Full-scale performance evaluation of tall buildings under wind

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1 ABSTRACT

Full-scale monitoring is an important tool to evaluate the performance of dynamically sensitive structures and assure that the design assumptions and methodologies are consistent with in-situ behaviors. Unfortunately, this is not a common practice for tall buildings, prompting the establishment of the Chicago Full-Scale Monitoring Project (CFSMP), which currently monitors three tall buildings embodying structural systems common to high rise design. This paper presents various stationary and nonstationary system identification techniques that have been used to determine the dynamic properties of these buildings and discusses the insights gained.

2 INTRODUCTION

The existing design procedures for tall buildings rely exclusively on computational and scaled experimental models tested in wind tunnels. Although these models have been extensively refined, there is still considerable uncertainty associated with the actual performance of structures under dynamic excitation. As structures become increasingly taller and more complex, it is imperative that engineers be able to accurately predict their performance in order to create cost-efficient designs satisfying survivability, serviceability, and habitability requirements. Full-scale monitoring provides the most faithful means to do so by determining the validity of the assumptions used during the design process. While several databases of full-scale properties of buildings have been created, data from tall buildings is generally lacking (Lagomarsino, 1993; Satake et al., 2003) and although several tall buildings in Asia have recently been monitored, including Di Wang Tower in China and the Bank of China in Hong Kong (Li et al., 2003a; Li et al., 2003b; Li et al., 2005; Xu et al., 2003), many of full-scale monitoring efforts directed toward tall buildings have not been sustained long enough to observe responses under a wide spectrum of wind events. In response to this need, nearly a decade ago, the University of Notre Dame, The Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario, and Skidmore, Owings, & Merrill LLP (SOM) in Chicago established the Chicago Full-Scale Monitoring Project (CFSMP) to monitor three tall buildings in Chicago. CFSMP is arguably the only sustained monitoring program for tall buildings that has generated a large volume of data for three signature tall buildings whose structural systems are representative of those common to high-rise design. At the request of the building ownership, the structures are referred to herein generically as Buildings 1-3.

3 DESCRIPTION OF INSTRUMENTED BUILDINGS

As discussed in Kijewski-Correa et al. (2006), the primary lateral load-resisting system of Building 1 is comprised of a steel tube with exterior columns, spandrel ties, and additional stiffening elements. This allows a near uniform load distribution on the columns across the flange face with very little shear lag so that the building is dominated by cantilever action. Building 2 is a reinforced concrete building with shear walls located near the core of the building to provide lateral load resistance. These are tied to the perimeter columns by reinforced concrete outrigger walls at two levels. Finally, Building 3 consists of a steel, moment-connected, framed tube comprised of closely spaced wide columns and deep spandrel beams along multiple frame lines. This system therefore behaves like a vertical cantilever that is fixed at the base when subjected to wind loads.

4 DESCRIPTION OF INSTRUMENTATION

4.1 *Instrumentation System for Building Response*

The primary instrumentation systems were installed in Buildings 1, 2, and 3 on June 14, 2002, June 15, 2002, and April 30, 2003, respectively. Each building is instrumented with four Columbia SA-107 LN high-sensitivity force-balance accelerometers that are capable of accurately measuring accelerations down to 0 Hz. The accelerometers were installed in orthogonal pairs at opposite corners of the ceiling at the highest possible floor of each building. The data outputs of the accelerometers are sampled every 0.12 seconds and are archived by a 15-bit Campbell CR23X data logger. The data logger is programmed to capture continuous 10-minute data outputs from the accelerometer. When motions exceed a user-defined threshold, the data logger automatically begins to capture continuous hour-long time-histories of data for as long as the threshold level is exceeded. Estimates of the N-S (y) and E-W (x) sway and torsional responses are obtained via algebraic manipulation of the accelerometer outputs (Kijewski-Correa et al., 2006).

Since wind-induced displacements include both resonant and background components and accelerometers are capable of recovering only the resonant contribution, a differential Leica MC 500 Global Positioning System (GPS) sensor pair was installed on Building 1 and on a nearby stationary reference building on August 26, 2002. This instrumentation uses a sampling rate of 10 Hz and is able to capture the static and quasi-static (background) displacements of Building 1 (Kijewski-Correa et al., 2006).

