Bridge Signature Development

Interim Report

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16. Abstract

Vibrational monitoring has been used to provide a global characterization of a Connecticut bridge using a prototype monitoring system. Loading was provided by random traffic. The vibrational data was processed to develop a bridge signature, useful for long-term monitoring purposes. Previous work at The University of Connecticut has demonstrated that the changes in the bridge which would occur when failure mechanisms develop will result in changes to this signature.

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PREFACE

The report has been abstracted from the master's thesis (1) of Dean A. Bagdasarian, graduate research assistant. It describes the development of a vibrational signature based on use of a prototype monitoring system. The laboratory testing, installation and field testing of the monitoring system were described in a previous report, C.E. 92-188.

The prototype bridge monitoring system was developed with a Connecticut Department of Higher Education Goodyear Cooperative High Technology Research and Development Grant. Vibra-Metrics, Hamden, Connecticut, built the system, and the Joint Highway Research Advisory Council of the University of Connecticut and the Connecticut Department of Transportation assisted in the installation of the system on a Connecticut bridge.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.093	metres squared	m²
yd²	square yards	0.836	metres squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometres squared	km²
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	Litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	m³

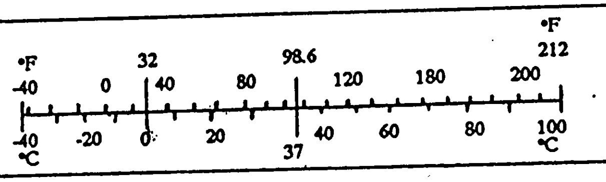
NOTE: Volumes greator than 1000 L shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

*SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



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Chapter 1

INTRODUCTION

Previous research at The University of Connecticut (reported in Ref. 2) has demonstrated that vibrational monitoring can be a feasible technique for application to bridges. A bridge "signature," similar to a human fingerprint, was developed using the Ambient Vibration Method for a bridge model constructed in the laboratory. The "signature" was comprised of the bridge's natural frequencies, mode shapes, and damping characteristics.

Subsequent laboratory testing of bridge models showed that as the structural stiffness of the model was altered, the "signature" also changed. Because the natural frequencies are a function of the bridge's stiffness, a change in stiffness results in a change in natural frequency. Studies also showed that mode shapes are strongly influenced by crack development and that damping ratios are unreliable for monitoring purposes. Vehicle mass, velocity, or varying roadway conditions did not have a substantial influence on the natural frequencies and mode shapes. However, they did affect the amplitudes of the natural frequencies.

The monitoring system was installed on a Connecticut bridge. The bridge chosen was the Interstate 84 eastbound overpass crossing Route 31 in Rockville. The bridge is a three-lane, 155-foot simple-span structure, constructed of six non-prismatic welded steel plate girders. The bridge cross section is shown in Figure 1. The steel is ASTM A588 Weathering Steel. A composite 8-1/2" reinforced concrete slab (f'_c = 3000psi) is used. A 2-1/2" bituminous concrete wearing surface overlays the concrete slab. The bridge is relatively new. This insured testing of a sound structure; therefore, there was no need to consider deterioration in this study.

A total of 16 accelerometers were magnetically attached to the bottom flange of the steel girders and positioned strategically throughout the entire floor plan of the bridge as shown in Figure 2.

The objectives of this report are to show how the signature is developed. It is first necessary to show how the spectra are used to obtain different parts of the vibrational information. Included in this are techniques for obtaining more accurate estimates of natural frequencies and mode shapes, which form the basis of the signature. The report also notes the need to base the signature on those portions of the vibrational data which do not vary under random traffic loading, yet which could change if a structural deficiency occurs.

