Identification of Dynamic Properties of a Tall Building from Full-Scale Response Measurements

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ABSTRACT: This study highlights the challenges associated with analyzing full-scale wind-induced response data manifesting intermittent beat phenomena, which limits the use of stationary analysis techniques and prompts this study's application of wavelet-based analysis to identify the onset of beating and explain the responsible mechanisms. As this behavior is not present in every wind event, it is shown that more classical stationary analysis techniques are still capable of identifying frequency and damping within this structure over a range of amplitudes. This data helps to affirm the findings of the wavelet analysis concerning the nonlinearity of the dynamic properties of this structure with closely spaced lateral and torsional modes that facilitates beat phenomenon.

KEYWORDS: system identification, wavelets, wind, full-scale, beating, high-rise buildings.

1 INTRODUCTION

There is a clear need for enhanced understanding of in-situ dynamic behavior of tall buildings, particularly in light of their increasing prominence in society and the importance of parameters such as damping in assuring acceptable habitability performance. For this reason, the initiation of full-scale investigations and the careful analysis of dynamic response data become important. This study hoped to enrich the existing database of full-scale damping estimates by including the properties of an 800-foot (245.7 m) steel building in Boston over a range of amplitudes measured during significant wind events. However, in the process, the work instead evolved into a treatise on the challenges of analyzing data characterized by coupled lateral-torsional response and intermittent beat phenomenon. Since these nonlinear and intermittent characteristics often preclude more traditional analysis frameworks, this paper will introduce the use of wavelet transforms to uncover the mechanisms and manifestations of beating in structures with closely spaced modes. In doing so, it is illustrated that there remain circumstances under which classical stationary analysis techniques can still be invoked for system identification. These stationary analyses further affirm the findings of the wavelets, demonstrating that the onset of beat phenomenon is facilitated by large amplitude response that softens torsion into sway and increase modal damping.

2 DETAILS OF MONITORING PROGRAM

A five-year full-scale monitoring program was initiated between 1973 and 1978 on an 800-foot (245.7 m) steel-framed building in Boston that had manifested some undesirable response characteristics and failure of building envelope components [1]. The extensive monitoring program included the collection of wind velocity 100 feet above the rooftop, pressures and

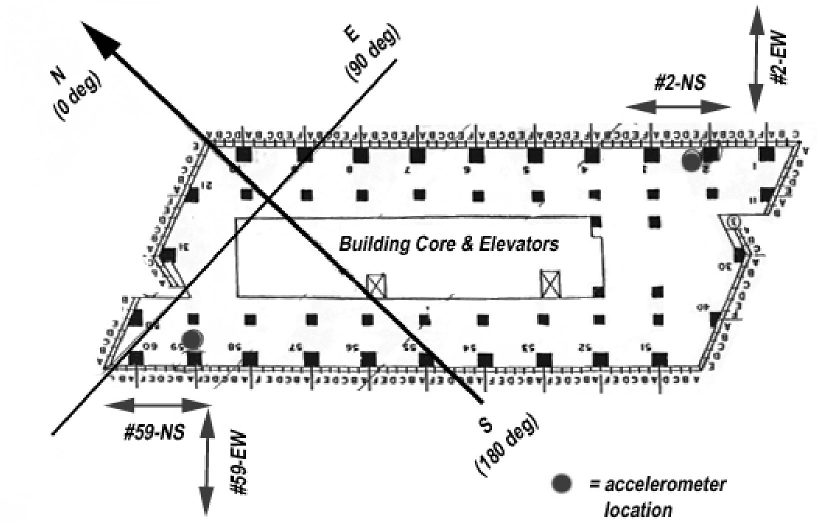

Figure 1. Plan view of monitored building with accelerometer locations and orientations.

accelerations at a number of locations, as analyzed in greater detail in [2]. The accelerometer data, which is of primary interest in this paper, was acquired at 8 locations in the building, with four sensors located on the 57th floor and another four at the 35th with the exact placements shown in plan view in Figure 1. The two sensors measuring the motion parallel to the longer face of the building were termed the “NS” sensors by the original monitoring team. The other sensors capturing motions parallel to the building’s shorter axis were termed “EW”. The sensor pairs are positioned at opposite corners of the building plan and named based on the column lines they are associated with, i.e., 2 or 59, as shown in Figure 1. In this paper, only the accelerations at the 57th floor are considered.

