Analysis of full-scale data from a tall building in Boston: damping estimates

T. Kijewski
NatHaz Modeling Laboratory, Dept. of Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA

A. Kareem
NatHaz Modeling Laboratory, Dept. of Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA

ABSTRACT: The following study addresses one of the issues facing modern skyscrapers by examining the dynamic characteristics of a 244 meter tall building through the analysis of measured full scale data. The building under consideration was studied for a period of five years, during which time it experienced numerous severe wind events. The acceleration and pressure data collected during this period provides an excellent opportunity to study the response of tall buildings under the action of wind in an urban environment and extract the dynamic characteristics, particularly, the inherent damping, over various levels of excitation through a host techniques including the random decrement technique and AR spectral estimations for random data.

1 INTRODUCTION

As the height and flexibility of modern skyscrapers grows, so too does the need for better understanding of their dynamic behavior, particularly to insure that such structures can be engineered with sufficient damping to withstand the demands of relentless winds which threaten habitability. However, unlike easily quantifiable properties like mass and stiffness, the level of damping is an ambiguous quantity, varying with the amplitude of the excitation and depending upon complex mechanisms within the structure, many of which are still not fully understood. As a result, the estimation of damping continues to pose significant challenges to the engineering community. While the demand for accurate damping estimates in design is becoming ever so urgent, there still is no one technique to estimate its level in structures. Furthermore, since forced vibration tests are not convenient for large structures, ambient excitation records must be considered, further complicating these efforts.

The following study addresses these issues by examining the dynamic characteristics of a 244 meter tall building through the analysis of measured full scale data. The building under consideration was studied for a period of five years during which time it was subjected to numerous severe wind events. The acceleration and pressure data collected during this period provides an excellent opportunity to study the response of tall buildings under the action of wind in an urban environment and extract the dynamic characteristics, particularly, the inherent damping, over various levels of excitation.

1.1 *Damping Estimation*

The estimation of system parameters such as frequency and damping from ambient records poses significant challenges, since no knowledge of the exact input is technically known, though the white noise assumption typically applies. This problem of system identification can be assessed by various techniques, including spectral-based techniques, adaptive filtering, free-decay curve analyses, stochastic approaches, and the random decrement technique. Arguably, spectral techniques have served as a primary mode for analysis via applications including half power method, spectral moments, and spectral curve fitting via least squares and maximum likelihood estimators (Montpellier et al. 1998); however, the requirements of stationary and lengthy records for adequate spectral resolution restrict their applicability. Wavelet-based analyses offer an alternative in that they exactly reproduce the signal energy which spectral approaches cannot due to the leakage that results in raggedness of the spectral curves. These approaches will be explored in future work as they give superior resolution at low frequencies in comparison to traditional spectral approaches. Alternatively, investigations into time domain approaches have yielded a variety of schemes which also overcome the limitations of spectral techniques, one of the most promising of which is the random decrement. This approach estimates damping from the ensemble average of segments of the structure's response, assuming the structure to be a linear system. The requirement of specific initial conditions for each segment in the averaging procedure yields a signature which represents free vibration of the system from an initial threshold, from which damping estimates are readily extracted. The application of this technique to the data collected from the 244 meter building is developed in this study. In addition the use of autoregressive modeling for obtaining spectral estimates of random data is also explored.

Consequently, this study marks the first in a series of critical evaluations of existing and new techniques to estimate damping in structures using full scale data, providing an insightful comparison and examination of available methodologies.

2 FULL SCALE DATA ACQUISITION

The 244 meter building under consideration was monitored for a period of five years by 33 transducers measuring pressure, window and mullion deflections, and horizontal building accelerations at various locations, along with the wind speed and direction. The data was selectively recorded at times when the wind speed, as determined from an anemometer mounted 30.5 meters above the building, registered wind speeds exceeding 13.4 m/s yielding 20,000 transducer hours of data. The first 2 years of data, sampled at a frequency of 2 Hz, was reduced to engineering units and transferred to magnetic tapes for analysis providing approximately 3000 transducer hours of data.