4.2 *Instrumentation System for Wind Field Characteristics*

It was necessary to obtain wind speed and direction measurements in downtown Chicago in order to decrease errors in the calculated building responses. In order to obtain an accurate measure of the wind speed at the structures, two ultrasonic anemometers were installed on masts 41 m above the rooftop of the tallest building in the program in the summer of 2004. The anemometers used in this study are the Vaisla WAS425 and FT Technologies FT702 ultrasonic anemometers with operating ranges of 0-65 and 0-70 m/s, respectively. Both have resolutions of 0.1 m/s in wind speed and 1° in wind direction and were installed in the summer of 2004 (Kijewski-Correa et al., 2006). In addition, wind field characteristics are described by the output of the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory (NOAA GLERL) sensor. This sensor is located approximately 4.83 km offshore of Chicago and samples wind velocity once every second. The samples are then recorded in five-minute average intervals (Bashor, 2011). This wind data is used to characterize the wind field corresponding to triggered events.

5 STATIONARY SYSTEM IDENTIFICATION

Ambient system identification (SI) techniques are used to analyze wind-excited structures by invoking the assumption that the excitation can be treated as white noise within the narrow bandwidth of typical civil engineering structures. Customarily, such analyses are executed in the Fourier domain, though they suffer from leakage and resolution issues when there is limited data, while longer records may suffer from non-stationarity. Time series methods may mitigate these issues to some extent, but, depending on the method, still have sensitivities to model order and the amount of data used in averaging and fitting procedures. As such, the analysis of stationary full-scale data from the CFSMP uses the Half Power Band Width (HPBW) Technique for spectral analyses, and an Analytic Signal Approach using Hilbert Transforms on Random Decrement Signatures (RDS) (Kijewski and Kareem 2002; Kijewski-Correa et al., 2006).

5.1 *Half Power Band Width*

The natural frequencies and damping estimates were determined from low-bias power spectral densities (PSDs) using HPBW, where the estimated natural frequency and critical damping ratio for a given mode are defined by:

$$f_n = 0.5(f_1 + f_2) \tag{1}$$

$$\zeta = \frac{f_2 - f_1}{2 f_n} \tag{2}$$

where f_n = natural frequency; f_1, f_2 = the two frequencies corresponding to half the amplitude of the resonant peak;; and ζ = critical damping ratio (Bendat and Piersol, 1986).

5.2 *Random Decrement Technique*

The Random Decrement Technique (RDT) generates an RDS through selective ensemble averaging of the time history of a signal with particular trigger conditions related to the amplitude and slope of the signal (Cole, 1973; Kijewski-Correa, 2003). As the RDS is proportional to the autocorrelation function, estimates of natural frequency and damping can generated by any number of methods that operate on decay curves of mechanical oscillators. In this analysis the stationary response data is first be pre-processed by Butterworth bandpass filters to isolate each mode of interest, and a positive point trigger value is enforced (Bashor et al., 2005). The resulting RDS is then processed using the Hilbert Transform and the frequency and damping estimates are determined from the phase and amplitude of the analytic signal, respectively (Bendat and Piersol, 1986; Kijewski and Kareem, 2003).

6 NON-STATIONARY SYSTEM IDENTIFICATION

Actual wind events are often non-stationary in nature, characterized by sudden changes in wind speed and wind direction. This is most notably the case for thunderstorm related winds, which induce bursts of high amplitude response from structures (Bentz and Kijewski-Correa, 2009a). It is evident from an analysis of thunderstorm databases around the world that thunderstorm winds represent the design wind speed for many locations outside of hurricane belts; however, these events are not taken into consideration during the design process. Thus, it is desirable to evaluate the effects of these events on tall buildings in full-scale (Bashor, 2011).

As the Fourier Transform cannot accommodate non-stationary data, alternate transforms must be invoked to investigate the time-frequency features of transient wind events. In this study, Wavelet Transform-Transformed Singular Value Decomposition (WT-TSVD) was used to decompose these signals. The TSVD is used to decompose the scalogram matrix to concentrate the densities into smaller regions and reduce the effect of noise and is better suited for this task than SVD of its superior ability to separate the energy density concentration of the signal without additional components that are mathematical artifacts. In conjunction with the WT-TSVD method, several techniques were used to extract the natural frequency and damping from the decomposed signals. These include a Feature Descriptor (FD), Wavelet Modulus Decay (WMD) envelopes, Maximum Likelihood Estimators (MLE), and HPBW (Bashor 2001). A brief primer is now provided for each of these methods.

