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Evaluation of Signal Processing Techniques for the Analysis of Large Civil Structures

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ABSTRACT

Several new methods of determining change in the data signature of a large Cable-Stayed bridge are examined and compared. Two sets of data, one taken in September 1995, and the second in June 2000 are studied. Structural changes are investigated using several techniques; 1) Modal behavior in the .3 to 3 Hz range is investigated using Transmissibility FRFs and the Random Decrement Method, 2) Quasi Periodic behavior in the 3 to 30 Hz frequency range is observed in several tests. Potential causes and characteristics of this behavior are investigated. 3) Some methods of non-linear analysis are applied to the bridge data and changes in behavior are evaluated. Capability and concerns with each method are addressed in conjunction with physical ambient excitation data and its signal properties.

1.0 BACKGROUND

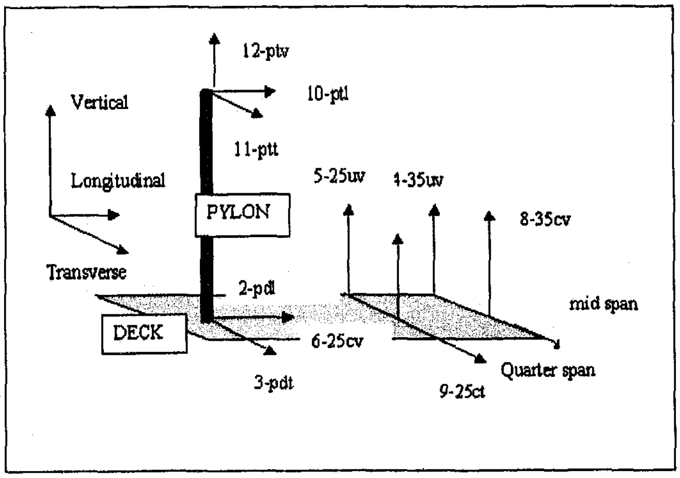
The Rama IX Bridge is a large cable stayed suspension bridge spanning the Chao Phraya River. It is the world's longest single plane cable-stayed bridge. The overall length is three kilometers. The distance between its two main supporters measured from Bangkok side to Thonburi side is 450 meters. Kinemetrics, Inc. instrumented the bridge with a number of acceleration transducers to provide acceleration response data from ambient bridge excitation. Data were acquired on two occasions, in September 1995 and in June, 2000.

2.0 MOTIVATION

The two available datasets, 695 and 900, represent acceleration time histories taken at identical locations over a five year time span. Analysis of this data gives some indication of the variability of the response of the large cable stayed bridge. Both linear and nonlinear response measures can be applied to the two datasets, which form excellent examples of "real world" structural data. These are positive reasons to complete and compare the results of several types of analyses. Lack of specific structural data does limit the analyses in that specific changes in the data characteristics are not readily readily related to changes in structural properties. However, both the similarities and changes in the data can be examined on their own merit.

3.0 AVAILABLE MEASUREMENT DATA

Figure 1 shows the transducer locations on the RAMA IX bridge. Transducers density is sparse, but does include locations on one pylon and the deck at one end of the bridge . Sparse spacing in the context of the total bridge means that low frequency global mode *shapes* cannot be obtained from the available data. Global modal frequencies, estmates of modal damping, and local modal behavior are all potentially available.



Transducer Locations on The Rama IX Bridge

Figure 1

1 CHANNEL NO.	Description
1	6BCE, Sidespan vertical
2	PD-L, pylon, deck level, longitudinal
3	PD-T, pylon, deck level, transverse
4	35UV, mid-span, outer, vertical
5	25UV, span ¼ point, outer, vertical

6	25CV, span ¼ point, center, vertical
7	35CT, mid-span, center, transverse
8	35CV, mid-span, center, vertical
9	25CT, span ¼-point, center, transverse
10	PT-L, pylon top, longitudinal
11	PT-T, pylon top, transverse
12	PT-V, pylon top, vertical
13	WIND-E
14	WIND-N
15	WIND-V
16	TEMP

Triaxial measurements are located on the base and top of the West support pylon. The west plyon is a central support feature of the bridge and provides one major mechanical transmission pats linking support, cable and deck vibrations. Deck transducers quantify deck motion and by implication, link deck and cable motion. Data are sampled at 250 samples/second using 24 bit digitizers. Time data consisting of 166,779 data points/channel are simultaneously acquired for each channel, for a total of 833 seconds/data per channel.

