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# Generation of correlated time history wind loads for performance-based wind design

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**ABSTRACT**

As performance-based wind design (PBWD) and inelastic wind design have been actively studied recently, demand for time history wind loads also has increased. Considering cost and time of wind tunnel tests, generated time history wind loads can be an alternative for the preliminary stage of PBWD. Unlike elastic design, correlations of directional wind loads should be implicit in time history wind loads for nonlinear analysis, because superposition of results is invalid. Thus, this study proposes a simplified generation method of correlated time histories based on correlation coefficient. The results of time histories generated by the proposed method are well matched with that by wind tunnel tests, if natural frequencies of directional modes are not the same. Because natural frequency of torsional mode is usually larger than that of sway direction, the proposed method can be used for PBWD of general buildings.

## 1. INTRODUCTION

Wind load is one of the main lateral design loads for buildings. The maximum load effect by directional wind loads should be considered. In design codes or standards, wind load combinations are used to consider the maximum load effect. Estimation methods of the maximum loads for each direction are presented using equivalent static wind loads. The estimated maximum wind loads for non-dominant directions are reduced by load combination factor, because probability of occurrence of the maximum of all directional loads at the same time is low. The wind load combination factors for directional wind loads are determined based on correlations of directional responses.

Recently, performance-based wind design (PBWD) has been widely studied. American Society of Civil Engineers (ASCE) published prestandard for PBWD (ASCE, 2019). In the prestandard, inelastic behavior under wind loads with return periods from 700 to 3,000 years is permitted. For inelastic performance evaluation, nonlinear time

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history analysis should be conducted; therefore, time history wind loads are necessary as input. Because design codes or standards do not provide time history wind loads, engineers rely on wind tunnel test results. Considering frequent design changes during PBWD and cost of wind tunnel tests, conducting tests for preliminary design stage may not be possible. In this case, time history wind loads generated from power spectral density (PSD) functions proposed by Shinozuka and Deodatis (1991) can be employed.

Because a superposition of analysis results is invalid in the nonlinear time history analysis, correlations of directional wind loads should be included in the generated time histories. However, limitation of the spectral method is a lack of consideration for correlation when generating two or more time histories. Thus, this study proposes generation method of correlated time histories based on spectral method.

## 2. CORRELATION OF AERODYNAMIC WIND FORCES

In Korean Design Standard (KDS 41:2019) (Ministry of Land, Infrastructure and Transport (Korea), 2019), wind load combinations for tall buildings are presented. Along-wind load is deemed to have no correlation with other directional wind loads, while across- and torsional-wind loads are correlated due to vortex-induced vibration. If there is a correlation in two time histories of *X* and *Y*, expected value of *Y* at the instant of maximum of *X* can be estimated from their correlation coefficient ($\rho$) (Somekawa et al. 2014) as follows:

$$Y_{\text{expected}} = \bar{Y} + \rho(Y_{\max} - \bar{Y}) \tag{1}$$

Where, $\bar{Y}$ and $Y_{\max}$ are mean and maximum of time history *Y*.

The wind load combination factors ($\kappa$) were determined from correlation coefficients of responses of two directions by octagonal-shaped approximation (AIJ, 2019).

$$\kappa = \sqrt{2 + 2\rho} - 1 \tag{2}$$

Because load combination factors in KDS 41:2019 were determined from correlation coefficients of responses, it cannot be directly applied to aerodynamic wind forces without resonant components. In the research by Somekawa et al. (2014) and Jeong and Kang (2021), correlation coefficients of responses highly depend on natural frequencies of directional modes and their ratios. Hence, it is difficult to estimate correlation coefficients of directional aerodynamic wind forces. In this study, correlation coefficients of aerodynamic wind overturning moments for square-shaped buildings were obtained as shown in Table 1 from the wind tunnel test results of Jeong and Kang (2021). Detailed setup of the wind tunnel tests was presented by Jeong and Kang (2021). As well known, along-wind aerodynamic forces have little correlation with those of other directions. Negative values for correlation coefficients are due to the setup of measurements of directional overturning moments.

