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EFFECT OF NOISE ON WIND FORCES ON A TALL BUILDING ESTIMATED BY MODAL ANALYSIS

構造ー振動

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Wind force estimation, Modal analysis, FDD Method
Noise effect, Natural frequency, Damping ratio

1. Introduction

1.1 Wind Force Estimation

Tall and light buildings are susceptible to dynamic forces such as extreme winds, making wind load analysis an integral factor in the design process. As the building gets higher and lighter, the increase in wind velocity and force causes large structural vibrations that may affect the serviceability and habitability of the structure. For this reason, accurate estimation of the actual wind forces acting on the structure has become of great importance.

Monitoring systems on structures record the wind-induced response of the building. These recorded responses can be used to determine the wind forces by performing output-only modal analysis on the structure. However, these recorded responses include random noises that can affect the accuracy of the calculation of wind forces. Therefore, it is necessary to take into account the effect of noises in the wind force estimation.

1.2 Dynamic Parameter Identification

Since wind loads are considered as dynamic forces, the dynamic properties of the structure, particularly the natural period and damping ratio, must also be given careful consideration in the estimation of wind forces [1]. These values are two very important but also highly uncertain parameters that greatly affect the dynamic response of a structure and an accurate prediction of these values must be guaranteed in the design process [2]. However, there is no absolute theoretical method to estimate the natural frequency and damping ratio and the assessment of these two parameters predominantly depends on full-scale data obtained from similar structures. Satake et al. [3], Shioya et al. [4], and Tamura et al. [5] conducted studies on the estimation of natural frequencies obtained from recorded data and all reported to have only 10 to 20% difference from the measured values. On the other hand, estimation of damping ratio from full-scale data can result to errors that can reach about 100-200%, or even 1000% if low quality measured data were used [2]. This amount of error can be detrimental to the structural safety of the building.

The proposed procedure for wind estimation in this paper is based on an output-only system, meaning only the response of the structure is needed. There are various methods proposed for parameter identification of such systems. One recently developed frequency-domain method is the Frequency Domain Decomposition (FDD) technique. This method can offer high accuracy for data with sufficient length, fine frequency resolution and well-separated modes [2].

1.3 Objective

The main objective of this paper is to determine the effect of noise added to the response of a tall building on the wind forces estimated by modal analysis and whose primary natural period and damping ratio are obtained by FDD method.

2. Theoretical Background

2.1 Modal Analysis

The equation of motion for a multi-degree-of-freedom (MDF) system subjected to external dynamic forces $\{P(t)\}$ is

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{P(t)\} \tag{1}$$

where, $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively. Also, $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$ and $\{x(t)\}$ are the acceleration, velocity and displacement vectors, respectively. This system of simultaneous equations in Equation (1) can be simplified by N separate SDOF models.

The dynamic response of an MDF system can be expressed as the sum of the modal contributions of each single-degree-of freedom (SDOF) model,

$$x_i(t)=\sum_{s=1}^{N} {}_s\phi_i \cdot {}_s q(t)\,,\quad \dot{x}_i(t)=\sum_{s=1}^{N} {}_s\phi_i \cdot {}_s \dot{q}\,(t),\quad \ddot{x}_i=\sum_{s=1}^{N} {}_s\phi_i \cdot {}_s \ddot{q}(t) \qquad \text{(2 a-c)}$$

where ${}_s\phi_i$ is the mode shape of the s^{th} mode on the i^{th} layer, N is the number of layers (N = 10), and $\ddot{q}\,(t)$, $\dot{q}\,(t)$, $q\,(t)$ are the modal responses. Substituting the vector form of this to Equation (1) and using the generalized form of the property matrices, Equation (1) becomes,

$$[{}_sM]\{\ddot{q}(t)\}+[{}_sC]\{\dot{q}(t)\}+[{}_sK]\{q(t)\}=\{{}_sP(t)\} \qquad (3)$$

where $[{}_sM]$, $[{}_sC]$, $[{}_sK]$ and $\{{}_sP(t)\}$ are the generalized mass, generalized damping, generalized stiffness matrices and generalized force vectors, respectively. Their values are given by the following equations:

$$[{}_sM]=[\phi]^T[M][\phi]$$
$$[{}_sC]=[\phi]^T[C][\phi] \qquad \text{(4 a-c)}$$
$$[{}_sK]=[\phi]^T[K][\phi]$$