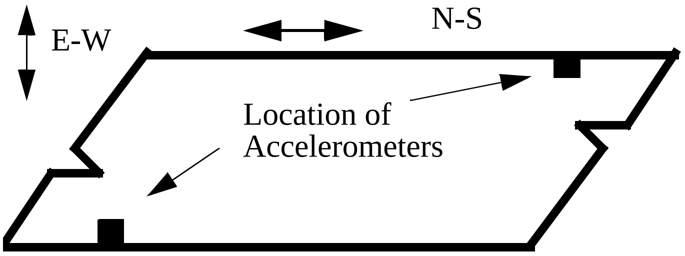

Figure 1. Plan view of building under study.

Of particular relevance to this study are the 8 accelerations, measured at two locations in the structure's plan, as shown in Figure 1, at both the 35th and 57th floors, which correspond approximately to mid-height and full height of the structure. The acceleration data, for both north-south and east-west motions, are representative of the structure at various stages in its lifetime, from modifications to the structural frame, to the addition of a TMD, and during occupation. More information on the monitoring study may be found in Durgin & Hansen 1987.

STATIONARITY ANALYSIS

The application of spectral approaches is contingent upon the existence of a stationary data set. As is often the case with wind-induced excitation, stationarity cannot be established for lengthy durations of time, as is the case for the data set in question. In particular, since the data assembled in this study was explicitly recorded during major wind events, the fluctuations in the wind speed, direction, and resulting acceleration responses are considerable, as illustrated by Figure 2. The first 50 minutes of data show considerable variation in the RMS acceleration. Note that the median value of the RMS acceleration is 0.4555 milli-g. Performing a Reverse Arrangements test for stationarity (Bendat & Piersol 1986) on the RMS accelerations, analyzing them in sequential 100 sample segments, revealed that 34% of the record shown did not pass the stationarity test for a 1% level of significance, indicating that one third of the record is not stationary for even short intervals of approximately one minute. Similar results were found for other records analyzed in this study and is a direct consequence of the extreme wind events monitored exclusively in this study. Typically, full scale monitoring projects are concerned with continuous observations of a structure in primarily moderate wind events, but the fact that the data provided herein typify extreme events, adds particular restriction to assumptions of stationarity.

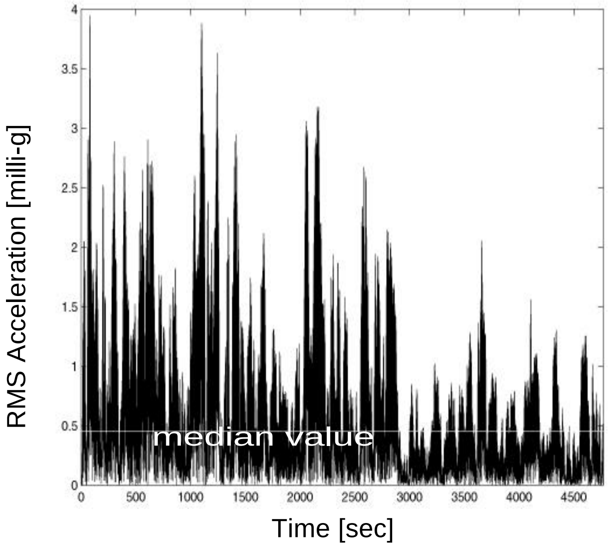

Figure 2. RMS acceleration for 1.5 hours of data.

3 DYNAMIC ANALYSIS

The following sections outline the dynamic analysis procedures applied in this study. Note that frequency domain analyses consider frequencies up to 1 Hz only, since the data acquisition process did not incorporate anti-aliasing filters. Since the data was sampled at a rate of 2 Hz, aliasing was not a problem since the contributions of frequencies above the Nyquist frequency of 1 Hz are assumed negligible.

