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Parameter Identification and Wind Force Estimation on a Tall Building by FDD Method and Modal Analysis

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Wind force Modal analysis FDD Method
Natural frequency Damping ratio

1. Introduction

Tall buildings are more susceptible to dynamic forces such as extreme winds. Because of this, wind load analysis has become an integral factor in the design process. Due to the unpredictability of wind forces, some structures require an extensive time-history analysis in order to evaluate the wind-induced response of the building [1]. In such cases, an accurate estimation of wind forces is highly necessary. Observed records from monitoring systems of a structure can be used to determine the input wind force causing the recorded responses. This can be done by performing output-only modal analysis. However, certain parameters such as natural frequency and damping ratio need to be identified for accurate estimation of wind forces [2].

This paper, therefore aims to identify the natural frequency and damping ratio of a tall building using Frequency Domain Decomposition Method (FDD) and estimate the unknown wind forces by output-only modal analysis.

2. Theoretical Background

2.1 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 [3]. It was selected because of its user friendliness and its strong ability to estimate the primary mode of building vibration.

2.2 Modal Analysis

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

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

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. The system of simultaneous equations in Equation (1) can be simplified by N separate single-degree-of-freedom (SDOF) models. The dynamic response of an MDF system is also the sum of the modal contributions of each SDOF model,

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

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 Equation (2) 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. The actual forces can be calculated by

$$\{P(t)\}=[\phi]^{T^{-1}}\{{}_sP(t)\}\,. \qquad (4)$$

3. Numerical Model

The model (Figure 1) is a simplified lumped mass 10-DOF system with a height H = 100 m, density ρ_u = 180 kg/m^3 and each floor area A = 625 m^2. The structure has a natural period T = 2.5 s. Rayleigh damping was used in the analysis where damping ratio h = 2%. The stiffness of each layer, k_i was calculated using Equation (5) in order to obtain a linear mode shape in the first mode 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.

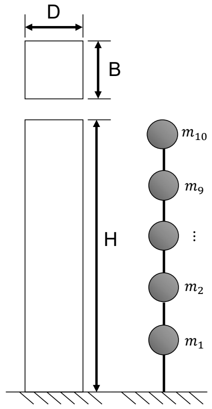

Figure 1. MDF model

$$k_i=\frac{{}_s\omega^2\cdot m_i\cdot{}_s\phi_i+k_{i+1}({}_s\phi_{i+1}-{}_s\phi_i)}{{}_s\phi_i-{}_s\phi_{i-1}} \qquad (i=1\sim N), \qquad (5)$$

The wind force used in the analysis was a 400-minute steady-state data in the across-wind direction.

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. Shown in Figure 2 is the singular values (SV) plot of the acceleration response obtained using the average of 40-ensemble data and the location of the 1st and 2nd mode peaks. The peak shown here was used to identify the mode shape vector of the 1st mode of vibration [3]. It can be seen in Figure 3 that the mode shape vector from FDD analysis is in good agreement with that of the theory (eigenvalue analysis).

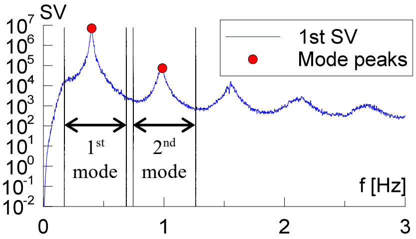

Figure 2. SV distributions and band-pass filter

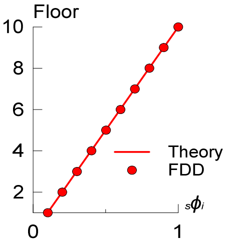

Figure 3. 1st mode shape

The SV near the peak is equal to the power spectral density (PSD) of the corresponding mode as an SDOF system [3]. Inverse FFT was used to calculate the time-domain of this PSD function. The time domain results were used to estimate the natural frequency and damping ratio of the 1st and 2nd modes of vibration. Figure 4 shows that the dynamic parameters (ω and h) estimated by FDD have high correlation with the theoretical values.

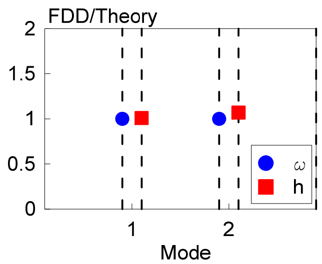

Figure 4. FDD results correlation

4.2 Modal Analysis

The stiffness matrix [K], modal matrix [ϕ] and damping matrix [C] were calculated using the 1st mode shape vector $\{_1\phi\}$, natural frequencies ($_1\omega$, $_2\omega$) and damping ratios ($_1h$, $_2h$) obtained from FDD analysis. Then, modal analysis was performed to estimate the wind forces using Equations (2), (3) and (4). Equation (6) shows the correlation formula used in this paper to check the accuracy of the estimated wind forces,

$$Correlation = \left(1 - \frac{\sqrt{\sum_{k=1}^{N} \left(\hat{y}(k) - y(k)\right)^2}}{\sqrt{\sum_{k=1}^{N} \left(y(k) - \bar{y}\right)^2}} \right) \quad (6)$$

where $\hat{y}$ is the theoretical or actual wind force value and $\bar{y}$ is the mean of the calculated wind force y.

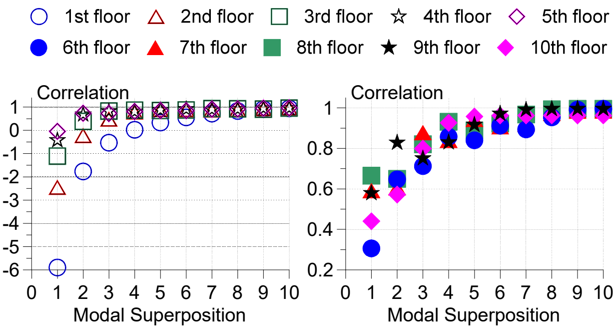

Figure 5. Correlation of wind forces

Figure 5 summarizes the correlation coefficient of the estimated wind force for each increment of mode in the superposition of the modal wind forces. It can be seen here that starting from Mode 1 only, the correlation of the top floor is 44%. However, as more modes are included in the modal superposition, the closer the correlation value is to 1.0. This can be clearly seen in the time-history plots of the top floor wind forces shown in Figure 6. It can be seen that by considering only until the 3rd mode of vibration, the correlation already reached 80% and considering all modes gave a correlation of 96%.

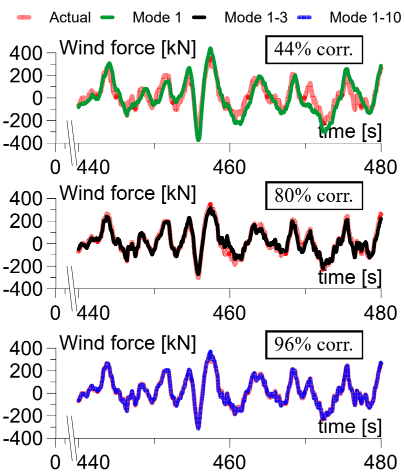

Figure 6. Wind forces (top floor)

5. Conclusion

Based on the results of the analysis, FDD method can accurately identify the needed dynamic parameters to estimate the wind forces by modal analysis. Also, since most monitoring systems cannot register higher modes of vibration, it was determined that modal superposition until the 3rd mode is sufficient to have at least 80% correlation in the upper floors.

References

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