$$\{P(t)\}=[\phi]^{T^{-1}}\{{}_sP(t)\} \qquad (5)$$

2.2 Frequency Domain Decomposition (FDD) Method

The FDD method is a technique to estimate the modal parameters of a structure from the system response or observed records without knowing the input exciting the system [6]. This method was selected because of its user friendliness and its strong ability to estimate the primary mode. The first step in identification using this method is to estimate the power spectral density (PSD) matrix G_{yy} $(j\omega)$ of the response, which is then decomposed by taking the Singular Value Decomposition (SVD) of the matrix

$$G_{yy}(j\omega_i)=U_iS_iU_i^{\,H}=\sum_i s_{ii}u_iu_i^{\,H}. \qquad (6)$$

Here superscript H corresponds to conjugate and transpose, the matrix U_i is a unitary matrix of the singular vectors u_{ij} at jth singular value, S_i is a diagonal matrix holding scalar singular values s_{ij}. The mode shape of a certain mode of vibration can be estimated by peak-picking procedure in the SVD. The values near peak is the SDOF density function of the given mode. The natural frequency and damping can be obtained from the PSD by obtaining its time domain [6].

3. Numerical Model

The structure to be analyzed and its properties are shown in Figure 1. It is simplified as a 10-DOF lumped mass system which has a natural period T = 2.5 s. Stiffness-proportional damping was used in the analysis where damping ratio h = 2%. The stiffness of each layer, k_i was calculated using Equation (7) in order to obtain a linear mode shape in the first mode

$$k_i=\frac{{}_s\omega^2\cdot m_i\cdot {}_s\phi_i+k_{i+1}({}_s\phi_{i+1}-{}_s\phi_i)}{{}_s\phi_i-{}_s\phi_{i-1}} \qquad (i=1\sim N), \qquad (7)$$

where ${}_s\omega$ is the natural circular frequency of the s^{th} mode of vibration, m_i is the mass of i^{th} layer, ${}_s\phi_i$ is the mode shape of the s^{th} mode on the i^{th} layer and N is the number of layers (N = 10). The wind force used in the analysis was a 400-minute steady-state data in the across-wind direction shown in Figure 2. The responses of the model (i.e., acceleration, velocity and displacement) are obtained by MDF analysis using the given wind force. The conceptual framework of the analysis is summarized in Figure 3.

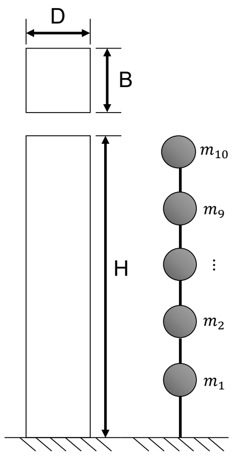

Figure 1. Analytical model

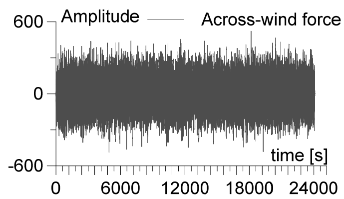

Figure 2. 400-min wind force

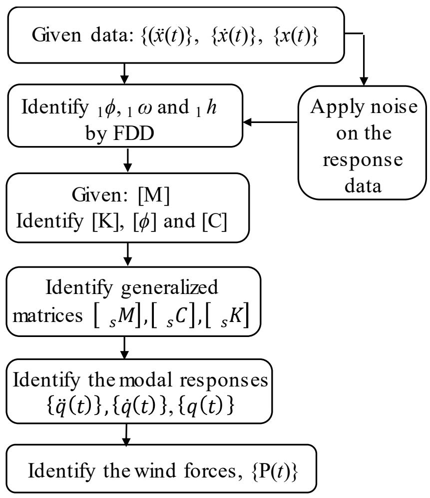

Figure 3. Conceptual framework

4. Results

4.1 FDD Analysis

A 400-minute acceleration response, separated into 40 ensembles of 10-minute each was used in the FDD analysis. Ensemble-averaging was done and it was found to be effective in reducing the noise in the PSD estimate. Obtaining the singular values (SV) of the acceleration response is the crucial step in FDD analysis. The peaks of the SV plots correspond to the structural modes of the model [6]. Shown in Figure 4 is the SV plot of the acceleration response (without noise) obtained using the average of 40-ensemble data and the location of the natural frequency of the first mode (peak). The peak shown here was used to identify the mode shape vector of the first mode of vibration. The results are shown in Figure 5. It can be seen here that the mode shape vector obtained from FDD analysis is in good agreement with that of the theoretical value obtained from eigenvalue analysis.