3.1 *Spectral fitting via AR model*

The use of spectral techniques is prohibited without the establishment of a stationary set, though assumptions of stationarity are often made in the analysis of wind-excited data without such validation. As shown previously, the establishment of such criteria proved especially challenging with this data, considering the lack of moderate ambient conditions in the available records. Irregardless, typical methods for evaluating damping and natural frequency require some knowledge of the approximate frequencies of the modes before any analysis may proceed, i.e. for the purpose of bandpassing data, etc. Considering the severe deficiency of stationary requirements in this data, alternative approaches were exercised to conduct a spectral analysis. A variety of approaches for simulation and analysis of stationary and transient processes have been explored including the application of autoregressive and moving averages or ARMA models (Li & Kareem 1990) and their resulting spectra (Cao et al. 1995).

An ARMA model consists of the summation of autoregressive terms and a weighted summation of white noise inputs. A model of order p and q, defined as a linear filter, permits the simulation of a random process by its past time histories and the past and present white noise process via:

$$x(k) = -\sum_{n=1}^{p} a_n x(k-n) + \sum_{n=0}^{q} b_n v(k-n) \tag{1}$$

which has a transfer function given by:

$$H(z) = \frac{B(z)}{A(z)} = \frac{b_o + b_1 z^{-1} \dots + b_q z^{-q}}{1 + a_1 z^{-1} \dots + a_p z^{-p}} \tag{2}$$

where v is a zero mean, white noise process with standard deviation σ_v, the a_i's are the autoregressive parameters and b_i's are the moving average parameters. By setting b_0=1 and all other b_i's to zero, an autoregressive model results, with power spectral density (PSD) given by:

$$Pxx(z) = \sigma_v^2 / (A(z)A(z^{-1})) \tag{3}$$

Note that the assumption of white noise input is traditionally valid for wind-excited structures. Thus, preliminary autoregressive parameters were determined using a Yule-Walker scheme applied to the zero mean acceleration data with a 2000 point buffer and 1500 point buffer overlap and 512 point spectral resolution. Since the AR scheme is a parametric spectral estimator, the selection of model order p becomes very important. In order to successfully fit spectral data with several modes, the models were first calibrated on a MDOF system with known damping and stiffness to establish that models on the order of 20 were necessary to adequately capture multiple modes of data. As Figure 3 illustrates, the all pole AR model provides a smooth fit to data which would otherwise fall victim to poor spectral resolution using typical fourier transform approaches, which are not valid due to the lack of sufficient stationarity.

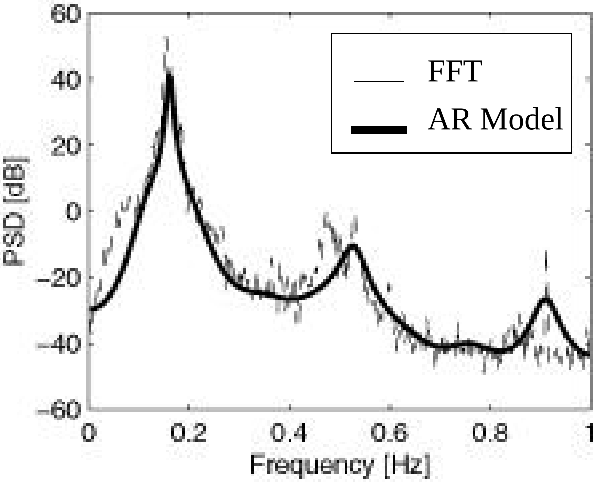

Figure 3. AR fit of power spectral density.

The spectra reveal the dominance of the first mode response, as typically observed under the action of wind. While the presence of higher modes was observed, the analyses which follow will be concerned with the fundamental mode of the structure.

3.2 *Spectral approach*

While spectral approaches are typically less desirable due to their limitations and the presence of bias and random errors, a half power bandwidth analysis was conducted on the AR fits of the first mode of the building to determine an estimate of damping and explore the validity of spectral estimates provided by AR models. By this simple method, the damping ratio, ξ, is given by:

$$\xi = (f_1 - f_2)/(f_1 + f_2) \tag{4}$$

where f_1 and f_2 are the frequencies corresponding to the value of the spectral peak/$(\sqrt{2})$, as illustrated in Figure 4. Since this technique is highly sensitive to spectral resolution, 2048 spectral points were used to produce a more refined, high order AR fit about the first mode, in efforts to obtain at least 4 spectral lines in the half power bandwidth and roughly 160 cycles of the fundamental frequency in the spectral estimate. As Figure 4 illustrates, linear interpolation was applied between the AR spectral estimates. Unfortunately, since damping is a nonlinear function of amplitude, this approach provides an estimate which averages the responses at all amplitude levels, giving no insight into the dependence of damping on the level of excitation (Jeary 1996).