3 DATA ANALYSIS CHALLENGES

The analysis of data obtained from this monitoring program is complicated by the fact that the structure is known to have all three fundamental frequencies closely spaced. Spectral analyses of the data from April 1973 through March 1974 in [2] demonstrated that the fundamental modal frequencies from lowest to highest are: NS sway, followed by EW sway, and finally torsion, as shown in Figure 2a over varying levels of mean hourly wind speed measured 100 feet above the rooftop. The amplitude dependence of frequency is clearly evident, as is the fact that the EW-sway and torsion more dramatically approach one another at higher wind speeds due to a more dramatic amplitude dependence of the torsional frequency. The fact that separation between these two modes diminishes with wind speed was the first indicator that beating may be occurring between the two. In fact, the power spectra produced in this analysis manifested a peculiar characteristic supporting this hypothesis. Depending on the wind speed and direction, the raw Fourier spectra may manifest a pair of peaks (Fig. 2b), corresponding to the known sway and torsion, but at times may demonstrate a single peak (Fig. 2d) or in other instances, three peaks corresponding to the aforementioned sway and torsional modes sandwiching a third peak at a frequency somewhat between the two (Fig. 2c). This latter finding in particular suggested that some intermittent characteristic was present in the time histories, potentially caused by the close proximity of the fundamental torsional and sway modes leading to beating, as

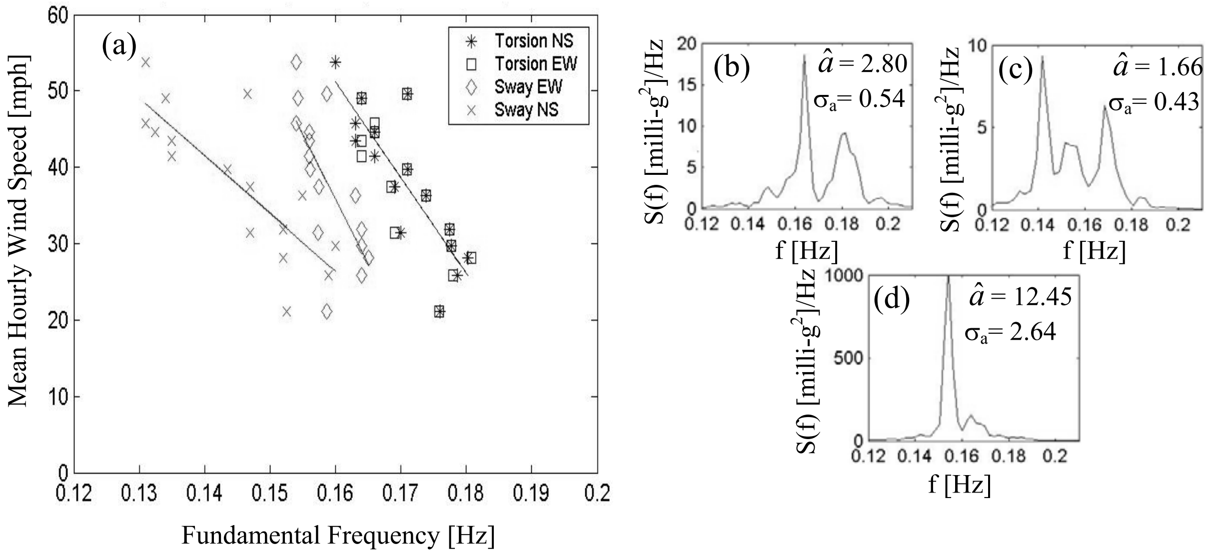

Figure 2. (a) Fundamental frequencies in sway and torsion detected by each of the four sensors at the 57th floor; example of Fourier spectra (without averaging) depicting three different modal responses: (b) 59-EW on 4/5/1973; (c) 02-EW on 11/1/1973; (d) 59-EW on 2/23/1974, insets indicate the peak accelerations and RMS accelerations, respectively, associated with that spectrum in milli-g.

demonstrated by the subsequent wavelet analyses. Note that the resolutions obtainable in Figure 2b-d are somewhat constrained by the length of data available.

