Analysis of Wind and Wind Effects Revisited - A Case Study of Deer Isle-Sedgwick Bridge

by

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ABSTRACT

In 1980 the Federal Highway Administration began a detailed study of the wind-induced oscillations of the Deer Isle-Sedgwick Bridge. The bridge is instrumented with an array of anemometers and accelerometers which measure wind velocity and bridge response. The present study analyzes the wind-induced motion of the bridge to determine fundamental frequencies and mode shapes. It introduces Proper Orthogonal Decomposition (POD) as a technique for determining primary frequencies and mode shapes and compares the results to those obtained using spectral analysis exclusively. It utilizes wavelet transform (WT) analysis to investigate energy content of temporal flow events and peaks of the bridge deck response. Both the POD and WT techniques are found to be useful in analysis of wind flow and wind-induced response of the bridge deck.

KEYWORDS: wind, proper orthogonal decomposition, wavelet analysis, bridge response, field measurements, aerodynamic response.

1. INTRODUCTION

The Deer Isle-Sedgwick Bridge (DISB) is a long-span suspension bridge similar in cross-section to the old Tacoma Narrows Bridge, which failed catastrophically in 1940 due to wind-induced structural vibration. The failure of the Tacoma Narrows Bridge made evident the need for detailed analysis of the dynamic behavior of long-span bridges subjected to wind loading. The DISB's design was augmented with many structural modifications to minimize wind-induced oscillations, but significant response is still observed. In 1980, the Federal Highway Administration (FHWA) began a detailed study of the wind-induced motion of the DISB. The present paper describes analysis of the FHWA data to establish wind characteristics at the bridge site and to determine mode shapes and natural frequencies of bridge oscillation. It introduces new tools for wind and bridge response data analysis: the Proper Orthogonal Decomposition (POD) and Wavelet Transform (WT) analysis. The POD is shown to be effective in determining vibrational characteristics of the bridge. The WT is employed in analysis of the bridge peak response.

2. BACKGROUND

2.1 Conventional Analysis

Conventional analysis of wind and wind induced effects on bridges, buildings and other structures is frequently carried out in frequency domain, using spectral approach.

2.1.1 Wind Field

Wind flow in the atmospheric boundary layer is usually described for wind components in three orthogonal directions: along-wind, lateral, and vertical. The characteristics of fluctuations of these components are typically specified by power spectra, which are compared with empirical

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spectral formulas based on field measurements. A number of such formulas have been proposed. The spectral models recommended by Kaimal, Harris, and Lumley and Panofsky, Simiu and Scanlan (1996), are considered in this paper.

2.1.2 Bridge Response

Fundamental frequencies of oscillation of lightly damped structures can be determined from spectral analysis of response measurements. The peaks in the autospectra of the response are either due to peaks in the excitation spectra or normal mode oscillations. The cause of such peaks can be determined by analyzing the phase information of the cross-spectra between measurements at different points on the structure. In case of a bridge deck, vertical (bending) and torsional modes can be distinguished by analyzing the cross-spectrum between measurements at two laterally spaced points on the structure. The measurements in phase indicate a vertical mode, while measurements that are 180 degrees out of phase indicate a torsional mode.

The fundamental modes of oscillation of a lightly damped structure can be defined using the autospectra of response measurements taken at different points on the structure. For a given natural frequency, the square root of the autospectral value at this frequency gives the magnitude of the ordinate of the mode shape at a considered location. The sign of this modal value is determined with respect to a reference point using the phase information from the cross-spectrum between the measurements at the reference point and the selected location.

The coherence function provides important information for determining fundamental frequencies and modal shapes. It can be used to estimate the random errors in the phase values and thereby establish the statistical significance of the phase information. In general, the autospectral values should be used to determine the fundamental mode shapes only if the cross-spectra between the considered locations produce near unity coherence and near 0 or 180 degrees phase, Bendat and Piersol (1993).

2.2 Proper Orthogonal Decomposition

Proper Orthogonal Decomposition, also called the Karhunen-Loeve expansion, is a mathematical technique to establish deterministic spatial function that is best correlated with a given random field. This is accomplished by finding the function of the largest projection (in the mean-square sense) on the field. The procedure leads to an eigenvalue problem involving spatial covariance.

The simplest implementation of the POD is for variables measured at uniformly spaced locations. In this case the POD for a variable r reduces to the following (discrete) eigenvalue problem

$$[R_r] = \lambda \{\Phi\}$$

where $[R_r]$ is the space covariance of the random variable r, λ is the eigenvalue, and $\{\Phi\}$ is the eigenvector (eigenmode). The eigenvectors are used in a series expansion of the variable r,

$$r(x,y,t) = \sum_n q_n(t)\Phi_n(x,y)$$

where the principal coordinates $q_n(t)$ can be computed (in a discrete form) as follows

$$q_n(t) = \frac{\sum_i \sum_j r(x_i,y_j,t)\Phi_n(x_i,y_j)\Delta x_i \Delta y_j}{\sum_i \sum_j \Phi_n^2(x_i,y_j)}$$

Each principal coordinate $q_n(t)$ corresponds to a specific eigenvector Φ_n, which in turn represents n-th modal shape of the variable r.

It is shown that the spatial distribution of the variance of r can be written in terms of the eigenvalues and eigenvectors

$$\overline{r^2(x,y)} = \sum_n \lambda_n \Phi_n^2(x,y).$$

It follows that the relative magnitude of the eigenvalue indicates contribution of a particular mode to the random field r.

In this study, the POD is employed to determine the eigenmodes and principal coordinates of approach wind flow and the natural frequencies as well as normal modes of the bridge deck oscillation. These quantities are then compared with the results obtained using spectral analysis.

2.3 Wavelet Transform Analysis

Conventional spectral analysis is based on Fourier Transform (FT), which is of a global nature. In the process, time localization of occurrence of extreme values of a given signal, such as peaks of wind speed and/or wind-induced bridge response, is lost. In addition, the standard FT is only applicable for stationary data. This limitation is to some extent overcome by a modified FT, the Short Time Fourier Transform (STFT). In this approach, short fractions of the original data record, resulting from application of fixed-duration filtering window, are used in the FT and a time-frequency decomposition of the original signal is obtained. However, the STFT has a number of shortcomings. The most critical is a limited frequency resolution.