Table 1 Correlation coefficients of overturning moments from wind tunnel tests

| Models | Along- and across-wind | Along- and torsional-wind | Across- and torsional-wind |
|---|---|---|---|
| S3 | $\rho$ = -0.0620 | $\rho$ = -0.0349 | $\rho$ = -0.3684 |
| S4 | $\rho$ = -0.0316 | $\rho$ = -0.0721 | $\rho$ = -0.4618 |
| S5 | $\rho$ = -0.0305 | $\rho$ = -0.0446 | $\rho$ = -0.5360 |

## 3. GENERATION OF CORRELATED TIME HISTORY WIND LOADS

Two time histories of $X$ and $Y$ can be generated by spectral method as follows:

$$X(t) = \sum_{i=1}^{n} \sqrt{2S_X(f_i)\Delta f} \cos(2\pi f_i t + \theta_{Xi}) \tag{3}$$

$$Y(t) = \sum_{i=1}^{n} \sqrt{2S_Y(f_i)\Delta f} \cos(2\pi f_i t + \theta_{Yi}) \tag{4}$$

Where, $S(f)$ is one-sided PSD, $\Delta f$ is interval of frequency, and $\theta$ is phase angle set. Subscripts $X$ and $Y$ indicate time histories $X$ and $Y$, respectively. The spectral method can be considered as superposition of cosine functions with different amplitudes and frequencies. The covariance of $i$-th cosine function of $X$ and $j$-th cosine function of $Y$ can be calculated as in the following equation.

$$Cov\left(X_i(t), Y_j(t)\right) = E\left[\sqrt{2S_X(f_i)\Delta f}\sqrt{2S_Y(f_j)\Delta f} \cos(2\pi f_i t + \theta_{Xi})\cos(2\pi f_j t - \theta_{Yj})\right] \tag{5}$$

Where, $E[\bullet]$ is expectation operator. If $i \neq j$, the covariance of cosine functions becomes 0. Therefore, covariance and correlation coefficient of generated time history of $X$ and $Y$ can be calculated as follows:

$$Cov\left(\sum_{i=1}^{n} X_i, \sum_{j=1}^{n} Y_j\right) = \sum_{i=1}^{n}\sum_{j=1}^{n} Cov\left(X_i(t), Y_j(t)\right) = \sum_{i=1}^{n} \sqrt{S_X(f_i)S_Y(f_i)}\Delta f \cos(\theta_{Xi} - \theta_{Yi}) \tag{6}$$

$$\rho = \sum_{i=1}^{n} \sqrt{\frac{S_X(f_i)\Delta f}{\int_0^\infty S_X(f)df} \cdot \frac{S_Y(f_i)\Delta f}{\int_0^\infty S_Y(f)df}} \cos(\theta_{Xi} - \theta_{Yi}) \tag{7}$$

Assuming constant phase angle difference of $\theta'$, a partial term for correlation coefficient can be designated as PSD shape similarity factor.

$$\phi_{PSD} = \sum_{i=1}^{n} \sqrt{\frac{S_X(f_i)\Delta f}{\int_0^\infty S_X(f)df} \cdot \frac{S_Y(f_i)\Delta f}{\int_0^\infty S_Y(f)df}} \tag{8}$$

If a target correlation coefficient is given, the constant phase difference can be calculated as follows:

$$\theta' = \cos^{-1}\left(\frac{\rho}{\phi_{PSD}}\right) \tag{9}$$

The process of generation of correlated time histories is summarized in Fig. 1.

