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Filtering of High Frequency Errors on the Wind Forces Estimated by Modal Analysis using Limited Acceleration Responses

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Wind force　Modal analysis　Cubic spline interpolation
Natural period　Filtering　Frequency domain integration

1. Introduction

Since modern structures are more susceptible to strong wind forces, accurate estimation of the time-history of wind forces is necessary to design such structures. These are commonly done by methods such as wind tunnel testing which still has limitations in accurately replicating the actual field conditions [1]. Recorded response from monitoring systems installed on the structure can be used to determine the wind forces and verify the existing methods [2]. However, only the acceleration response on limited stories is usually recorded in practice. Soriano et al. [3] used modal analysis to estimate the wind forces on models with different damping ratios from limited acceleration responses. Their results had shown that determination of the unknown acceleration responses by interpolation caused high frequency errors in the wind force estimates. To improve these results, the high frequency errors obtained must be filtered out.

This paper aims to formulate a general equation to determine the low-pass filter (LPF) cut-off frequency needed to remove the high frequency noise that the acceleration interpolation causes in the wind force estimation by modal analysis.

2. Theoretical Background

2.1. Response Identification

A simplified 10-degree of freedom structural model is analyzed in this study as shown in Fig. 1. The locations of the acceleration sensors are shown in Figure 1. The unknown accelerations are identified by cubic spline interpolation [4] using the built-in *spline* function in MATLAB. The velocity, $\dot{x}(t)$ and displacement, $x(t)$ are calculated by integration of the acceleration responses, $\ddot{x}(t)$ in the frequency domain [5].

2.2. Modal Analysis

The estimation of wind forces, $\{F(t)\}$ by modal analysis revolves around the equation of motion for dynamic systems shown in Equation (1).

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

where $[M]$, $[C]$, and $[K]$ are the mass, stiffness, and damping matrices of the given model. Assuming that the parameters needed to determine these matrices are all known, and using the responses identified from the previous section, the wind forces acting on the model can be estimated. The accuracy of the results is measured by the correlation between the estimated and actual wind forces calculated using Equation (2) where $\hat{F}$ is the actual wind force value and $\bar{F}$ is the mean of the estimated wind force value F. Equation (2) is also used to determine the accuracy of the identified responses by replacing the force with response values.

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

2.3. LPF Cut-off Frequency

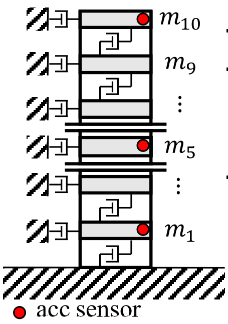

Figure 1. Model

Table 1. Tested models

Model	H (m)	T (s)	${}_1\zeta$(%)	${}_2\zeta$(%)
MH-30	30	0.75	2.0	2.0
MH-50	50	1.25		
MH-100	100	2.50		
MH-150	150	3.75		

The high frequency errors on the wind forces estimated by modal analysis using acceleration responses identified from interpolation must be filtered out and the frequency at which the high frequency errors start to influence the wind forces (*LPF cut-off frequency*) must be determined. In this paper, the *LPF cut-off frequency* of different models with different first mode natural periods, T are investigated (see Table 1) and a general equation to determine this value for other models is formulated. The wind force used in the analysis is a 400-minute steady-state data in the across-wind direction. First, the cut-off frequency at which the maximum average correlation is obtained (*max*) is determined for all models. Then, least squares method (LSM) is used to determine the relationship of *max* values and the natural periods. The relationship is then verified by comparing the maximum and the new average correlation of the wind forces.

4. Analysis Results

4.1. Response Identification

Figure 2 shows the accuracy of the identified responses using cubic spline interpolation for the acceleration and integration for the velocity and displacement. It can be seen in Figure 2a that interpolating the 1st, 5th, and 10th story accelerations demonstrated a significant error in the identified accelerations of the unknown stories for all models, particularly for the short-period models (MH-30 and MH-50). The error is due to the limitation of the method to estimate the high frequency peaks of the actual acceleration response as shown in the time-history and amplitude spectra of the 8th story acceleration in Figure 3. Despite that, the obtained velocity and displacement responses from the integration of the calculated acceleration still obtained high accuracy as shown in Figures 2b and 2c.