Limitations of the FT and STFT are overcome by the Wavelet Transform (WT). Instead of using a window of a fixed time duration, the base functions of span dependent on time-scale (or frequency) of interest, are employed. Typically, these functions have a wavy nature and their duration is finite. These "small waves" are labeled wavelets. This is in contrast to harmonic (sine and cosine) waves of infinite span, employed in the FT. The WT base functions are obtained by dilatation (stretching or compressing) of a reference function, called the mother wavelet. A number of the mother wavelet functions have been developed. One of the functions - the Mexican hat wavelet- is employed in analysis presented in this paper.

The WT unfolds the signal as a time-frequency (or time-scale) function represented by wavelet coefficients. It leads to a good time-frequency resolution for both short and long-duration components of the signal. The parameter similar to the autospectrum (calculated for example using the STFT), the wavelet modulus or its square, can be computed. It is typically plotted as a function of time and frequency (or scale) and such representation of the WT results is called a scalogram. The volume enclosed by the surface of the scalogram is directly related to the energy of the signal, just as the volume under the STFT autospectrum and the area enclosed by the conventional FT autospectrum, correspond to the variance of the analyzed signal.

The real, continuous WT is defined by the following transform pair

$$X(a,t) = \int_{-\infty}^{\infty} x(u)\psi_{at}(u)du$$

$$x(t) = \frac{1}{C}\int_{-\infty}^{\infty}\int_{0}^{\infty} X(a,u)\psi_{at}(u)\frac{1}{a^2}dadu$$

where

$$\psi_{at}(u) = \frac{1}{\sqrt{a}}\psi\left(\frac{u-t}{a}\right)$$

and

$\psi(u)$ = mother wavelet function,
a = scale parameter,
t = time instant,
$x(t)$ = original signal,
$X(a,t)$ = wavelet transform, and
C = normalization constant.

The choice of the mother wavelet depends on the intended use. The 'Mexican Hat" wavelet function

$$\psi(u) = (1-u^2)e^{(-u^2/2)}$$

was used in the analysis presented herein.

3. FIELD CONFIGURATION

3.1 Deer Isle-Sedgwick Bridge

The Deer Isle-Sedgwick Bridge (DISB) is a long-span, girder-stiffened suspension bridge, on the Atlantic coast of Maine, which connects the mainland at Sedgwick with Deer Isle , in the NE-SW direction. It was constructed in 1938 and opened to traffic in 1939. Its main span is 1080 feet long, while the two side spans are 484 feet in length. In addition, there is a 100-foot long approach span on each end giving a total bridge length of 2248 feet. The 20-feet wide deck carries two traffic lanes and it has an H-type cross-section, similar to that of the old Tacoma Narrows Bridge. Originally, the deck was supported only with vertical hangers from the main cables. Later, cable stays, traverse bracing, and cable ties were added to increase the bridge resistance to wind. Although these modifications were effective in attenuating wind-induced bridge oscillations, instances of excessive response attributed to wind are still observed. As a result, the bridge continues to be the subject of an ongoing field measurement program carried out by FHWA, in collaboration with the State of Maine.

3.2 Instrumentation

The bridge is instrumented with an array of anemometers and accelerometers to monitor the wind speed and bridge accelerations, see Figure 1. There are six tri-axis Gill anemometers mounted on outriggers which extend 12 feet from the side and 3 feet above the deck. In addition, two skyvane anemometers are mounted on the east tower. One is located 18 feet above the tower top, while the remaining anemometer is at the tower base, approximately 33 feet above the water surface. The anemometers provide information on three components of the wind velocity: horizontal normal to the deck, horizontal along the deck, and vertical, see Figure 1.

Six pairs of single-axis servoaccelerometers are distributed along the span of the bridge, with four pairs of accelerometers on the main span and two pairs of accelerometers on the North side span, see Figure 1. Three additional accelerometers are used to measure the motion of one of the bridge towers. Signals from pairs of the accelerometers on the deck are combined to monitor the torsional and vertical (heaving) motion of the deck, while the response in torsion, bending, and sway is extracted for the tower. Readings from the anemometers and accelerometers are acquired nearly simultaneously, with a sampling rate of approximately 20 samples per second and a typical record length of 10 minutes.

4. DATA ANALYSIS

4.1 Conventional Data Analysis

4.1.1 Wind Field

The wind data were broken into 4096-data point records, of approximately 205-second length. Typically three such records were employed in spectral and cross-spectral analysis, which included ensemble averaging. The spectra were corrected for the frequency response of the anemometers, using approach proposed by McMichael and Cleveland (1978). Representative normal to the deck horizontal and vertical velocity spectra (uncorrected and corrected for the frequency response of the anemometers) are shown in Figure 2. They are compared with empirical wind spectra models proposed by Harris, Kaimal, and Lumley and Panofsky, Simiu and Scanlan (1996).

4.1.2 Bridge Deck Response

Since the analyzed data was dominated by the response in vertical (heave) direction, the results presented herein are limited to this direction. Representative autospectra of the deck vertical motion are depicted in Figure 3, while the natural frequencies and modal shapes, determined from the spectral/cross-spectral analysis are shown in Figure 4. A comparison of the natural frequencies for the three vertical modes is presented in Table 1. A very good agreement with the results reported by Kumarasena et al.(1991) can be observed.

4.2 Proper Orthogonal Decomposition

4.2.1 Wind Field

As mentioned earlier, the POD analysis is significantly simplified when the data is specified at (spatially) uniformly distributed locations. From the data set defined by anemometer locations in Figure 1, approximately equally spaced anemometers 2, 5, and 6 were selected for the POD calculations. Representative results are shown in Figures 5 and 6, where the convergence of the reconstructions of the horizontal (normal to the deck) and vertical velocity components near the deck mid-span (anemometer location 5) are presented. It can be seen that the reconstruction involving only one POD mode was sufficient to fully recover the original time series of the vertical velocity component. Similar conclusions were found for the remaining anemometer locations.