6.1 *Feature Descriptor*

Feature descriptors require the determination of the temporal and spectral moments of the process, as given by Equations 3 and 4, respectively:

$$\left\langle t^m \right\rangle = \int_{-\infty}^{\infty} t^m \left| s(t) \right|^2 dt \tag{3}$$

$$\left\langle f^n \right\rangle = \int_{-\infty}^{\infty} f^n \left| S(f) \right|^2 df \tag{4}$$

where *t* and *f* are time and frequency vectors, *m* and *n* represent the moment order, *s(t)* represents the signal, and *S(f)* is the Fourier Transform of the signal. The time and frequency can then be described as a feature descriptor, defined as

$$F_i = \left(\frac{\sigma_i}{\sigma_1}, \langle t \rangle_i, \langle f \rangle_i, \sqrt{\langle t^2 \rangle_i - \langle t \rangle_i^2}, \sqrt{\langle f^2 \rangle_i - \langle f \rangle_i^2} \right) \tag{5}$$

where for the *i*th feature σ_i and σ_1 are singular values, $\langle t \rangle_i$ and $\langle f \rangle_i$ are the first moments of time and frequency, and $\langle t^2 \rangle_i$ and $\langle f^2 \rangle_i$ are the second moments (Brenner, 2003).

6.2 *Wavelet Modulus Decay*

In this technique the frequency and damping are estimated at a particular frequency value of the wavelet coefficients. When wavelets such as the Morlet wavelet are used, the real and imaginary components of the wavelet coefficients provide a direct estimate of the analytic signal without the need for Hilbert Transforms (Kijewski and Kareem, 2003); Though this technique can only be applied to extract damping estimates from impulse responses or free-vibration decay.

6.3 *Spectral Approaches for Nonstationary Signals*

Spectral approaches for nonstationary signals include HPBW and MLE. While HPBW can be used effectively for stationary signals, this technique is not as effective for non-stationary signals, especially short signals and those exhibiting slow variations in frequency (Bendat, 2000). However, it has been shown that there is an analogy between a normalized spectral density function and a probability density function (Vanmarcke, 1972). This implies that the right singular vector can be treated as a density function and allows spectral analysis techniques to be used for system identification. This analysis is also complemented by the MLE derived on the basis of fitting data to a prescribed linear system transfer function (Bashor, 2011).

7 ANALYSIS AND RESULTS

7.1 *Stationary System Identification*

The dynamic characteristics of the three tall buildings in the CFSMP were determined for two wind events using stationary SI techniques, where stationarity was verified using three separate tests including Run and Reverse Arrangement tests. Blocks of data passing at least two of the three stationarity tests were considered to be sufficiently stationary. The natural frequency and damping ratios estimated using both time and frequency domain techniques for the two wind events are presented in Tables 1 and 2. The wind speed for Wind Event 1 was approximately 20 m/s with an average wind direction of 225° (SW). The wind speed for Wind Event 2 was approximately 23.8 m/s with an average wind direction of 288° (WNW). As can be seen in both Tables 1 and 2, the estimates for natural frequency are consistent for both events between HPBW and RDT; however, the damping estimates show some variability, as expected.

Table 1. Estimated Dynamic Properties for Sample Wind Event 1

Direction	Test	Building 1		Building 2		Building 3	
		f_n (Hz)	ζ (%)	f_n (Hz)	ζ (%)	f_n (Hz)	ζ (%)
X-Sway	HPBW	0.204	0.65	0.178	1.62	0.116	1.46
	HPBW Error (%)	19.61	19.61	17.41	17.41	28.87	28. 87
	RDT	0.204	0.87	0.178	1.42	0.116	1.04
	RDT CoV (%)	0.10	23.88	0.22	7.43	0.25	20.63
Y-Sway	HPBW	0.141	1.14	0.177	2.07	0.116	1.06
	HPBW Error (%)	27.74	27.74	17.41	17.41	28.87	28.87
	RDT	0.141	0.88	0.177	2.41	0.116	1.21
	RDT CoV (%)	0.19	8.89	0.68	8.01	0.14	22.96
Torsion	HPBW	0.503	0.74	0.293	3.14	0.223	1.31
	HPBW Error (%)	13.74	13.74	17.41	17.41	20.41	20.41
	RDT	0.503	0.87	0.293	3.59	0.223	1.33
	RDT CoV (%)	0.07	14.95	0.71	13.41	0.14	16.92