4.0 Feature Selection

Time series data are generally difficult to interpret, so features like autospectral density functions, frequency response functions, modes, and probability density functions are used to quantfiy and to visualize of structural data. To some extent, all of these functions relate measured data to structural properties, though the relationship may be intuitively based.

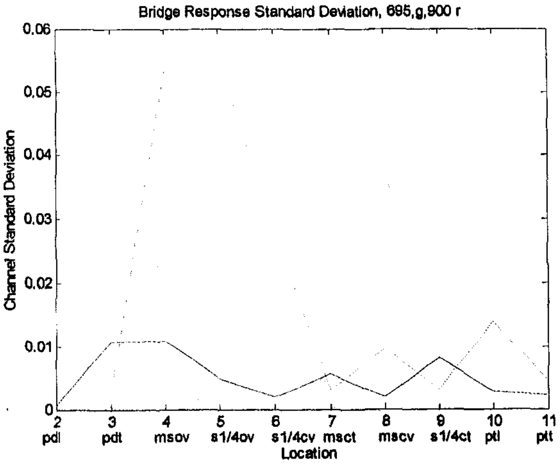
Time series, by their very nature, have lots of points. While these points are not all independent, they are some numerous that time series are generally of high dimension, Features, derived from functions of the time series data, may consist of just a single number, like standard deviation or RMS value, or of a set of numbers, like modal frequencies, mode shapes, and modal damping values.. All of these features are generally of much lower dimension than the original time series. They are based on averaging regularities in the time series and as such are "average" properties. Feature extraction is thus seen as a dimensional reduction process, where certain selected features are derived from the long, complicated time series using a functional averaging process.

Since the excitation in this case is ambient, consisting of wind, traffic and perhaps other unknown sources, the time series responses are quite complicated and intelligent feature extraction is critical. The remainder of this paper uses a range of features to analyze the bridge data with the objective of drawing conclusions regarding typical structural responses. In Section 5 RMS values and autospectral density give basic insights into broadband data levels and the range of frequencies present. A pecular and persistent 3 Hz. signal, including harmonics of 3 Hz. is present in both the 995 and 600 data, though the distorted 3 Hz. signal is much more evident in the 995 data. Below 3 Hz. both signals are data sets are dominated by a series of resonant response peaks at bridge modes.

Section 5 compares the results for RMS and autspectral values. Section 6 details transfer function computations in the modal data range (0-2.5 Hz) and compares modal assurance criteria, derived from the modal decrement method, for both data sets. Features in Section 6 emphasize linear behavior. Section 8 considers probability density, skewness, and Kurtosis as quantifiers of data Gaussianity. Kurtosis measures the degree to which the data follow a Gaussain Distribution. State space time series analysis (Section 9) using singular spectrum analysis models the distorted 3.0 Hz. signal. Finally, section 10 summarizes the results of Sections 2-9 in a hopefully coherent format.

5.0 MAGNITUDES AND AUTOSPECTRA

Even the most cursory review of the 995 and 600 time series shows that the 995 acceleration levels are much larger than the 600 levels. This observation is quantified in Figure 2, above. Levels at locations 4 (mid span vertical), 5 (quarter span vertical), and 6 (pylon base transverse) are especially higher, implying much larger deck motions in the earlier data. Figures 3, 4, and 5 clarify the data frequency content.