4.2.2 Bridge Deck Response

The POD analysis of the bridge response was carried out for accelerometer data at locations 7 through 12. The signals from three pairs of the accelerometers (7-8, 9-10, and11-12) were combined to obtain vertical and torsional accelerations at three, equally spaced bridge deck locations (quarter-span, half-span, and three-quarter-span), respectively. These six quantities (vertical and torsional accelerations at three locations) were used to calculate the space covariance matrix $[R_r]$, of the dimension six-by-six. Next, six eigenvalues, eigenmodes and principal components of the bridge accelerations were computed. Each eigenmode was arranged into two parts: (1) associated with the vertical degree of freedom and (2) associated the torsional motion. In this format the six vertical-torsional pairs of the modes are depicted in Figure 7, together with the corresponding six eigenvalues. The modes are arranged in a descending order of the eigenvalues. It can be seen that the first three modes are essentially vertical, while the remaining three modes are torsional. Included also in Figure 7 are power autospectra of the six principal coordinates q_n. The frequency of the dominant spectral peak is marked for the first four modes. It can be seen that the (three) POD vertical modes in Figure 7 closely resemble the natural modes obtained from spectral analysis. Also a comparison of the natural frequencies in Table 1 and spectra in Figure 7, shows that the spectral peak frequencies in Figure 7 are equal to the natural frequencies in Table 1. When the POD modes are ordered according to a descending magnitude of the spectral peak frequencies in Figure 7, then there exists one-to-one equivalency between the POD results and the natural modes and frequencies resulting from conventional spectral analysis.

The last three modes in Figure 7 are torsional. As is indicated by the spectra of the principal coordinates associated with these modes, their participation in the bridge deck response is significantly smaller than that for the vertical modes. Mainly due to this fact, extraction of torsional modes was difficult using spectral analysis. It follows that this limitation is overcome when POD approach is employed.

Further analysis, not presented herein, shows that regardless of nature of the acceleration signals and the level of participation of natural modes in the structural response, the POD always leads to a set of the natural frequencies and structural modes. However, this approach has also a drawback. The number of modal contributions possible to be detected using the POD can not exceed the number of input signals used in analysis. If the number of the data channels is higher than the number of expected significant modes, this may not be a problem. Effort to apply the POD results to aid determination of the modal structural damping is currently underway.

4.3 Wavelet Transform Analysis

Wavelet transform (WT) analysis was used in this study to investigate frequency content of (temporal) peaks of the wind field and bridge deck response. Scalograms involving WT modulus were employed in the study. Also the wavelet coefficients were used in (wavelet) filtering and reconstruction of the analyzed signals.

4.3.1 Wind Field

Representative results of WT analysis of wind field are shown in Figure 8, for the anemometer near the deck mid-span, anemometer 5 in Figure 1. A fraction of the record of the horizontal (normal to the deck) velocity component and plot of the corresponding WT modulus are depicted. The time series in the figure is centered at the time instant of occurrence of the peak vertical acceleration at the center of the deck. This scalogram highlights discontinuities in the wind velocity signal and reveals the spectral content of the wind velocity peaks. Significant contributions reaching down to 0.18 Hz, at several time instants, are exhibited.

4.3.2 Bridge Deck Response

Figures 9 and 10 show representative results of WT analysis of the bridge deck response. A fraction of the time series of the deck response a the mid-span location (accelerometers 9-10, Figure 1) is shown in Figure 9, together with its WT scalogram. The scalogram indicates a slightly modulated harmonic signal, with maxima at approximately 0.7 Hz. A closer examination of the numerical values of the WT modulus shows that the peaks actually occur at the frequency of 0.698 Hz. This is in a close agreement with the POD results in Figure 7, where a dominant participation (in the vertical motion) by the mode with the natural frequency of 0.698 Hz is apparent. Compare also spectral results in Figure 3.

Application of the WT results in decomposition and reconstruction of the bridge response time series is illustrated in Figure 10. The original signal (upper plot), the signal contribution at the frequency of 0.698 Hz (middle graph), and the signal reconstructed using the WT results (lower plot) are shown. It can be seen that indeed the 0.698 Hz-component of the signal is dominant (middle graph) and that the original signal can be reconstructed from the WT results.

It has been shown elsewhere, Bienkiewicz and Ham (1997), that the cross-wavelet analysis of the approach wind and wind-induced loading may provide useful physical insight, not available using traditional (e.g. FT based) techniques.

5. CONCLUDING REMARKS

The Deer Isle-Sedgwick Bridge data displays motion dominated by vertical modes of oscillation. Bridge response in the first three vertical modes was identified using traditional spectral approach. Compatible results were obtained using the POD analysis. In addition, by application of the POD it was possible to identify modes of vibration not clearly apparent from FT spectral analysis. Wavelet transform was found useful in time-frequency analysis of extreme wind speed and bridge response. It made possible determining energy content of both the peak wind speed and bridge deck acceleration.

Further investigation is needed to fully evaluate the potential of application of the proper orthogonal decomposition and wavelet transform, as well as other novel techniques, in study of wind effects on long-span bridges and other wind-prone structures.

6. REFERENCES

Bendat, J. S., and Piersol, A. G. (1993) Engineering Applications of Correlation and Spectral Analysis, John Wiley and Sons, Inc.

Bienkiewicz, B. and Ham, H. J. (1997), Wavelet Study of Approach-Wind Velocity and Building Pressure," Journal of Wind Engineering and Industrial Aerodynamics, Vol. 69-71, pp. 671-683.

Bienkiewicz, B., Ham, H. J. , and Sun, Y. (1993) "Proper Orthogonal Decomposition of Roof Pressure," Journal of Wind Engineering and Industrial Aerodynamics, Vol. 50, pp. 193-202.