Table 2. Estimated Dynamic Properties for Sample Wind Event 2

Direction	Test	Building 1		Building 2		Building 3	
		f_n (Hz)	ζ (%)	f_n (Hz)	ζ (%)	f_n (Hz)	ζ (%)
X-Sway	HPBW	0.204	1.37	0.178	1.66	0.117	1.59
	HPBW Error (%)	18.57	18.57	22.36	22.36	33.33	33.33
	RDT	0.204	0.89	0.178	1.52	0.117	1.01
	RDT CoV (%)	0.13	12.61	0.31	11.33	0.15	10.18
Y-Sway	HPBW	0.141	0.88	0.176	2.53	0.117	2.01
	HPBW Error (%)	26.73	26.73	22.36	22.36	33.33	33.33
	RDT	0.141	1.00	0.176	2.95	0.116	1.44
	RDT CoV (%)	0.13	6.43	0.96	5.54	0.34	24.20
Torsion	HPBW	0.503	0.71	0.294	3.26	0.224	1.35
	HPBW Error (%)	13.13	13.13	22.36	22.36	23.57	23.57
	RDT	0.502	0.50	0.289	4.20	0.224	1.47
	RDT CoV (%)	0.11	6.08	0.49	5.04	0.09	17.98

7.2 *Comparison of Stationary SI Results with Finite Element Models*

Several hundred storms were identified and analyzed using the SI methods discussed above in Bashor (2011). In general there is good agreement between HPBW and RDT, however HPBW estimates contain more scatter. An important aspect of the CFSMP is to compare the design practices with full-scale data, in which the observed natural frequency and damping values are compared to the natural frequency and damping predictions using finite element models. As demonstrated in Table 3, the predicted natural frequencies for Building 1 were confirmed in full-scale. The discrepancy between predicted and measured natural frequencies in Building 2 are likely because the finite element models assumed a level of cracking in the concrete not yet seen in full-scale. For Building 3, the natural frequency measured in full-scale is lower than that predicted by the models. This discrepancy may stem from a number of sources, including panel-zone deformations, as discussed in Bentz et al. (2010).

The assumed critical damping ratios are generally not consistent with in-situ observations. The assumed damping is larger for Building 1; while the opposite trend is true for Buildings 2 and 3, though it should be noted that the assumed damping for Building 2 is generally less than one would invoke for concrete structures. Though Buildings 1 and 3 are both steel structures for which 1% damping is often assumed, Building 3 is characterized by significantly greater frame action, which has been shown to correlate well with enhanced energy dissipation (Bentz and Kijewski-Correa, 2008).

Table 3. Comparison of Periods and Critical Damping Ratios

Direction	Test	X-Sway T_n (s)	X-Sway ζ (%)	Y-Sway T_n (s)	Y-Sway ζ (%)	Torsion T_n (s)	Torsion ζ (%)
Building 1	FEM /Design Assumption	4.9	1.0	7.0	1.0	2.0	1.0
	Wind Event 1 HPBW	4.9	0.7	7.1	1.1	2.0	0.7
	Wind Event 1 RDT	4.9	0.9	7.1	0.9	2.0	0.9
	Wind Event 2 HPBW	4.9	1.4	7.1	0.9	2.0	0.7
	Wind Event 2 RDT	4.9	0.9	7.1	1.0	2.0	0.5
Building 2	FEM /Design Assumption	6.7	1.0	6.4	1.0	4.6	1.0
	Wind Event 1 HPBW	5.6	1.6	5.6	2.1	3.4	3.1
	Wind Event 1 RDT	5.6	1.4	5.6	2.4	3.4	3.6
	Wind Event 2 HPBW	5.6	1.7	5.7	2.5	3.4	3.3
	Wind Event 2 RDT	5.6	1.5	5.7	3.0	3.5	4.2
Building 3	FEM /Design Assumption	7.7	1.0	7.6	1.0	4.5	1.0
	Wind Event 1 HPBW	8.6	1.5	8.6	1.1	4.5	1.3
	Wind Event 1 RDT	8.6	1.0	8.6	1.2	4.5	1.3
	Wind Event 2 HPBW	8.5	1.6	8.5	2.0	4.5	1.4
	Wind Event 2 RDT	8.5	1.0	8.6	1.4	4.5	1.5