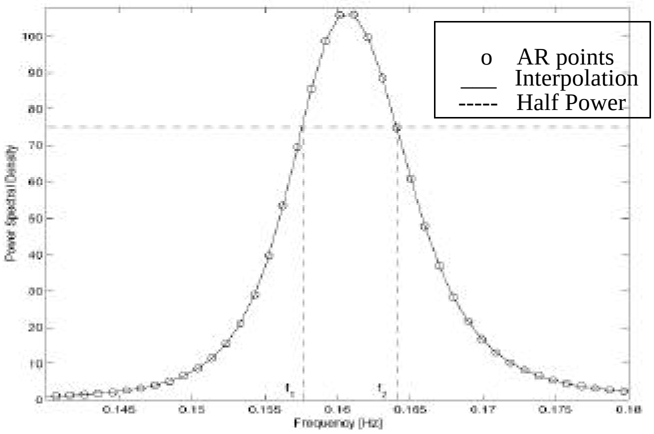

Figure 4. Half power bandwidth applied to AR fit.

3.3 *Random decrement technique*

The requirements for stationarity can be eased through the use of the random decrement technique (RDT), as first proposed by Cole (1973) to estimate the damping in spacecraft. The concept is based upon the fact that the response of system can be assumed to be a linear superposition of several components:

$$x_T = x_{xo} + x_{\dot{x}o} + x_F \tag{5}$$

those being that due to an initial displacement, an initial velocity, and the forced response, respectively. Through the selective ensemble averaging of segments in the response, the latter two terms average out, leaving a free vibration decay or decrement signature, described by:

$$\eta(\tau) = \frac{1}{N}\sum_{i=1}^{N} x_i(t_i + \tau) \tag{6}$$

where N is the number of segments in the ensemble and x_i is the threshold value which occurs at time t_i.

RDT may be easily executed on sets of data by preselecting a threshold value and storing the portion of the time history which corresponds to the subsequent passing of the threshold value. However, prior to analysis, the data must be bandpass filtered about the natural frequency, since the approach is restricted to SDOF systems. An eight pole elliptic bandpass filter was well-suited for this task.

Since the response of a building, under the broadband action of wind, is typically a narrowband process, the assumption of a Gaussian, stationary, white noise input is valid, the decrement signature can be treated as a free vibration response and damping can be approximated by any appropriate method, e.g. logarithmic decrement, half amplitude (Kareem & Gurley 1996).

In addition to overcoming more stringent requirements for stationarity, RDT is also attractive in that the decrement signature may be referenced to a specific amplitude, allowing investigation of the influence of response amplitude on dynamic characteristics that is otherwise not possible through spectral-based techniques (Tamura & Suganuma 1996). Statistical analysis of the acceleration data in this study revealed the mark of a Gaussian distribution, and thus random decrement thresholds examined were chosen as multiples of the standard deviation of the acceleration response: 0.5σ, 1.0 σ, 1.5 σ, 2.0 σ and 2.5 σ. Figure 5 illustrates four signatures which were produced from a given record with four different threshold values. The number of samples in the ensemble ranged between 100 and 1000, depending on the threshold value. While there has been some discussion on the number of ensemble averages required to produce accurate results, Jeary (1996) has noted that 100 averages produced acceptable results, though up to 2000 averages is optimal (Tamura & Suganuma 1996).