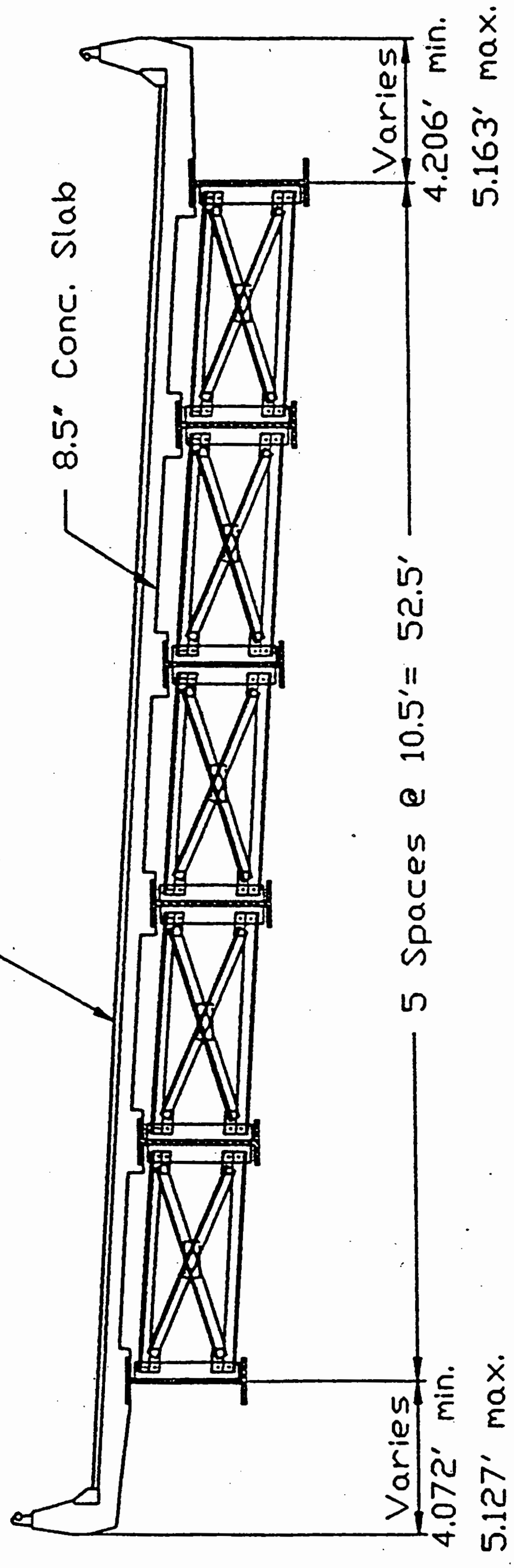


Figure 1. Bridge Cross Section.

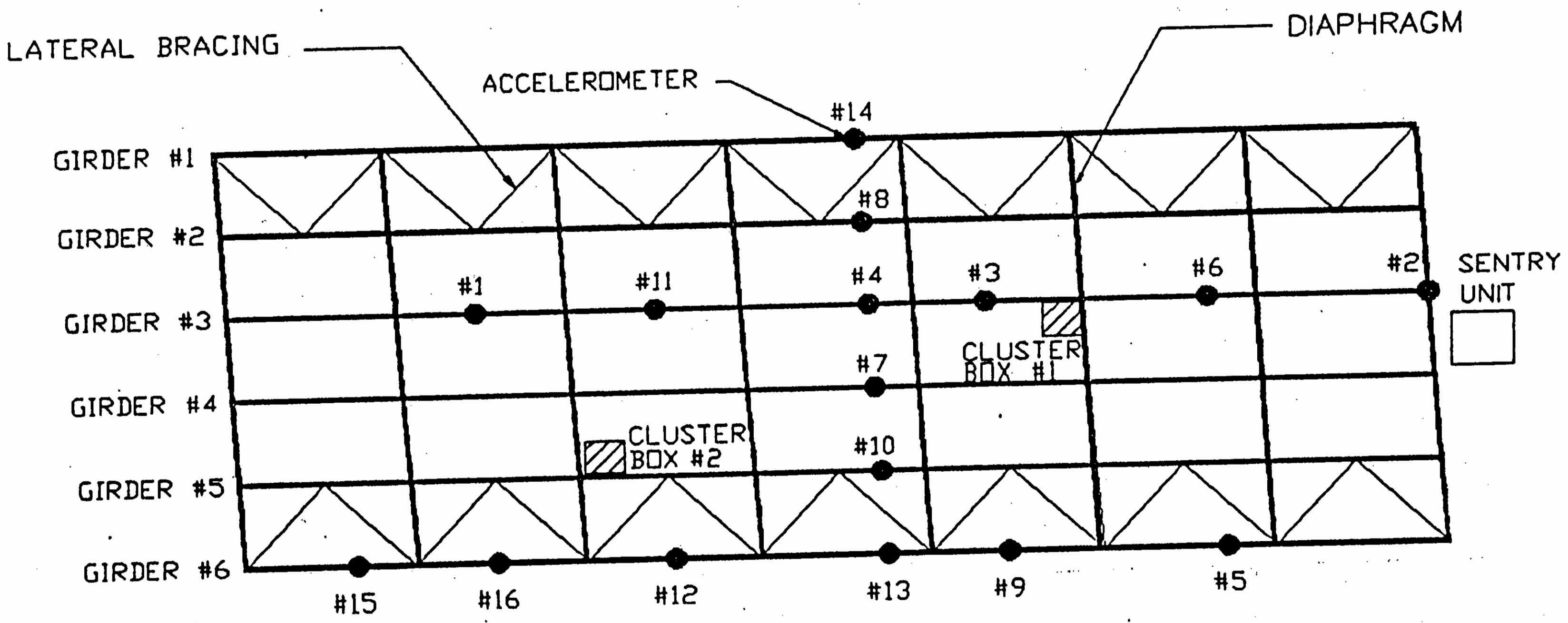


Figure 2. Plan of Bridge with Accelerometer Locations.