RMS VALUE AT EACH LOCATION
995 AND 600 DATASETS
Figure 2

The autospectrum in Figure 3 is unusual for structural response. Normally structural response consists of a series of discrete peaks at resonant frequencies of the structure. Here distinct resonant peaks are evident at frequencies between 0.1 and 1.0 Hz. Above about 0.8 Hz. the response is dominated by broadband response, up to about 2.0 Hz., and then by a series of harmonically related signals to over 10 Hz. In Figure 4 the Harmonic response range is rather arbitrarily indicated to start at about 2 Hz and the modal range to include frequencies below 2.0 Hz.

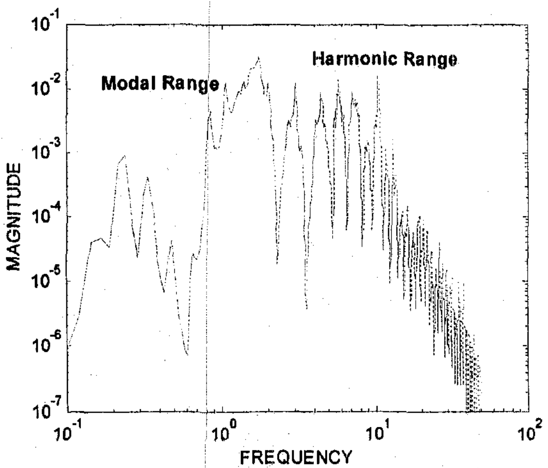


Figure 3. Autospectra, 995 Data, Pylon Deck Transverse.

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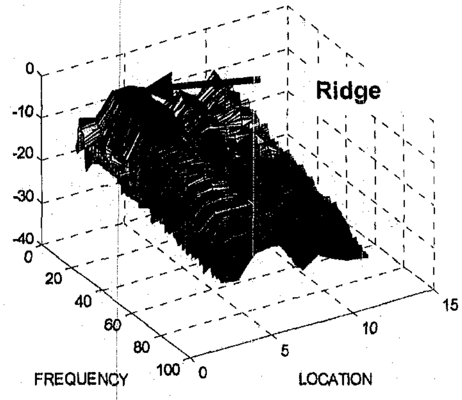

Figure 4. Autospectra, 995 Data, All Locations.

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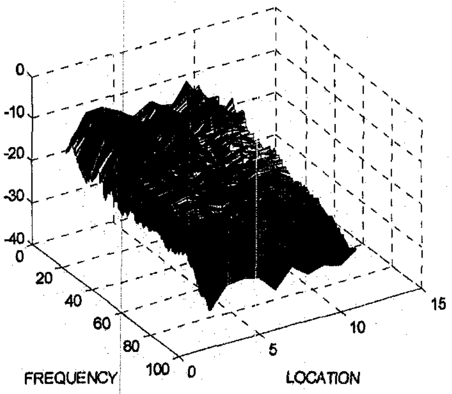


Figure 5. Autospectra, 600 Data, All Locations.

In Figures 5 and 6, three dimensional plots are used to depict autospectral magnitude as a function of both frequency and locations. Note the linear frequency and location scales and the logarithmic vertical magnitude scale. In the 995 data frequencies above 2 Hz. form a distinct "ridge" in the autospectrum at locations 4,5, and 6. A similar ridge is present in the 600 data at the same locations, but is much lower in amplitude. Something phenomena is generating a distorted 3 Hz. signal, either in the data system (like noise), or in the bridge mechanics (a 3 Hz. limit cycle, either wind or traffic induced). These possibilities will be examined further in Section 8.

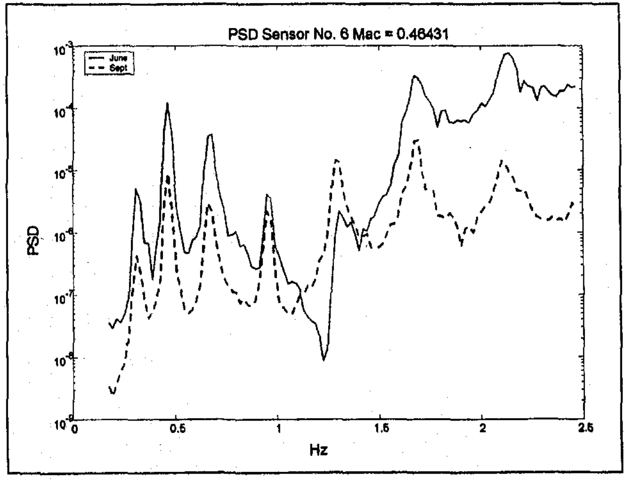
In the next section (7) we concentrate on modal properties below 2.5 Hz. while section 8 addresses periodic signals above 2.5 Hz. The increased response at deck locations 4-6 in the 995 data is attributable to very large, apparently harmonically related signals in the 2-100 Hz. range. The source of these signals is unclear, but the existence of a suspension related limit cycle is probable.