Bosch, H. R., and Miklofsky, H. A. (1993) "Monitoring the Aerodynamic Performance of a Suspension Bridge," Proceedings of the 7th U.S. National Conference on Wind Engineering, Los Angeles, CA, Vol. I, pp.125-134.

Kumarasena, T., Scanlan, R. H., and Morris, G. R. (1989) "Deer Isle Bridge: Field and Computed Results," Journal of Structural Engineering, Proc. ASCE, Vol. 115, No. 9, pp. 2323-2328.

Kumarasena, T., Scanlan, R. H., and Ehsan, F. (1991) "Wind-Induced Motions of Deer Isle Bridge," Journal of Structural Engineering, Proc. ASCE, Vol. 117, No. 11, pp. 3356-3374.

McMichael, J. M. and Cleveland, W. G. (1978) "Characteristics of Helicoid Anemometers," NBSIR 78-1505, National Bureau of Standards, Washington, D.C., 1978.

Simiu, E. and Scanlan, R. H. (1996), Wind Effects on Structures, 3rd Edition, John Wiley and Sons, Inc.

Table .1 Natural Frequencies of Deer Isle-Sedgwick Bridge

Vertical Mode	Spectral Analysis [Kumarasena et al.]	POD Analysis [Present Study]
1st Symmetric	0.28 Hz	0.308 Hz
1st Anti-symmetric	0.49 Hz	0.508 Hz
2nd Symmetric	0.68 Hz	0.698 Hz