Nevertheless, even in cases where the Fourier spectra did not manifest this third intermediate peak, the customary algebraic manipulation of the time histories to separate the sway and torsional contributions were often unsuccessful due to the inability of floor diaphragms in completely engaging the lateral system over the entire building cross-section. As a result, the torsion could never be completely canceled to leave the sway response, requiring the data to be treated as a two-degree-of-freedom system (2DOF), as discussed in Section 5.

4 WAVELET ANALYSIS FOR MARCH 10, 1974 RECORD

To demonstrate the unique characteristics of intermittent beat phenomenon observed in this building, a wavelet analysis is offered for a record obtained on March 10, 1974 that resulted in the largest levels of peak accelerations observed in the data set. Over the course of this hour-long record, the mean wind speed, measured at 100 ft (30.5 m) above the rooftop, was 53.7 mph (24 m/s), gusting to 77.3 mph (34.5 m/s), primarily out of the west-northwest at 290°. Referring back to Figure 1, this indicates that the winds are impacting the corner of the building near the sensors at column line 59 (windward corner).

For the sake of brevity, the details of the wavelet-based analysis framework cannot be fully detailed here, however some rudimentary information is provided for those who do not have experience with the transform and other references, e.g., [3], provide additional details, while the full description of this framework may be found in [4]. The transform and parent wavelet used herein are provided by the following expressions:

$$W(a,t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(\tau) g^{*}\left(\frac{\tau - t}{a}\right) dt \qquad \text{where} \quad g(t) = e^{-|t|^{2}/2} e^{j2\pi f_{o} t} \qquad (1)$$

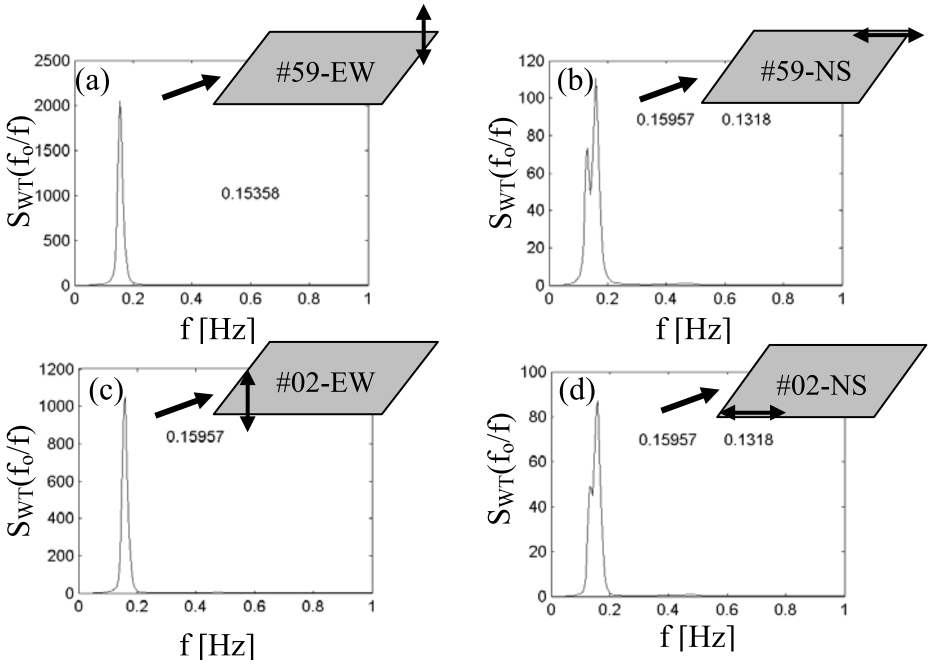

Figure 3.Wavelet marginal spectra for the four accelerometers at the 57th floor.