7.0 Data Modal Properties.

7.1 Evaluation of Power Spectral Density from 0-2.5 Hz.

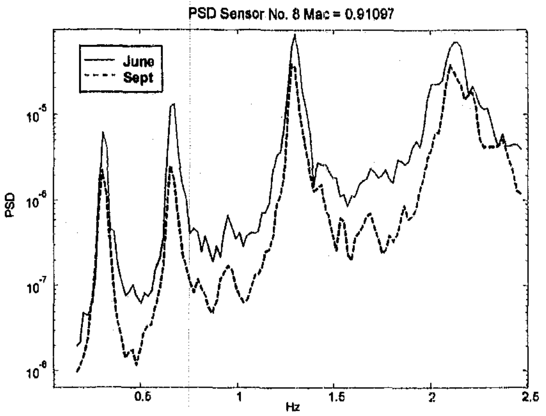
Since modes are hard to recognize above about 2.5 Hz. modal inspection of the data records was limited to 0-2.5 Hz. The data are low pass filtered at 2.5 Hz. and ten decimated to an effective 10 Hz. sample rate. The resulting data record, to which methods in this section are applied, has a length of 8192 samples

Inspection of the PSD records in Figure 6 (sensor 6, quarter span center, vertical) three main points. First, the resonant frequencies from 0-1.0 Hz. remained consistent between 995 and 600. second Second, resonant frequencies above 1.0 Hz are similar between 995 and 600, but the form of the autospectral curve has changed. Third, the overall response levels have changed considerably (up to one and one half orders of magnitude). Consistent modal frequencies indicate that the global system modes are consistent. Llocal responses have changed, perhaps due to differences in ambient excitation level, or alternately, to structural changes (like damping) in the system.



Autospectra, 695 and 900. Sensor 6
Figure 6

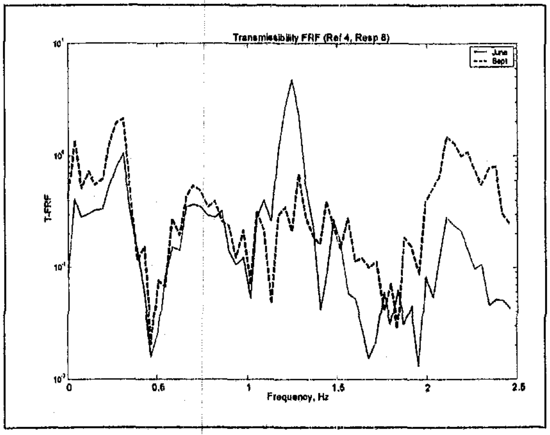
Pylon deck vertical (Sensor 8, Figure 7) below, like Figure 6, shows common resonances throughout the 0- 2.5 Hz. range. Both frequencyand amplitude, match reasonably well up to 2.5 Hz.