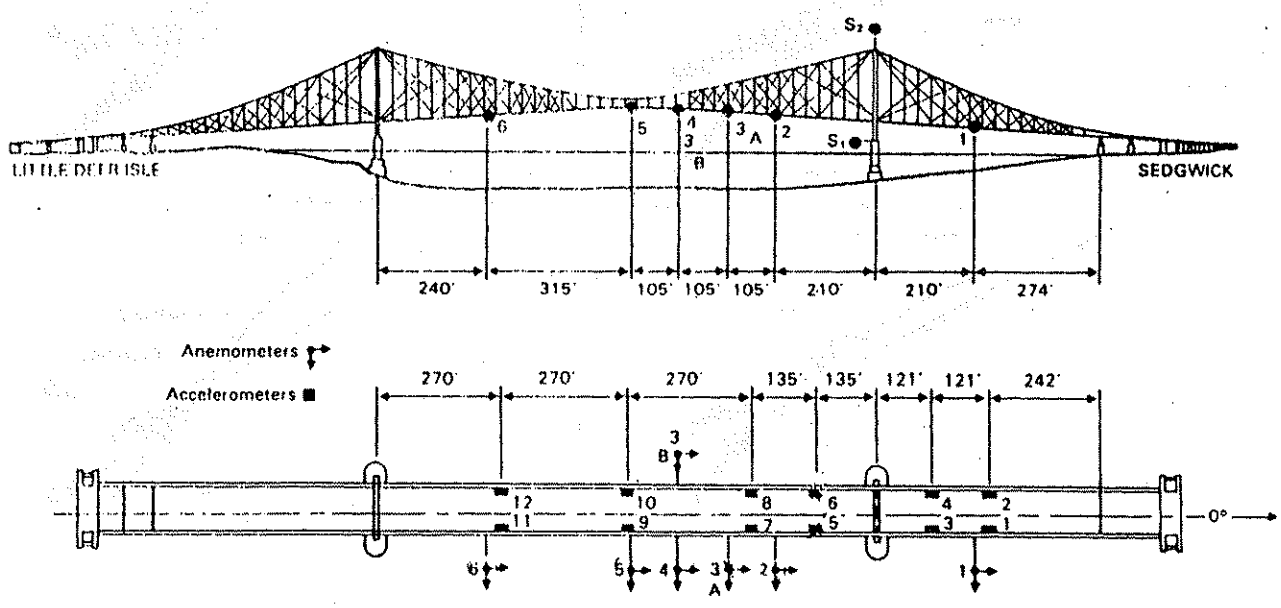

Figure 1. Deer Isle - Sedgwick Bridge -- Instrumentation Layout

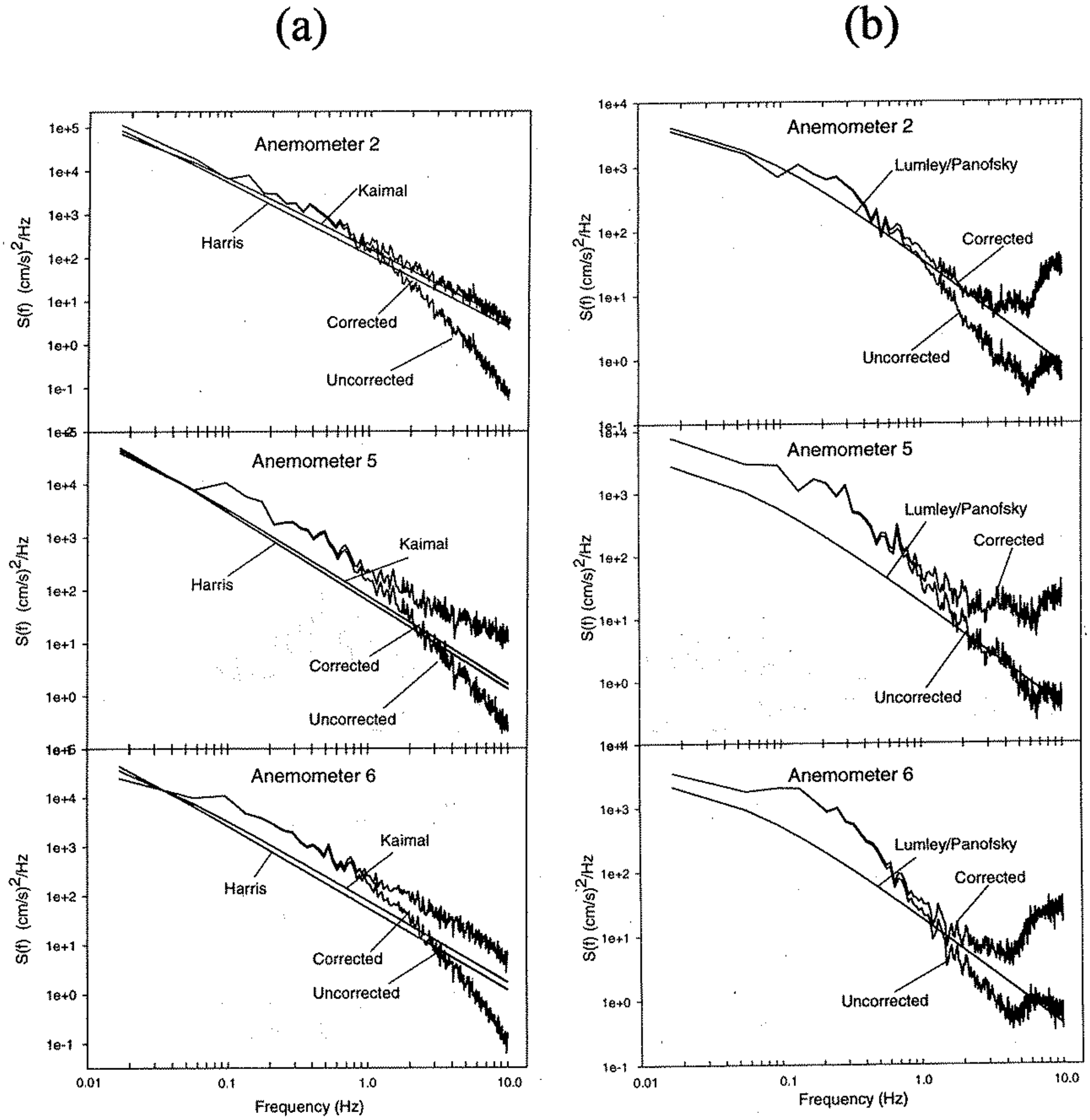

Figure 2. Autospectra of Horizontal (a) and Vertical (b) Velocity Components

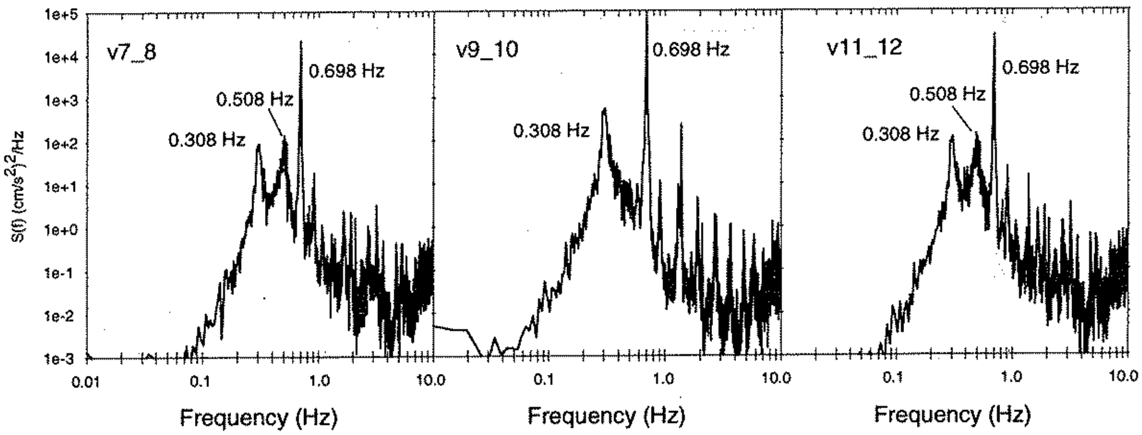