The continuous wavelet transform matches scaled and translated versions of a parent wavelet *g(t)* to the signal *x(t)* at every instant in time to determine the energy density as a function of both time and scale *a*. While a host of parent wavelets are available in the literature, the Morlet in Equation 1 is adopted here due to its unique analogs to the Fourier transform and its direct relationship between the wavelet's scale *a* and Fourier frequency *f*: the two are inversely related via the Morlet wavelet's central frequency f_o ($f = f_o/a$). This central frequency parameter dictates the time and frequency resolution of the wavelet, as well as its ability to separate closely spaced modes [4]. Therefore f_o = 3 Hz was selected, capable of achieving this separation down to 0.012 Hz. The resulting energy density associated with time t_j can be isolated to form a *wavelet instantaneous spectrum,* $SG(f_o/f,t=t_j)$, which will be investigated to track the time-dependent signal characteristics. By integrating theses instantaneous spectra over all time, a *wavelet marginal spectrum*, $S_{WT}(f_o/f)$, similar to a Fourier spectrum, is obtained for a global perspective of the signal frequency content, as shown in Figure 3 for each accelerometer output during this event, with the mean wind direction and sensor placement shown by schematic insets.

Figures 3b and 3d manifest two modes -- the softer of the two associated with the fundamental sway mode along the NS axis, while the higher frequency is associated with the first torsional mode. Note interestingly that in Figures 3a and 3c, the other sway mode is oddly not present, with only dominant torsion detected in the EW sensors. In fact, all the spectra reflect that the motion is dominated by torsion. This is a disturbing feature since torsional accelerations are the most perceivable motions from an occupant comfort perspective. The consistency between Figures 3b and 3d affirms a torsional frequency of 0.160 Hz and NS sway of 0.132 Hz, while the EW sway cannot be identified from the marginal spectra in Figures 3a and 3c. The torsional frequency is again confirmed as 0.160 Hz according to Figure 3c; however, Figure 3a provides the most interesting point of discussion: here at the leeward face of the building, the torsional frequency appears to be softer (0.153 Hz) and associated with a far greater spectral amplitude than its counterpart. Hence, these global spectra for the EW sensors would indicate that the building is twisting at two different frequencies and moving markedly more at the