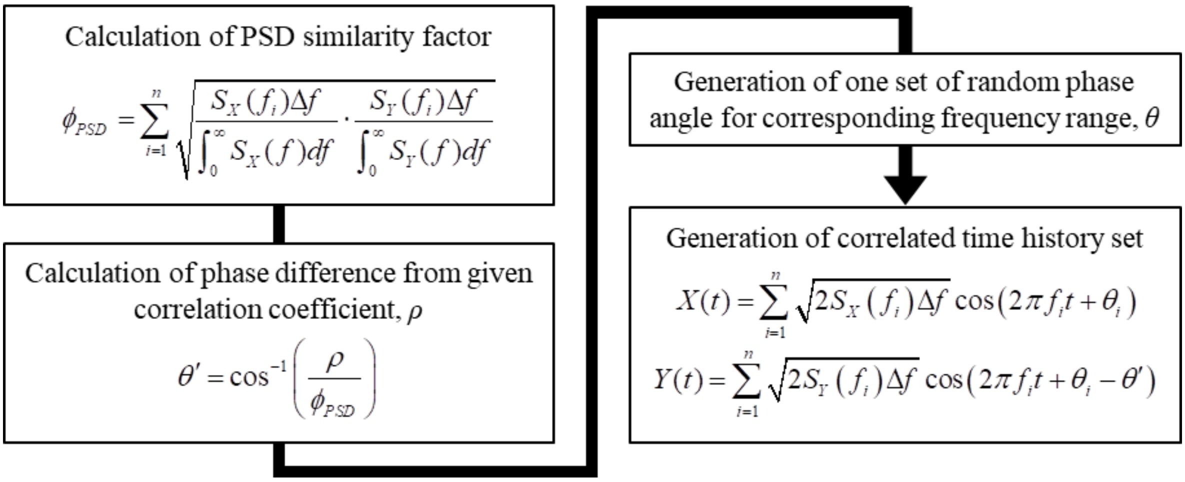


Fig.1 Generation process of correlated time histories

## 4. VERIFICATION AND CONCLUSION

For verification of the proposed time history generation method, correlation coefficients of across- and torsional-wind direction responses by wind tunnel tests and generated time histories were compared using single-degree-of-freedom (SDOF) systems. Time history wind loads for S5 model and wind direction $\alpha = 0°$ were used. Fig. 2 shows correlation coefficients depending on the normalized frequencies and natural frequency ratios of SDOF systems. The normalized frequencies and natural frequency ratios were determined based on the natural frequency of across-wind direction ($f_X$). As discussed by Jeong and Kang (2021), the correlation coefficients of responses highly depend on the natural frequency ratio of directional modes. Except for the cases where natural frequencies were the same, the responses of generated time histories were well matched with results by wind tunnel tests. Correlation coefficients from load combination factors in KDS 41:2019 were overestimated in the low normalized frequency range compared with analysis results. Because phase differences were assumed to be constant regardless of frequency, if natural frequencies are the same, the correlations of responses by generated time histories were similarly high regardless of normalized frequency. Nonetheless, the proposed method can be utilized for general buildings, because natural frequency of torsional mode is usually larger than that of sway direction.

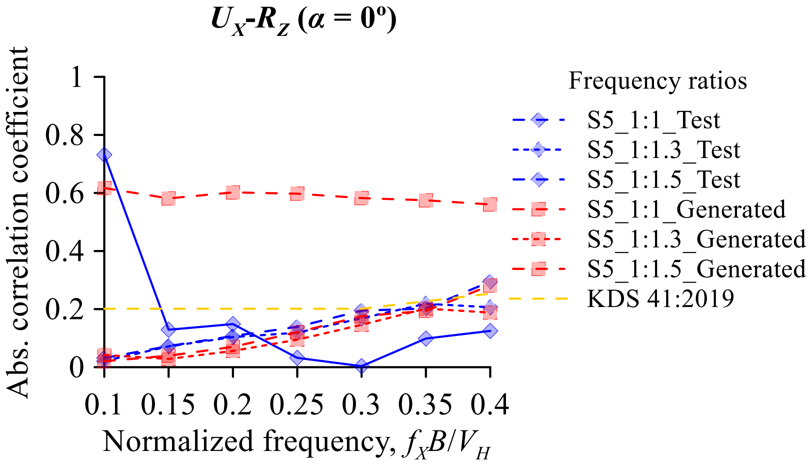


Fig.2 Absolute correlation coefficients of across-wind direction ($U_X$) and torsional direction ($R_Z$) responses

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