Figure 3. Autospectra of Vertical Accelerations of Bridge Deck

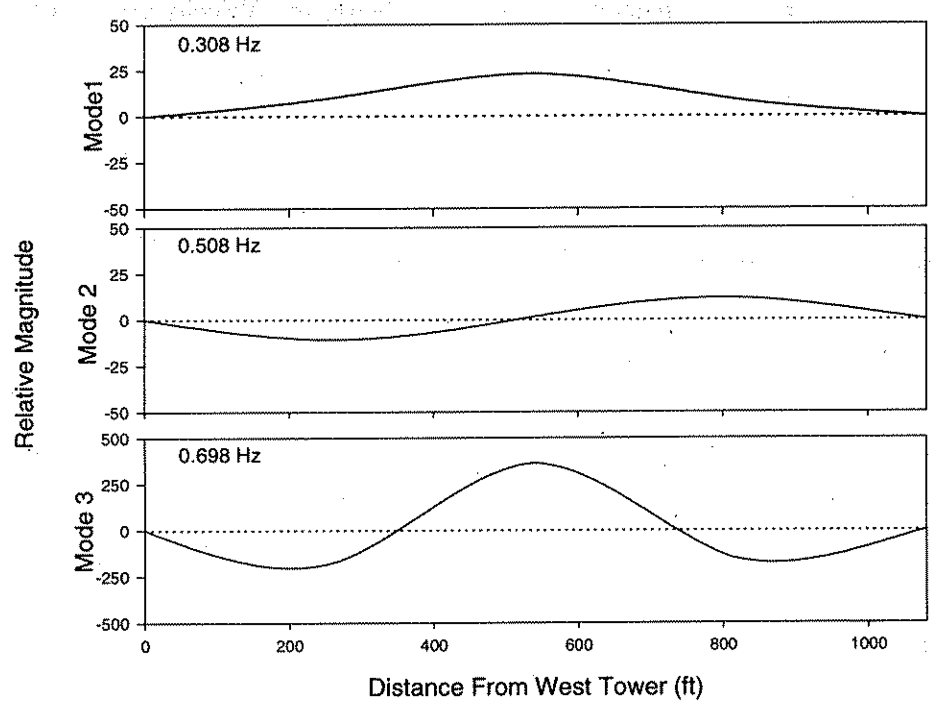

Figure 4. Natural Modes and Frequencies Determined from Spectral Analysis

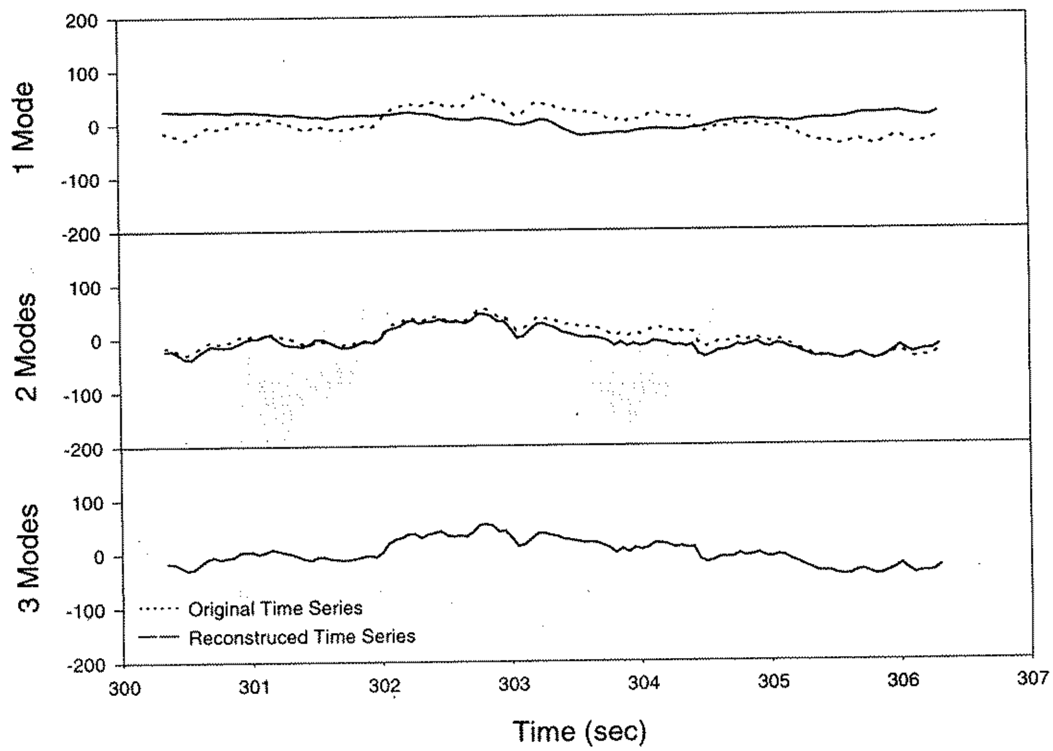

Figure 5. POD Reconstruction of Horizontal Velocity Component