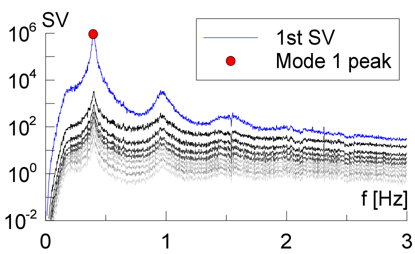

Figure 4. SV distributions of PSD matrix

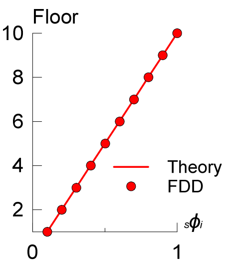

Figure 5. 1st mode shape

The SV near the peak is equal to the PSD function of the corresponding mode as an SDOF system [5]. The SV values enclosed in the band-pass filter shown in Figure 6 corresponds to the PSD of the first mode of vibration as an SDOF system. The time-domain of this PSD function can be obtained by inverse FFT and represents the auto-correlation function to estimate the natural frequency and damping ratio of the 1st mode of vibration, as shown in Figure 7. The natural period and damping ratio were estimated using the least squares method (LSM). The width of the band-pass filter used in isolating the SDOF density function for the 1st mode and the number of cycles of the autocorrelation function used for the LSM was decided based on the accuracy of the identified parameters from a number of trials.

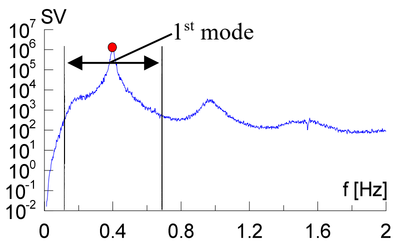

Figure 6. Mode 1 band-pass filter

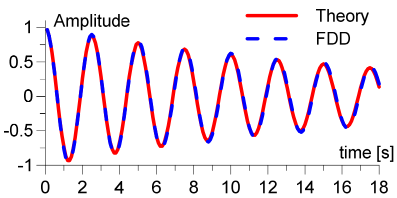

Figure 7. Autocorrelation function

The FDD procedure discussed in this section was applied to the acceleration response with and without noise. Gaussian white noise was added to the given responses to simulate the noise gathered by observation devices. Different values of the ratio of the standard deviation of the generated noise σ_N and that of the response signal σ_{acc} were tested as indicated in Table 1. The comparison between the acceleration time-history with and without noise for a standard deviation ratio of 0.010, which is the maximum among the tested ratios in this study is shown in Figure 8. It can be observed that at high amplitude values, the noise is not that visible in the time-history plot of the response. This shows that the maximum noise added is so minimal to be that evident.

Table 1.

Tested σ_N/σ_{acc}
0.002
0.004
0.006
0.008
0.010

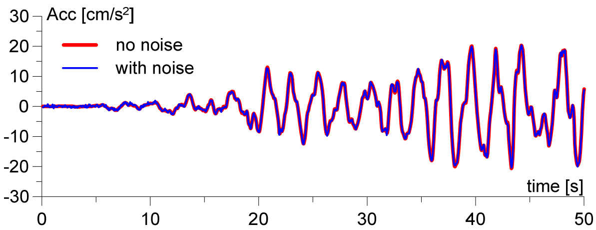

Figure 8. Acceleration time-history

The ratio of the estimated Mode 1 parameters by FDD analysis and eigenvalue analysis for the responses with and without noise can be seen in Figure 9. It is shown here that the ratios obtained are highly accurate, having a ratio of almost 1.0. Also, the FDD/Eigenvalue ratios did not change significantly despite the added noise in the responses.