Autospectra, 695 and 900. Sensor 8
Figure 7

7.2 Transmissibility FRF comparisons

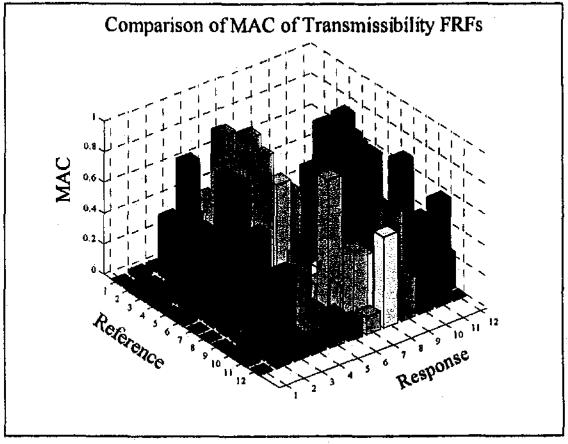
A transmissibility FRF is essentialy a frequency response function with the input reference replaced by one of the measured outputs. Transmission paths can be analyzed without explicitly measuring the applied input. By examining these *constructions*, *detect changes in the systems global* behavior (resonances, damping) and local behavior (changes in specific transmission paths).



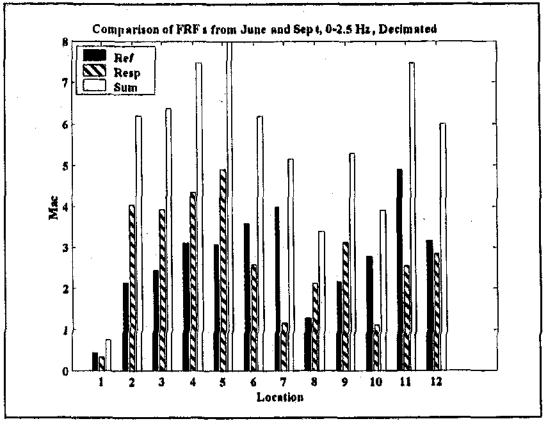
Frequency Response Function,
Reference 4 Response 8
Figure 9

Figure 7 above illustrates the transmissibility FRF from 4 (mid span outer vertical) to 8 (mid span center vertical), lit is clear that some changes have occurred. Below 1.0 Hz. the FRF's are similar, above 1.0 Hz. they are dissimiliar. There are several candidate methods to quantifiably evaluate the changes. The one applied here is the MAC (Modal Analysis Criterion) between transmissibility FRF's measured in 995 and 600. A MAC value of unity means identical FRF's and implies similar transmission paths. Lower MAC values imply correspondingly reduced similairity between the FRF's. .A comparison of the FRF's/MAC for all possible input/output relations is shown in Figure 10. Diagonal elements are set to zero to remove them from consideration, since the MAC comparison of a frequency response function to itself is always unity.

Data from sensor number 1 is not reliable so transmissibility FRFS between one and other sensors should not be considered. If the FRF's at 995 and 600 were unrelated, the MAC would be zero, if they were identical the MAC would be unity. Many MAC values in Figure 10 range from 0.6 to 0.8, while others (excepting the first front row) range from 0.1 to 0.2. Evidently many transmission paths have similar FRS's, while a few (like 11-6) are quite different. Overall the MACs are reasonably high for a structure tested under different environmental and boundary conditions.



MAC, Transmissibility FRF's, 995 and 600
Figure 10

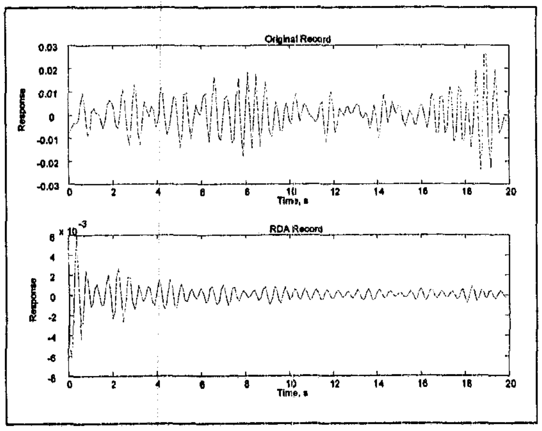


MAC, Row-Column Sum, 995 and 600
Figure 11

In Figure 11 the results of summing over the rows of the MAC matrix are illustrated. If a indicator is high (5-7) local changes not indicated , if it is low a change at that location is indicated. Locaton 1 has a known bad sensor, so the low value at location 1 does not indicated a change in the structure. Locations 7-10 are lower. Locations 7-9 are deck transducers, so the implication in Figure 11 is that the deck transmissibilities below 2.5 Hz. are different between the two cases. Pylon related locations, in contrast, are more similar between 995 and 600.