Once a signature was produced, the damping estimates were extracted by two techniques, the logarithmic decrement with damping ratio defined as:

$$\zeta = \frac{1}{2\pi(j-i)}\ln\left(\frac{p_i}{p_j}\right) \tag{7}$$

where p_i and p_j are the ith and jth peaks in the decay signature, and a least squares fit of the decrement signature with a free vibration response described by:

$$\begin{aligned}\eta(\tau) &= x_i\cos\left(2\pi f_n\sqrt{1-\zeta^2}\tau\right)\exp(-\zeta 2\pi f_n\tau)\\ &+ \frac{\zeta}{\sqrt{1-\zeta^2}}x_i\sin\left(2\pi f_n\sqrt{1-\zeta^2}\tau\right)\exp(-\zeta 2\pi f_n\tau)\end{aligned} \tag{8}$$

where f_n is the natural frequency. Both of these techniques were applied over 5 cycles in the signature. Also note that a frequency estimate was determined from the RDT by averaging the signature's frequency of 5 consecutive cycles. Figure 5 illustrates the presence of nonlinearities, as the least squares fit and the RD signature begin to deviate beyond 5 cycles. These frequency results were later compared with a least squares fit of the AR spectra.

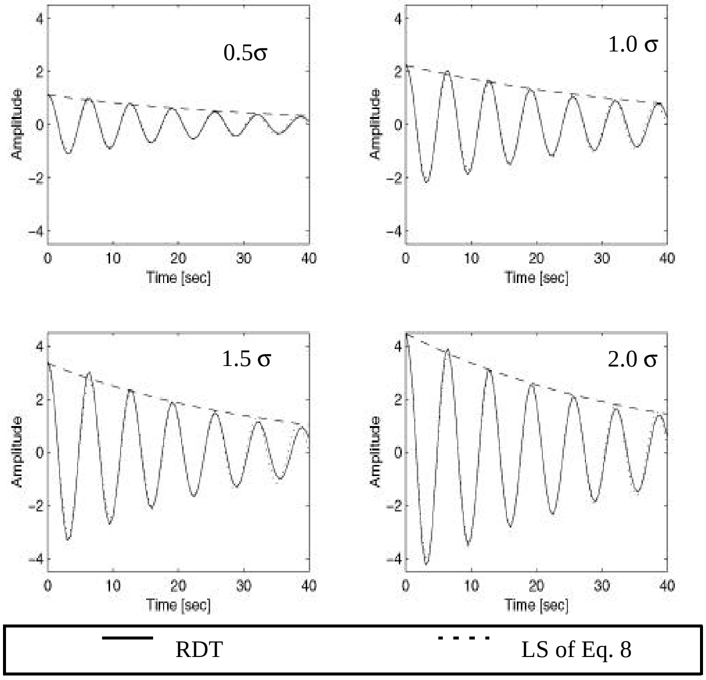

Figure 5. RDT signatures for various thresholds.

4 DISCUSSION OF RESULTS

Table 1 features a comparison of selected damping estimates provided by the half power bandwidth and random decrement techniques. The mean of the frequency and damping determined by the least squares fit of Equation 8 for the RDT signature is presented for a comparison, in the average sense, with the AR spectral estimates. In addition, Table 1 contains the natural frequency estimated by a least squares fit of the AR spectral data for comparison with the frequency estimated from the random decrement technique, along with the percent deviation of the half power estimate from the RDT estimate, and the RMS acceleration of the record. As expected, the frequency estimates show excellent agreement. More importantly, the AR spectra produces damping estimates in an averaged sense which correspond well with mean values estimated by the random decrement technique. Typically, the use of spectral estimates would not be possible due to the non-stationarity of the data set, however, the parametric AR model produces spectral estimates that compare well with the decrement generated estimates.