7.3 *Non-Stationary System Identification*

High amplitude bursts have been observed during thunderstorms recorded by the CFSMP and related monitoring programs (Bentz and Kijewski-Correa, 2009a). The rapid amplitude modulations of response associated with the rise and fall of wind speed and variations in wind direction result in acceleration levels that escalate over short durations causing discomfort to building occupants, according to anecdotal evidence obtained from the occupants (Bentz and Kijewski-Correa, 2009b). An example burst is plotted in Figure 1, along with the time-varying mean and standard deviation to demonstrate its non-stationary features. Therefore, a detailed time-frequency analysis of these measured transient responses in conjunction with a similar analysis of the measured wind conditions is necessary to understand the response of such tall buildings due to transient wind events.

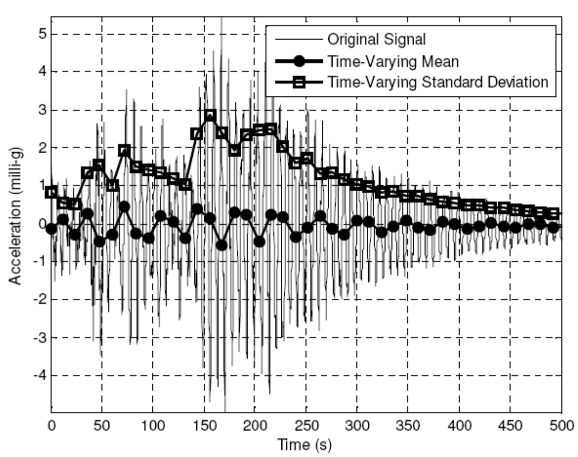

Figure 1. Example Burst from CFSMP with Time-Varying Mean and Standard Deviation for Building 1

The aforementioned techniques were used to estimate the natural frequency and damping of the three structures of the CFSMP during transient wind events. The results of this analysis for the signal in Figure 1 are provided in Table 4, along with estimates of the structure's dynamic properties obtained from previous analysis of stationary full-scale data from the building involving long records during extra-tropical wind events as well as design-stage estimates/assumptions. The natural frequency estimates were found to be consistent with those obtained from stationary wind events for all the non-stationary methods; however, the damping estimates show considerable variation, as expected. Both FD and HPBW over-estimate the damping, likely due to their sensitivity to variance in the marginal spectrum. MLE and WMD were found to give damping estimates slightly below the Stationary SI damping value of 0.90%. In general, the damping values obtained from MLE and WMD with WT-TSVD were determined to be the most consistent with stationary event results.

Table 4. Estimates for Full-Scale Burst Using WT-TSVD, Building 1, Y-Sway

Technique	Natural Frequency Estimate (Hz)	Damping Estimate (%)
Design	0.141	1.00
Stationary SI	0.141	0.90
FD	0.140	1.42
WMD	0.143	0.88
HPBW	0.141	1.47
MLE	0.141	0.77

8 CONCLUDING REMARKS

This study presented both stationary and non-stationary analysis techniques suitable for extracting dynamic properties from the full-scale response of tall buildings. Applications to representative records from the Chicago Full-Scale Monitoring Program demonstrate that frequency estimates determined using stationary methods like Half Power Bandwidth and Random Decrement Technique and non-stationary methods like Wavelet Transform-Transformed Singular Value Decomposition were very consistent; however, the damping estimates determined using these analyses were highly variable. Furthermore, Building 1 demonstrates in-situ properties most consistent with design estimates and assumptions, likely due to its relatively pure structural form (cantilever-dominated) and use of steel. In contrast, the frequency predictions for Buildings 2 and 3 showed greater discrepancies with in-situ values, due to assumptions made in modeling various aspects of their structural systems. These attributes of their lateral systems are likely also contributors to their higher in-situ damping levels. Regardless of the cause, these discrepancies in the dynamic properties may lead to underestimates of the predicted accelerations with direct implications for occupant comfort, potentially leading to buildings that do not satisfy habitability requirements.

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