7.1 Random Decrement Averaging.

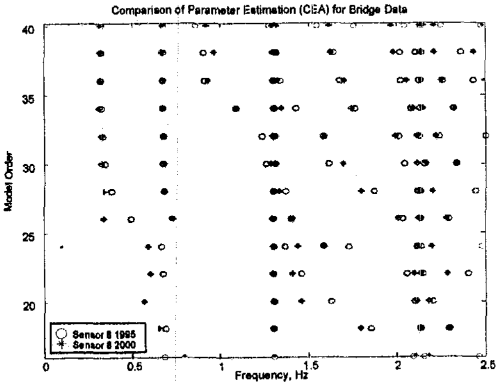
The random decrement method is recovers the system's characteristic response (step-release or impulse) from a single, continuous measurement signal through repetitive averaging of sections exhibiting similar waveforms. This approach is advantageous for several reasons. With large scale civil structures the most practical excitation method is ambient, so input signals are not measured. This is normally because they are difficult to measure, so a post-processing technique that reconstructs the impulse response record hasf great merit, both for computation of the modes and for noise reduction.



Random Decrement Method, Original and Reconstructed Time Records.
Figure 12

Figure 12 shows the application of the random decrement method to Sensor 8, mid span center vertical, Dataset 995, where the step response is reconstructed in the lower graph. The upper plot shows a section of the original data. The lower plot shows the averaged, reconstructed response. Averaging has lowered the level, since the force is only present at t=0 and averaging has occurred. The response looks relatively classical and noise free.

Due to limited length of the record in this case (total response record length =2000 samples) the complex exponential analysis method was chosen to estimate the system poles. (If the data record had been of longer length, calculation of the traditional H1 FRF would have been done.) Similar results were obtained for all sensors; results for sensor 8 are presented in Figure 13 below. Modes haven't changed significantly between 995 and 600, as can be seen by comparing the * and o.



Modal Stability 9-95 and 600 Data
Figure 13

In summary, modal frequencies are pretty consistent between the 995 and 600 datasets. Global, lower frequency modes are quite consistent. As modal frequency increases, some transmission paths have changed, due either to noise, environmental effects, or local structural changes.

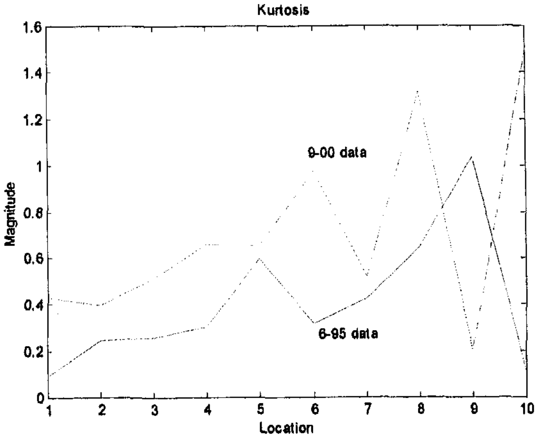
8.0 Probability Density and Kurtosis

Probability density, which quantifies the probability that the value of a waveform will be within a given range, is a fundamental characteristic of time series data. Most algorithms assume that the probability density is Gaussian. Gaussian probability density is described by Equation 1.

$$p(x) = \frac{1}{\sigma\sqrt{2}} e^{-x^2/2\sigma^2} \qquad (1)$$

where x is signal amplitude and σ is the standard deviation of the data. The bridge data are all roughly Gaussian. Many distributions differ from Gaussian at higher signal magnitudes by exhibiting either more high amplitude spikes than Gaussian (for acceleration signals characteristic of hardening or rattling behavior) or fewer high amplitude spikes than Gaussian (characteristic of softening stiffness).