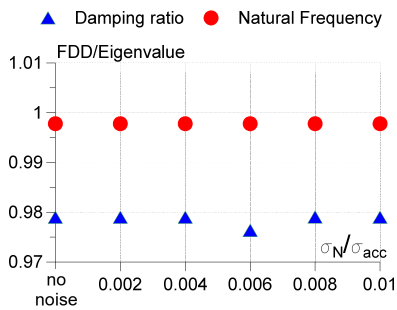

Figure 9. Effect of noise on FDD identification

4.2 Wind Force Estimation

Using the 1st mode shape and natural frequency obtained from FDD analysis, the stiffness matrix [*K*] was calculated. Using this result and the given mass matrix [*M*], eigenvalue analysis was carried out and the modal matrix $[\phi]$ was obtained. The damping matrix $[C]$ was then calculated using both the 1st mode damping ratio and natural frequency from FDD results. Then, modal analysis was performed to estimate the wind forces. The accuracy of the wind forces obtained by modal analysis was confirmed by calculating the correlation coefficient for each increment of mode in the modal superposition. Equation (8) shows the correlation formula used in this paper, where $\hat{y}$ is the theoretical or actual value and $\bar{y}$ is the mean of the calculated value y.

$$Correlation = \left(1 - \frac{\sqrt{\sum_{k=1}^{N}\left(\hat{y}(k) - y(k)\right)^2}}{\sqrt{\sum_{k=1}^{N}\left(y(k) - \bar{y}\right)^2}} \right) \tag{8}$$

4.2.1 No noise

Figure 10 summarizes the correlation coefficient of the estimated wind force for each increment of mode in the modal superposition using the responses without noise and the dynamic parameters obtained from the FDD analysis (no noise). It can be seen here that as more modes are included in the modal superposition, the closer the correlation is to 1.0. It can also be seen here the low correlation value for the lower floors which can be neglected since these stories experience relatively low wind forces compared to the upper floors. On the other hand, from Mode 3 onwards, the upper floors have good correlation with the actual wind forces.

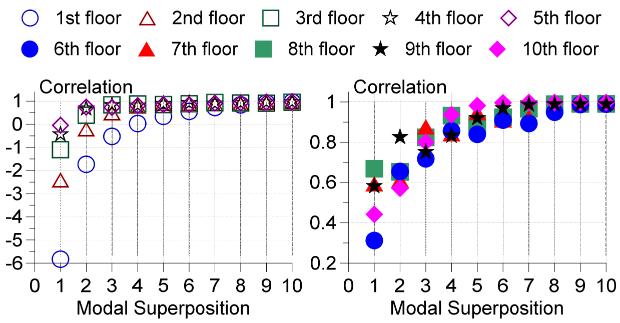

Figure 10. Correlation of wind forces (no noise)

4.2.2 Effect of noise on wind-force estimation

The estimated wind forces for the responses with noise were also calculated. The correlation of the estimated wind force for the upper floors for each tested noise-response ratio is shown in Figure 11 (Modes 1-10). It can be observed here that as the amount of noise increases, the correlation between the estimated and the actual wind forces significantly drops. Also, it is noticeable that the decrease in value for the top floor is less than compared with the other floors. Note that however, when the σ_N/σ_{acc} reaches 0.01, the value of the correlation of the top floor is 60% which is already considered as low correlation. Shown in Figure 12 are the time-history comparison of the actual and estimated wind forces for the 10th and 6th floors.

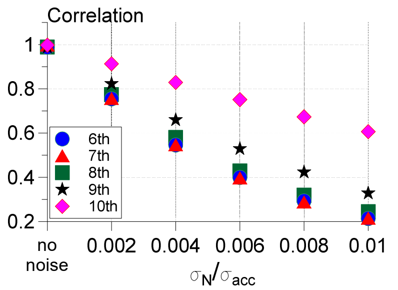

Figure 11. Effect of noise in the estimated wind forces (Modes 1-10)

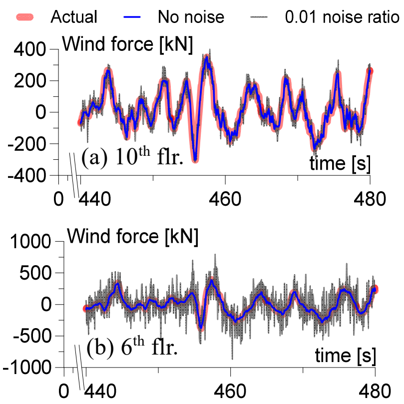

Figure 12. Wind forces (Modes 1-10)

5. Conclusion

Based on the results discussed, added noise in the acceleration response did not significantly influence the parameter estimation by FDD method. However, the results of modal analysis showed that added noise in the responses affected the estimated wind forces significantly.

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