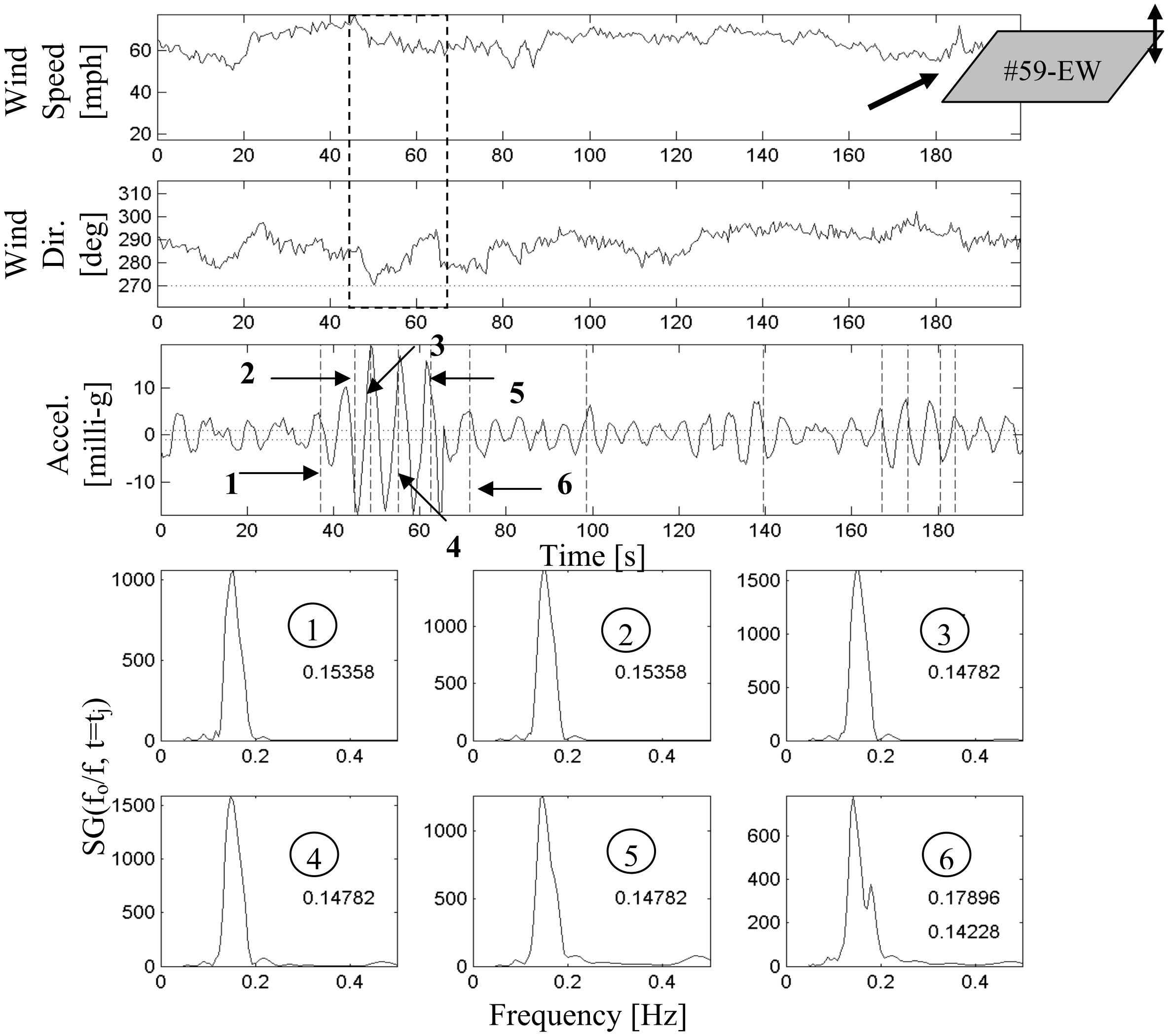

Figure 4. Wind speed, direction and acceleration at #59-EW with wavelet instantaneous spectral analysis.

leeward corner, effectively fishtailing in the wind suggestive of eccentricity between mass and elastic center, an intriguing feature that will be explored utilizing wavelet transforms.

The analysis of this feature and its explanation can commence through an analysis of the largest amplitude motion observed during this record using instantaneous wavelet spectra taken at varying points in the response. These spectra are shown in Figure 4 with the numbering sequence identifying the points in the time history associated with each instantaneous spectrum. During this event, the highest amplitude response occurs when the wind direction shifts and aligns with the corner of the building (270°). It is just prior to and following this highly energetic burst that the single mode response, identified in the global marginal spectrum at 0.153 Hz, is observed. Note the large bandwidth associated with this spectral peak, broadening toward the high frequencies, suggestive of a coalescence of the two modes. The wide bandwidth of the response in conjunction with the wind direction supports the conclusion that both the EW sway and torsional responses are sufficiently large and simultaneous in the response, leading to beating that is characterized by a melding of spectral bandwidth. In instantaneous spectra 1-3, this strong vibration is stimulated by the wind direction shift, proving critical for this building's