One measure of the nonlinear properties is the Kurtosis, the fourth moment of the time series amplitude distribution. Normalized Kurtosis is zero for Gaussian data.
An excess of peaks gives positive Kurtosis and a deficit of peaks, negative Kurtosis. Figure 5 illustrates the Kurtosis for the 9-95 and 9-00 data as a function of response location.



Kurtosis as a Function of Location, 995 and 600
Figure 14

Kurtosis is higher in the 9-00 data at every location except 9 (1/4 span center transverse). Increased Kurtosis generally means increased "rattling" type behavior, and is caused by an excess of peaks in the time series data. Higher frequency behavior is often related to local signals, so the 900 data indicate more local high frequency behavior than do the 695 data.

9.0 Singular Spectra, 3 Hz and Higher Signals.

Usually auto spectra are dominated by a series of resonant peaks. In this case the auto spectra, especially in the 695 case at locations 4,5,and 6 are dominated by harmonic behavior A specific plot is shown in Figure 13, where the channel 4 auto spectrum is plotted.

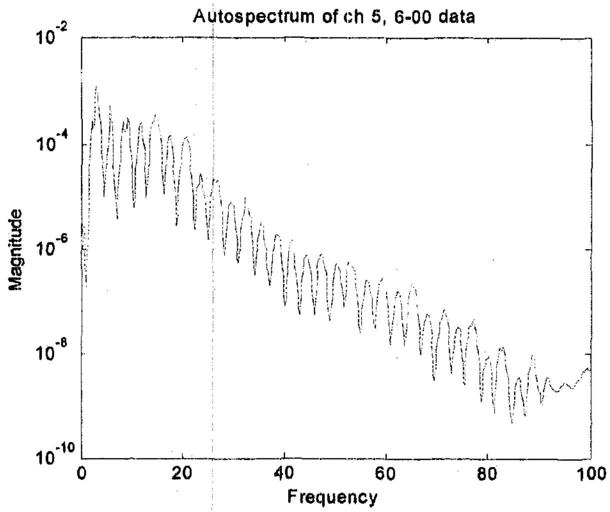
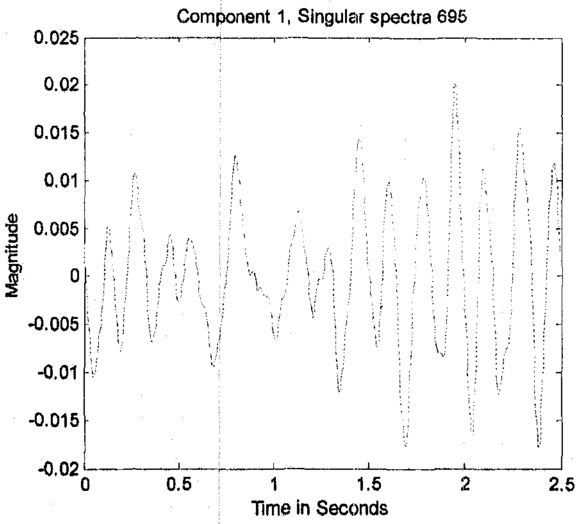
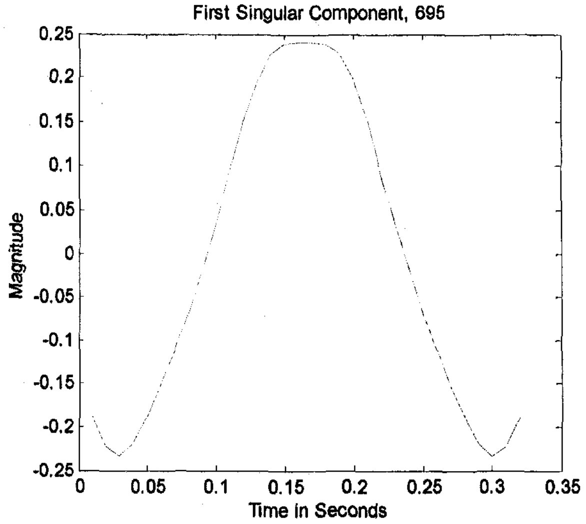


Figure13. Autospectrum of Channel 5, 600 Data.