Figure 6 illustrates the influence of threshold amplitude on the frequency and damping of the structure. The squares and circles indicate the results of frequency and damping estimates obtained for accelerations recorded in year 1, while the diamonds and stars represent estimates from data one year later. As one would expect, there is a moderate decrease in natural frequency with increasing amplitude. Interestingly, the first year data has a markedly higher frequency. This may be due to the fact that the building was in various states of occupation and design during the study, emphasizing the significance of the structure's function and state at the time of dynamic testing. In contrast, the damping estimates, despite significant scatter, increase with amplitude, with the estimates from year 2 manifesting lower levels of damping. This may be due once again to changes in the structure and its occupancy, or resulting from the fact that some of the RD signatures for year 1 lacked a sufficient number of cycles for analysis. This raises an often overlooked consideration. Though RDT does not have as stringent requirements for lengthy stationary records, the records should represent a self-stationary set. While Jeary (1996) observed that careful screening of the data for great changes in amplitude will allow the data to be essentially forced into stationary sets; however, due to the variability in the data which was collected during these significant wind events, such screening was not possible. Thus, signatures were inherently limited to the stationary length of the record, which, as section 3 illustrates, were only on the order of one minute.

Table 1: Comparison of dynamic properties estimated by AR approach and RDT least squares fit.

		AR Spectra		RDT		% Difference	
Location	σ_a [milli-g]	f_n [Hz]	ξ [%]	f_n [Hz]	ξ [%]	Δf_n	$\Delta\xi$
35th Floor/South End	0.784	0.162	1.95	0.159	2.25	1.89%	13%
35th Floor/North End	1.38	0.160	3.07	0.156	2.81	2.56%	9.25%
57th Floor/South End	2.28	0.162	2.01	0.158	2.15	2.53%	6.5%
57th Floor/North End	4.97	0.161	2.38	0.156	2.69	1.03%	7.43%

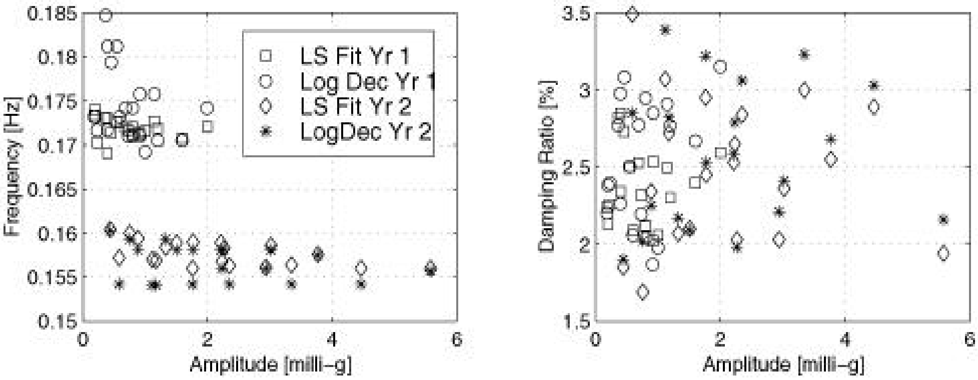

Figure 6. Comparison of dynamic properties of the first mode as a function of amplitude using RDT.

For a building of significant period, this implies only 5 to 8 cycles are available for least squares fit by Equation 8, clarifying this study's selection of the first five cycles for least squares fit, permitting some level of consistency between estimates. Understandably, less scatter would be expected if more cycles were available for the fit. Investigations of systems with known damping and frequency indicate that this error may be +20%. In general, however, the least squares and logarithmic decrement estimates seem to agree well over the range of amplitudes.

5 CONCLUSIONS

This study initiates an ongoing examination of ambient data for a 244 meter building under extreme wind conditions to further understand the dynamic response of tall buildings. Since the data set consists primarily of "storm" events, lengthy stationarity requirements could not be met; however, an AR approach proved to be helpful in producing a spectra suited for analysis of the dynamic characteristics of the building. Still, spectral representations give no insight into the variation of dynamic properties with amplitude, but instead provide information in an "averaged" sense. Accordingly, dynamic estimates extracted from these spectra agreed well with the mean of amplitude-dependent random decrement estimates. However, it should be noted that such models must be used with care as they are very sensitive to model order, which should be high enough as to yield sufficient spectral resolution. The random decrement technique was investigated, permitting meaningful analysis without strict stationary requirements and allowed for the study of the influence of the level of excitation upon the dynamic characteristics, a feature obscured by spectral approaches.

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