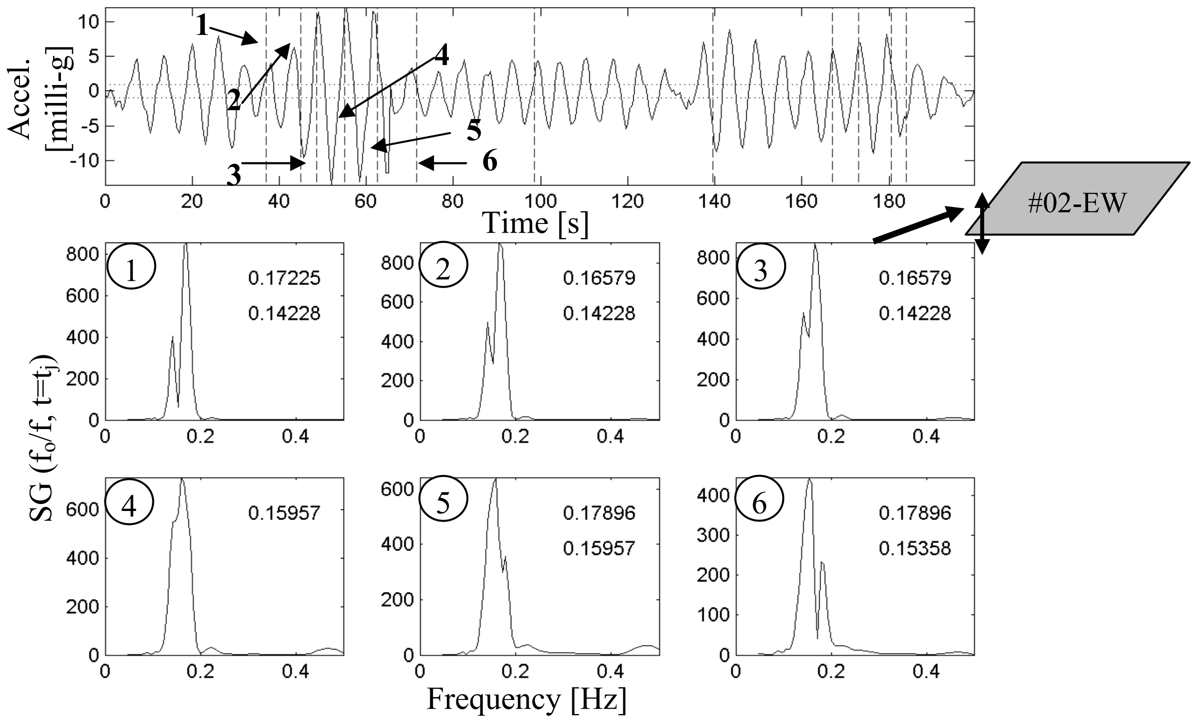

Figure 5. Acceleration response at #02-EW with wavelet instantaneous spectral analysis.

geometry within the site-specific surroundings. Of the data collected, this wind direction shift is only observed in this record and this is consequently the only time motions of this structure reach the 20 milli-g levels. As the amplitude increases in the 3rd, 4th and 5th spectra, a shift of this spectral peak to a lower frequency of 0.148 Hz occurs. This is the characteristic temporary softening of frequency that has been observed in full-scale measurements during large amplitude events and even on a global scale, as shown in Figure 2a. More importantly, as the wind direction shifts back toward 280°, the response level diminishes and spectra 5 and 6 begin to separate into two peaks reminiscent of the anticipated bi-modal response. This behavior indicates that the isolated high amplitude motions are associated with beat phenomenon facilitated by the presence of significant sway and torsion. It is hypothesized that the onset of beat phenomenon within the system is aided by the nonlinearities in stiffness (Fig. 2a) and damping that can shift the torsional and sway modes toward one another and markedly accentuate spectral bandwidths.

An investigation of the behavior of the #02-EW sensor, measuring the same direction of motion but at the windward corner of the building provides added insights. At the windward face, where global spectra in Figure 3c previously did not detect a discernable bi-modal response, the instantaneous wavelet spectra in Figure 5, taken at the same times as those shown in Figure 4, clearly manifest both modes prior to the high amplitude response, though torsion again dominates. Interestingly, these two modes occupy the same spectral band as the single mode response shown previously in the instantaneous spectra numbered 1-4 in Figure 4. During high amplitude motion, spectra 2-3 manifest some melding and softening of torsion into the lower sway mode. At the highest amplitude of motion, the two modes nearly coalesce as observed at the leeward face of the building, but this transformation is not ever fully realized, reinforcing the particular local features that facilitate this behavior. As a result, full melding never occurs in spectra 4-6, as torsion diminishes and sway starts to dominate. The continuous

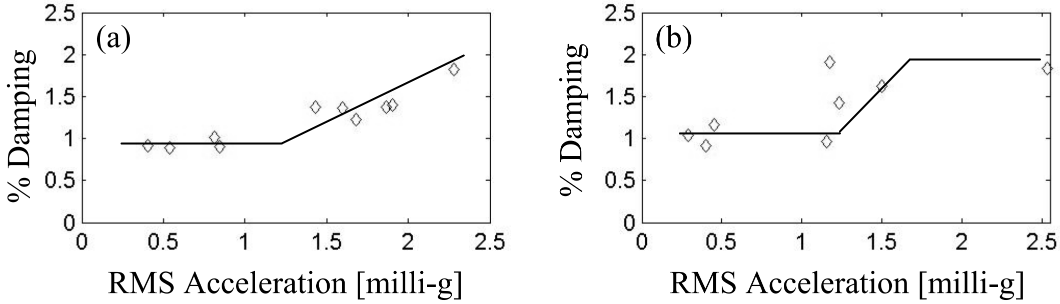

Figure 6. Variation of sway damping with amplitude of motion in EW sensors. Damping estimated from (a) 2DOF fit to power spectra and (b) from half power bandwidth of power spectrum.

