicate the peak factor, standard deviation of displacement, turbulence factor for fluctuating wind speed, background response factor, and resonant response factor, respectively.

$$G_Y = \frac{Y'}{\bar{Y}} = 1 + g_Y \frac{\sigma_Y}{\bar{Y}} = 1 + g_Y \gamma \sqrt{B + R} \tag{1}$$

$$\gamma = 0.75 \times 2 \times \frac{1 + 2\alpha + \beta}{1 + \alpha + \beta} I_H = \left(\frac{3 + 3\alpha}{2 + \alpha}\right) I_H \tag{2}$$

$$\sigma_Y^2 = \int_0^\infty S_Y(n)dn = 4\bar{Y}^2 I_v^2 \int_0^\infty |\chi(n)|^2 |H(n)|^2 \frac{S_v(n)}{\sigma_v^2} dn \cong 4\bar{Y}^2 I_v^2 [B + R] \tag{3}$$

$$\frac{\sigma_Y}{\bar{Y}} = 2 I_v \sqrt{B + R} \tag{4}$$

In Table 1, equations of normalized wind speed PSD functions are provided. Since KBC 2016 uses Karman's equation, it can be figured out that both equations are essentially equivalent. To obtain normalized displacement PSD function, other factors should be considered with a wind speed PSD function. The turbulence factor γ is defined in Eq. (2) by assuming that the deformation of the structure is proportional to the linear mode shape ($\beta = 1$). In Eq. (3) and Eq. (4), detailed procedures are provided to determine a standard deviation of displacement σ_Y, which is derived from the relationship that the area of the displacement PSD is equivalent to the square of the standard deviation of the displacement. In this point of view, it can be figured out that the aerodynamic admittance factor $|\chi(n)|^2$ and mechanical admittance factor $|H(n)|^2$ play a key role in the estimation of wind load responses of structures. This is because if these two functions are not correctly defined, the standard deviation of the displacement σ_Y may not match with the actual value during the integration with the wind speed spectrum $S_v(n)$.

Table 1 Comparison between normalized wind speed PSD

	KBC 2016	Karman (1948)
Normalized PSD	$\frac{fS_v(f)}{\sigma_v{}^2} = \frac{4fL_H/V_H}{(1+71(fL_H/V_H)^2)^{\frac{5}{6}}}$	$\frac{fS_v(f)}{\sigma_v{}^2} = \frac{4f_L}{(1+70.8f_L^2)^{\frac{5}{6}}}$
Turbulence length	$L_H = 100(H/30)^{0.5}$	$L_u = 300(H/300)^{0.46+0.74\ln(z_0)}$

2. DERIVATION OF MECHANICAL ADMITTANCE

Normalized displacement PSD function in the KBC code provisions was derived based on the single degree of freedom assumption. In other words, the response of building was determined only by the first mode of the building itself. However, as Fig.1 suggests, there could be one or more modes that affect critically to the response of building. Moreover, cross-modal contribution might be more influential than the existing theory (or code provision) considers.

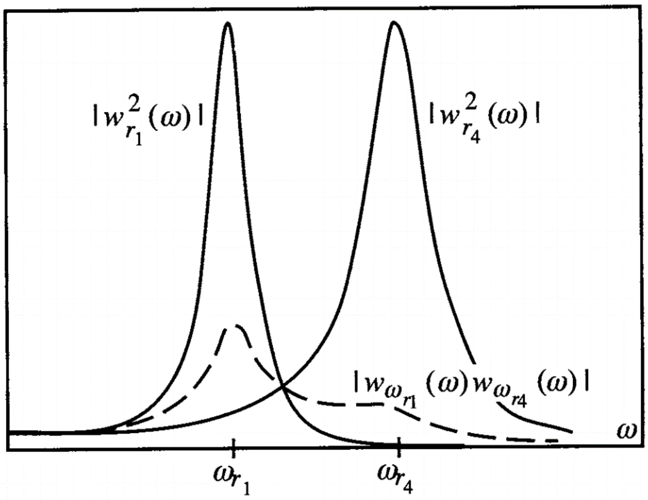

Fig. 1 Cross-modal contributions to auto-spectral density
(Lutes and Sarkani, 2004)