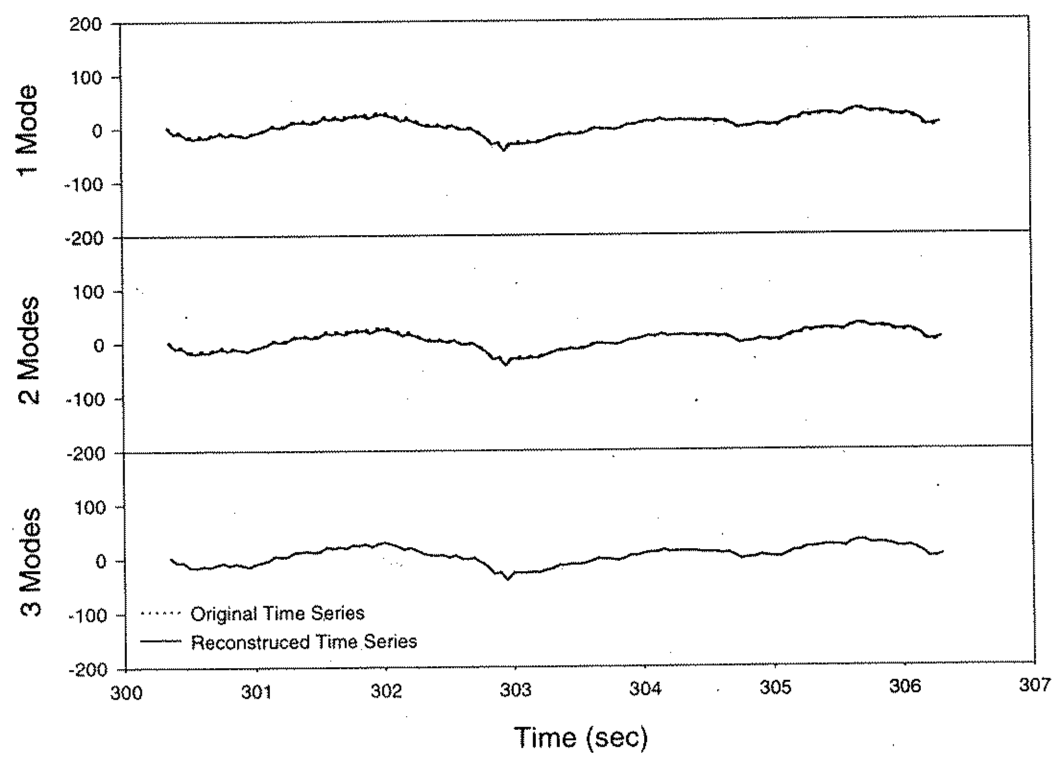

Figure 6. POD Reconstruction of Vertical Velocity Component

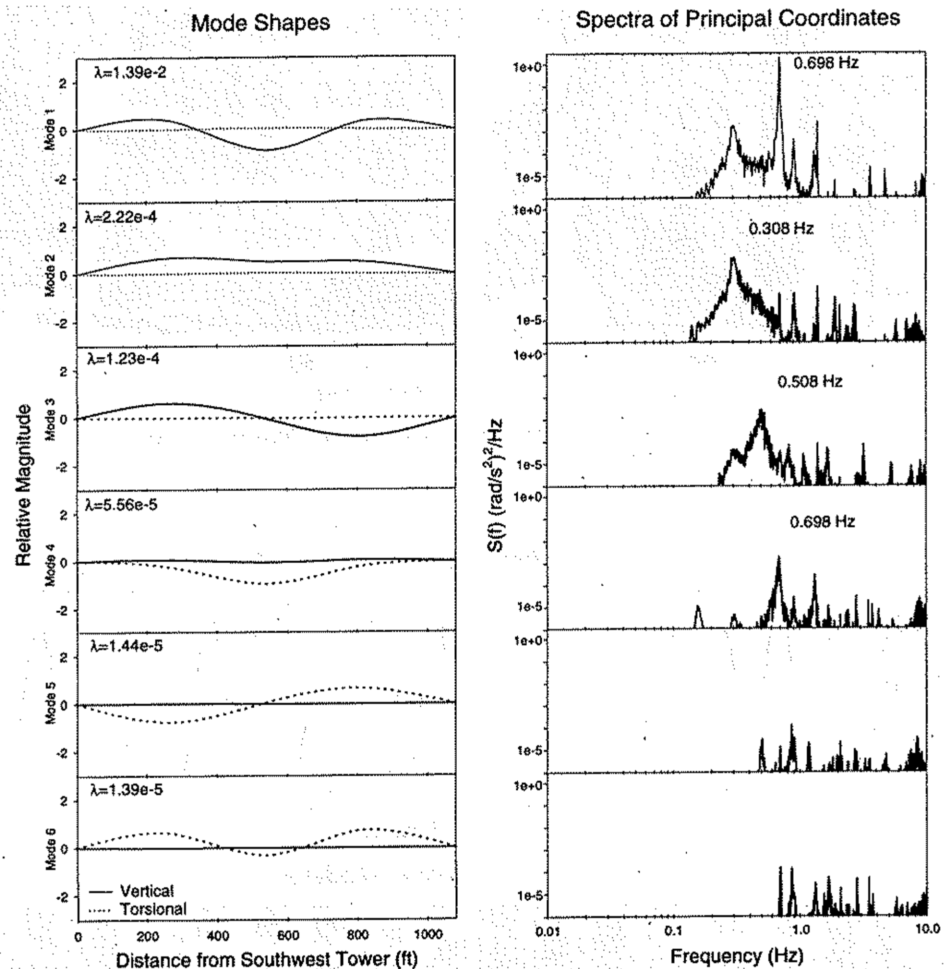

Figure 7. POD Mode Shapes and Autospectra of Principal Components

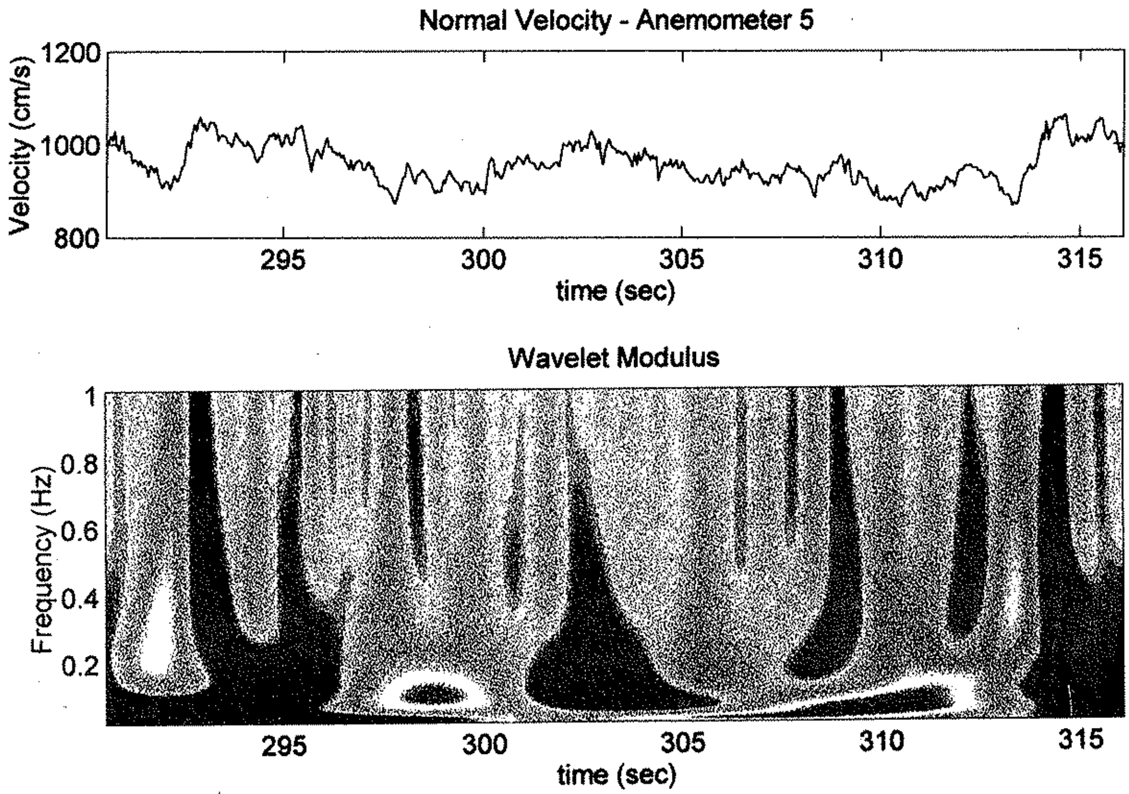