This auto spectrum is characteristic of a distorted periodic signal, like a square wave. In an attempt to isolate a component of the response that produces the "lobed" harmonic responses a singular spectrum analysis of the signal is performed. Singular spectra are computed using singular value decomposition. A singular spectrum analysis decomposes the signal into a set of mutually orthogonal data dependent basis waveforms. The concept is similar to Fourier analysis, but in Fourier analysis the basis waveforms are sinusoids, while in singular spectrum analysis the components, though often sinusoidal like, are determined by the data.



First Singular Component ,695 Data Location
Figure 15



First Singular Component Basis Waveform Location 695 Data
Figure 15

The time shape of first singular component, channel 4 mid span outer vertical, bridge data 6-95 is illustrated in Figure 14 above. Figure 14 shows a longer signal reconstructed from this singular component. Note flattened top of waveform. This waveform, multiplied by a constant, constitutes one "dimension" of the response time signal for channel 4, Figure 14, for the 6-95 bridge data. Since this waveform isn't a clean sinusoid, in the frequency domain it is formed from a series of harmonics. These are observed in the auto spectral plots.

Relationships shown by the singular spectra and corresponding autospectra above indicate that data from <u>both</u> 6-95 and 9-00 have the "peculiar" lobed harmonic character of the auto spectrum, so it isn't characteristic of a single data set, its just much stronger in the 6-95 data. A nonlinear relationship between channels, though not illustrated here, can be demonstrated. This sort of nonlinear relationship is described as a "limit Cycle", and is a form of driven, nonlinear resonant-like behavior (1)(2). The cause of this behavior is unclear. It could be electrical noise contaminating the data system signals, and, as such, independent of structural response. In this case it would be analogous to the commonly observed 60 Hz and harmonics often seen on data acquired in the US, though of course this data is different in frequency content.

Another possibility is that we are observing evidence of a mechanical "limit Cycle" in the data in both instances, but in the 900 data the limit cycle is of lower amplitude for some reason. In this case, the behavior would be described by a nonlinear differential equation of Van der Pol form resulting from negative damping induced by wind or traffic. If a mechanical limit cycle is present, it is surprising the behavior is absent from the channel 8 (mid span center vertical).

10.0 Conclusions

1. The data quality is questionable, particularly regarding zero offsets, low frequency noise contamination, and loss of data for channel 1 in the

9-00 dataset.The unusual frequency spectrum of channels 4,5, and 6 in both the 6-95 and 9-00 data is another reason for concern. Consequently responses assumed structural in the data may in fact be some form of noise.

2. Higher standard deviations in the 6-95 data are especially evident in channels 4,5, and 6. The spectra of these channels is dominated by harmonics in the Frequency domain. These harmonics are present in both sets of data, but are of higher amplitude in the earlier 6-95 data. If these signals are noise, than elimination of the noise is the primary concern so the actual structural responses can be revealed. If the signals are real structural response, then we can proceed with further analysis based on the assumption of mechanical nonlinear “limit cycle” behavior.
3. Modal frequencies are fairly consistent, especially below 1.0 Hz., indicating consistant global modal behavior.
4. Local transmission paths are fairly consistent, with the least consistency evidenced in the bridge deck.
5. Excessive peaks are present especially in the acceleration responses for the 9-00 data. These could correspond to “rattling” behavior associated with gap opening and closing. Their significance is difficult to interpret because of the data noise concerns addressed in points 2 and 3 above.
6. The reduced amplitudes in the 9-00 data as compared to the 6-95 data could have several causes. It is most critical to determine what is structural response and what is noise. If the increased standard deviation is primarily noise, then the first move is to get rid of the noise and look at real structural response. If the increased standard deviation is structural, then it is possible that energy dissipation (damping) has increased from viscous effects or from increased rattling. It is also possible that some other structural change has modified limit cycle behavior.

2 REFERENCES

[1] Moon, Chaotic Vibrations.

[2] Parker and Chua, Practical Numerical Algorithms for Chaotic Systems.