Therefore, in this study, the background theory of mechanical admittance function $H_i(f)$ is revisited to consider multiple modes. Mechanical admittance function $H_i(f)$ could be derived as shown in Eq. 4. Here, unlike the single degree of freedom system, effective participation matrix A_k should be considered to reflect the effect of the mode participation ratio.

$$S_X(f) = \sum_{k=1}^{n}\sum_{l=1}^{n} A_k\, S_P(f)H_i(f)H_j^*(f)A_l^T \tag{5}$$

$$H_i(f) = \frac{1}{(f_i^2 - f^2) + 2i\zeta_i f_i f} \tag{6}$$

$$A_k = Q\varphi\gamma_k \quad (7)$$

With the suggested multi degree of freedom mechanical admittance function, $H_i(f)$, normalized displacement PSD functions can be derived. Since the code provision utilizes single degree of freedom assumption, two displacement PSD functions are compared in Fig. 2. As shown in the figure, dominant resonance effect occurs at the first mode frequency. However, the displacement PSD function based on the suggested mechanical admittance indicates that peaks also occur at the second and third mode frequencies. In the case of the second and third peaks, one may claim that effects of considering two more peaks would be insignificant because values of PSD function are smaller than that of the first peak. However, as shown in Fig. 1, cross-modal contribution may amplify the influence of the second and third peaks in the building response stage. Therefore, in this study, Newmark-beta method is adopted to validate the suggested mechanical admittance function $H_i(f)$.

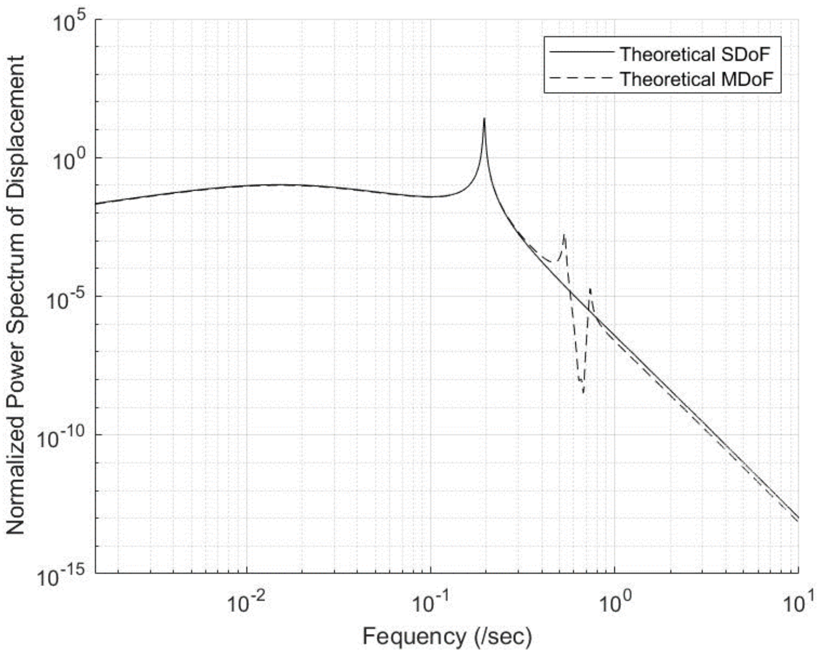

Fig. 2 Comparison of two normalized displacement PSD functions

3. CONCLUSIONS

In this study, a theoretical background of mechanical admittance function $H_i(f)$ is revisited. Since code provisions adopted a single degree of freedom assumption for resonance behavior of high-rise buildings, mechanical admittance function for single degree of freedom system has been used to consider the displacement PSD functions. To scrutinize the validity of the single degree of freedom assumption, mechanical admittance function $H_i(f)$ for multi degree of freedom system was derived by utilizing the random vibration theory. Then, the verification process was conducted through the results of Newmark-beta method analysis.

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