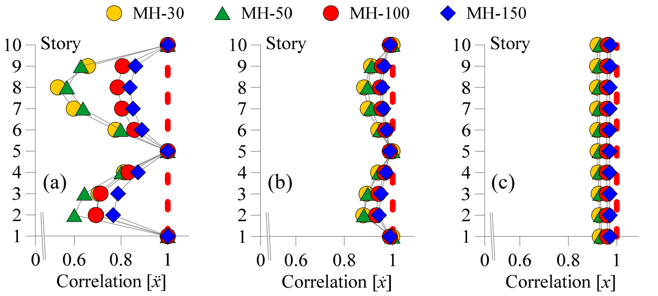

Figure 2. Correlation of identified responses

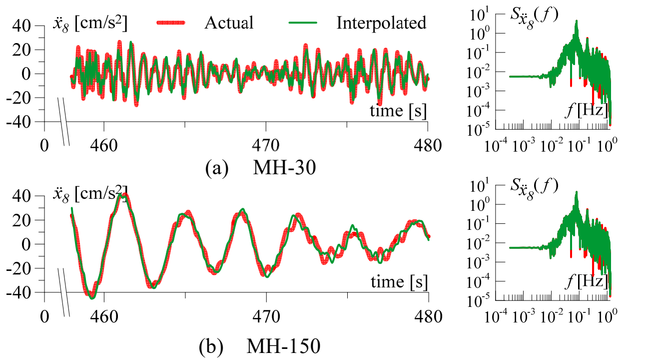

Figure 3. Time-history and amplitude spectra of acceleration

4.2. Wind Force Estimation by Modal Analysis

Shown in Figure 4a is the correlation values of the estimated wind forces for all the models. It can be seen from this figure that the short-period models (MH-30 and MH-50) obtained more accurate results as compared to the models with higher natural periods (MH-100 and MH-150) despite having the lowest correlation in the response identification. This is because the errors for the short-period models occurred in higher frequency range than those of the long-period models as shown in the power spectra density (PSD) plot of the wind forces shown in Figure 5. Different cut-off frequencies were tested to determine the *max* value. The relationship of the *max* value and the natural period obtained by LSM is given by:

$$LPF\ cut-off\ frequency = 3/T \tag{3}$$

Using the LPF cut-off frequency obtained using Equation (3), the new average correlation can be obtained. This is compared to the maximum average correlation, *max* value obtained as shown in Figure 6 and Table 2. It can be seen here that although the frequency values shifted, the average correlation of the wind forces is not significantly affected which shows that using the relationship from Equation (3) gave very good results.

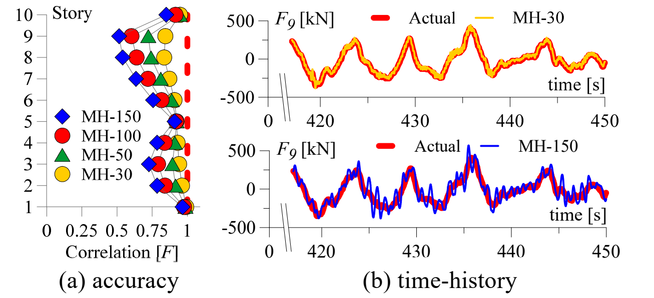

Figure 4. Estimated wind forces by modal analysis

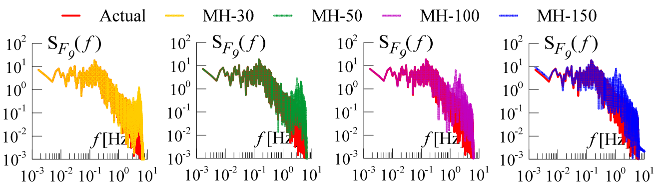

Figure 5. Power spectra of estimated wind forces

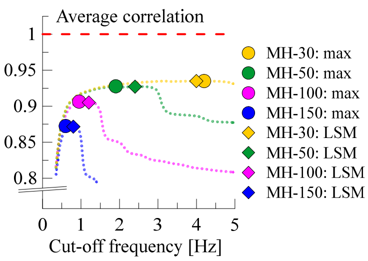

Figure 6. Average correlation of the estimated wind forces

Table 2. Average correlation of estimated wind forces

Model	Modal analysis	Filtered (max.)	Filtered (LSM)
MH-30	91.6	93.5	93.5
MH-50	87.4	92.8	92.7
MH-100	80.7	90.6	90.5
MH-150	76.9	87.2	87.2

5. Conclusion

Based on the results of the analysis, the frequency at which the high frequency errors obtained from interpolation of the acceleration response starts to affect the estimated wind forces by modal analysis is at $3/T$ and must be filtered out from there.

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