Figure 8. WT Spectrogram of Normal Velocity

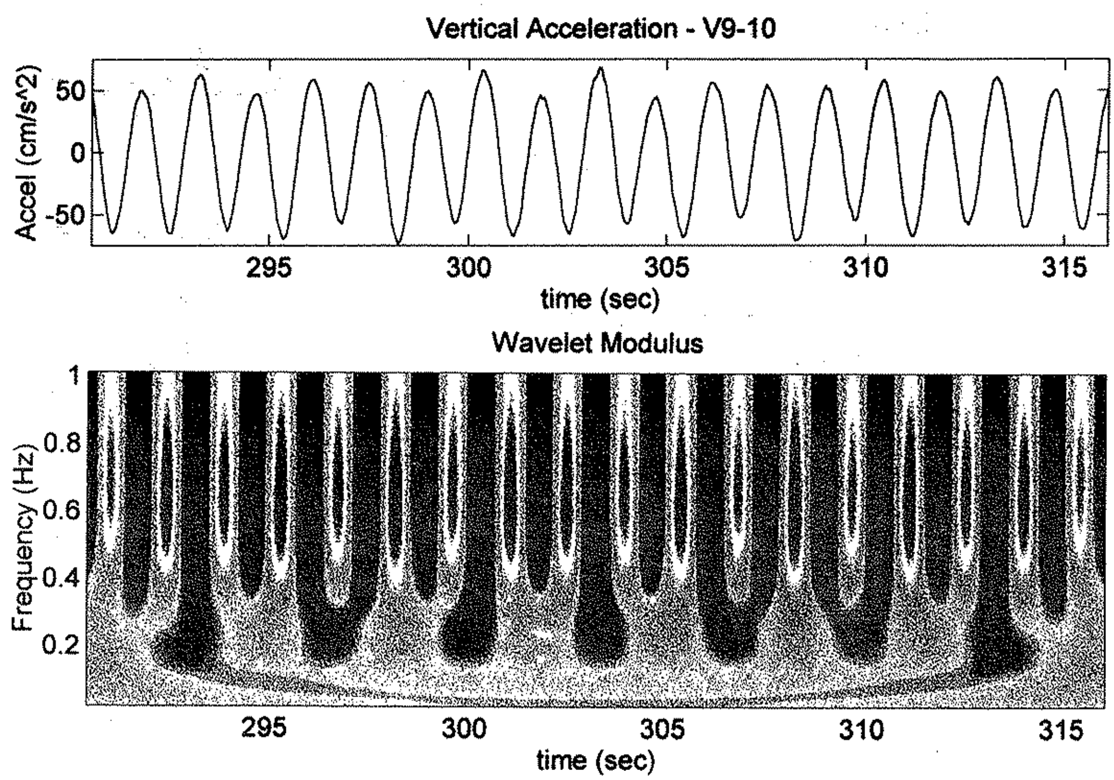

Figure 9. WT Spectrogram of Vertical Acceleration at Deck Mid-Span

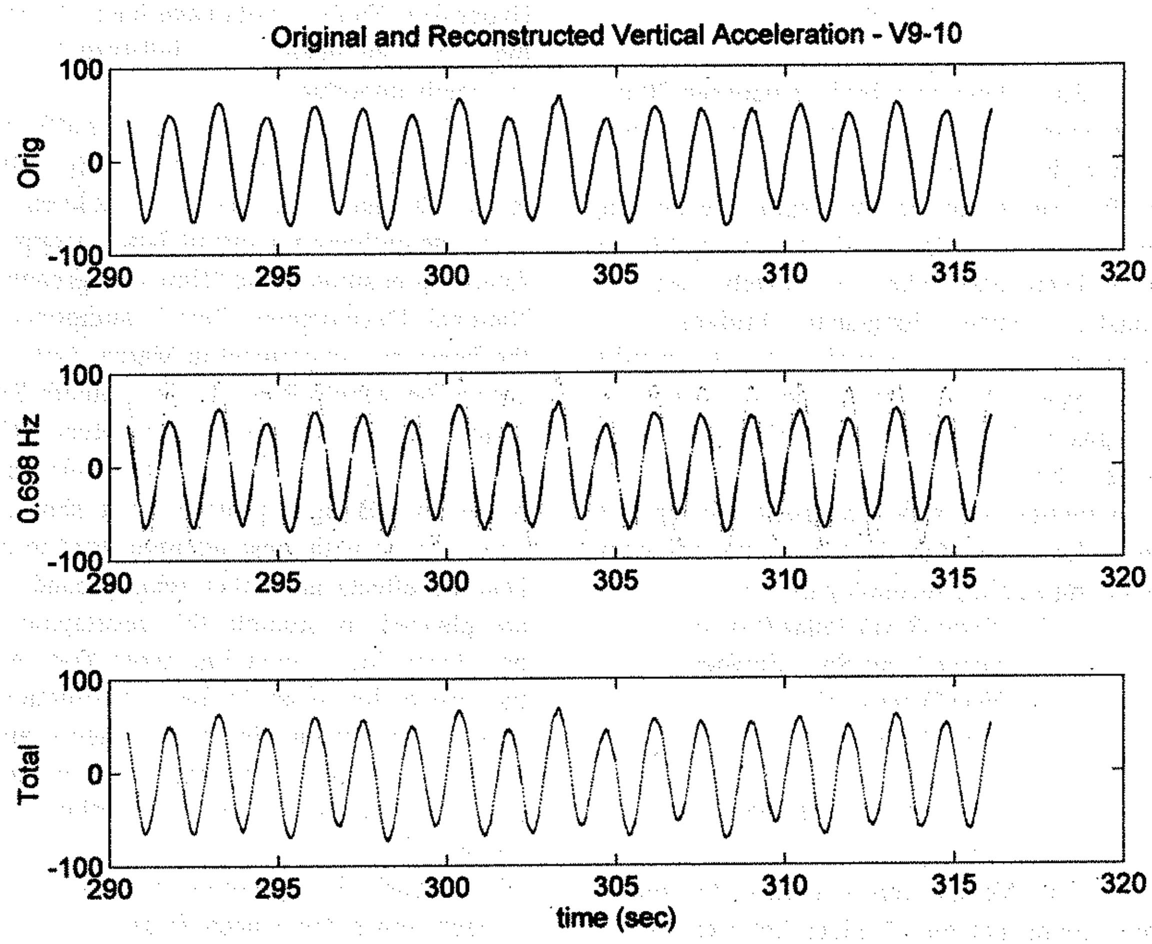

Figure 10. Wavelet Transform Reconstruction of Vertical Acceleration at Deck Mid-Span