beating observed previously in Figure 4 was not observed at this location due to the fact that both the sway and torsional response components were not in equal measure at this location, emphasizing the localized features of the energetic event shown in Figure 4. On the other hand, when examining the two sensors capturing the NS response, not shown for brevity but provided in [4], the leeward sensor again manifests a moderate beat phenomenon, though not as distinct due to the lesser magnitude of the NS response in comparison to EW sway. However, this is not observed at the windward sensor, again affirming the localized nature of this high-amplitude motion.

5 SYSTEM IDENTIFICATION

Considering the transience of the beat phenomenon discussed in Section 4, only records that did not manifest the three spectral peaks shown in Figure 2c could be considered for stationary Fourier spectral analysis. Further, as mentioned previously, the diaphragm flexibility often results in an unequal distribution of response over the cross section, a feature especially evident in the NS measurements, as affirmed by diminished response in the leeward NS sensors. For this reason, the estimation of damping presented herein will only consider the EW sensor information, for which the assumption of a rigid diaphragm is more warranted. However, even in the EW sensor data, concerns over diaphragm rigidity surface to a lesser extent, as the customary algebraic manipulation is still proves incapable of separating the torsional components from the sway response. In addition, as shown by Figure 2a, due to the close proximity of the modes, traditional digital filtering is equally incapable of separating the sway and torsion. As a result, the damping will be estimated by two methodologies: by fitting the transfer function of a 2DOF system to the power spectra from the EW sensors and by a half power bandwidth approximation of the power spectral peaks associated with each mode. Since the narrow bandwidth of the system requires significant amounts of data to minimize spectral bias, limiting the number of spectral averages to reduce variance, the former technique likely produces a more reliable estimate of damping.

The EW sensor sway damping was identified in this manner from records associated with varying response levels (Fig. 6). Though there is limited useable data at higher amplitudes, the apparent trend of the data set is consistent with the findings of Jeary [5], showing a lower plateau of damping that then transitions with the amplitude of motion toward higher damping levels consistent with increased frictional losses in the structural system. This nonlinearity of damping, affirmed by both system identification approaches, affirms the overall theory that a nonlinearity of frequency as well as damping, helps to contribute to the beat phenomenon in this structure. As discussed by Yalla & Kareem [6], in systems with closely coupled modes, the bi-modal beat phenomenon is suppressed as the two modal frequencies coalesce into a single frequency, as observed in the wavelet analyses in Figure 4. The authors demonstrate that this is particularly facilitated through an increase in damping, though it is hypothesized here that the combined effect of nonlinearities in stiffness, accompanied by an increase in damping, achieves the same effect in this structure, though this requires amplitude levels sufficient to induce the nonlinearity.

6 CONCLUSIONS

This study demonstrated that the evolution of a coalescent beat phenomenon is not apparent from a Fourier spectral perspective. Through the use of wavelets, the coalescence characterizing beat phenomenon was found only to occur under unique situations where the amplitude of motion is high enough to enhance nonlinearities in period and damping and when the sway and torsional contributions are of comparable magnitude to beat with one another. However, this phenomenon appears to be highly local, since this coalescent phenomenon was most pronounced at the leeward corner of the building. Fourier spectral analyses affirm the nonlinearity of frequency and demonstrate that the torsional frequency more significantly varies with amplitude, eventually approaching the EW sway. The analysis of data deemed to be sufficiently stationary revealed an increase of sway damping with amplitude that could be equally credited to increase spectral bandwidth. The combination of these two features and the comparable presence of sway and torsion beating one another are responsible for the coalescence observed in the wavelet analyses. The analysis herein ultimately demonstrates that Fourier perspectives fail to treat intermittent phenomenon, demanding careful interpretation of such stationary perspectives, and often requires the use of emerging time-frequency analysis frameworks.

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