Chapter 2

DETERMINATION OF VIBRATION DATA USING SPECTRAL ANALYSIS

SPECTRAL ANALYSIS

Accelerations are collected as time passes. This is known as working in the time domain and its result is a time signal or time history plot. The time history plot is the sum of any number of sinusoids (sine waves) which may have different frequencies and amplitudes. The sum is shown on the right in Figure 3.

Sometimes, working in the time domain may not be the most convenient method. For many applications, there are advantages in following the behavior with respect to the frequency instead of time. This is known as working in the frequency domain and its plot is referred to as a frequency spectrum. One significant advantage of working in the frequency domain is that one can separate the total signal into their individual components which are more directly related to the structural displacements.

Figure 4(a) shows the time and frequency domains in three dimensions. Figure 4(b) represents the time domain view looking down the frequency axis. Figure 4(c) represents the frequency domain view looking down the time axis. It should be apparent that viewing the response with respect to different parameters is often more useful.

Unfortunately, acquiring the data directly in the frequency domain is not readily possible. It is necessary to collect the data in the time domain and then transform the data into the frequency domain. The FFT (Fast-Fourier Transform) is often used for this transformation.

Time signals received from a vibrating system are slightly different than the simple, continuous, periodic sinusoids previously discussed. For a vibrating system, the sinusoids represented in the time signal are transient or decaying in nature, due to the damping characteristics of the vibrating system. The resulting frequency spectrum is no longer a set of lines as shown in Figure 4(c). Instead, it appears as a slightly widened peak as shown in Figure 5.

Thus, the time signals and frequency spectra received from the bridge monitoring system in the field do not lead to clean, simple spectra. Many factors, such as noise levels, FFT leakage, and resolution restraints cause the response spectra to be very complex. This, therefore, makes the signature more difficult to establish.

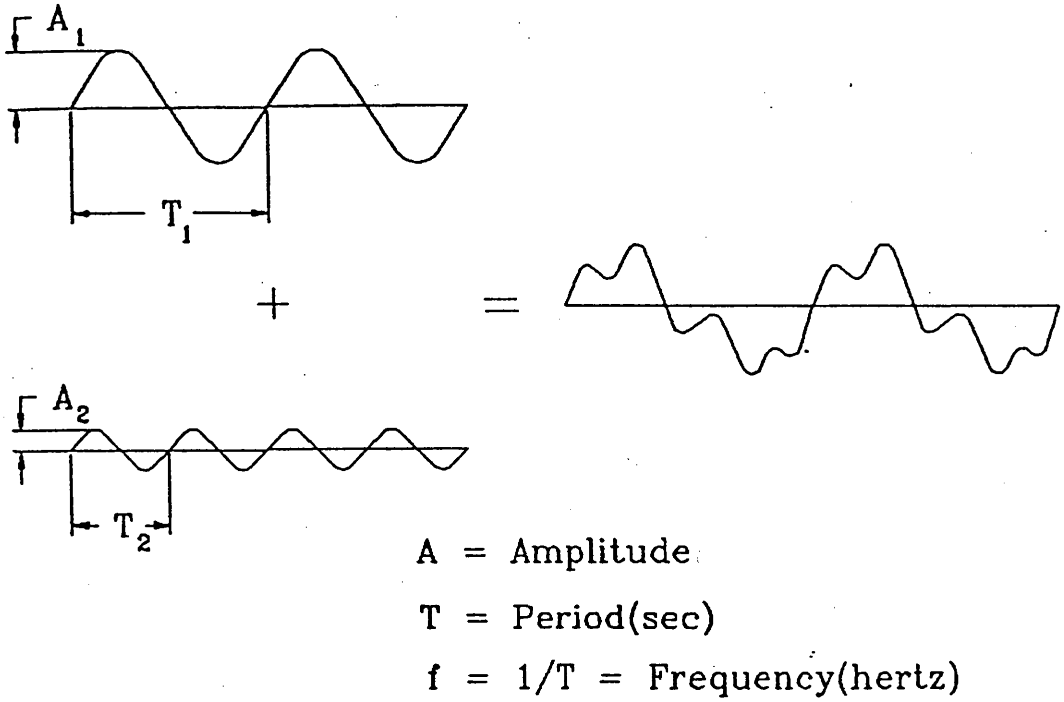


Figure 3. Equivalent Sum of Time History Plots.

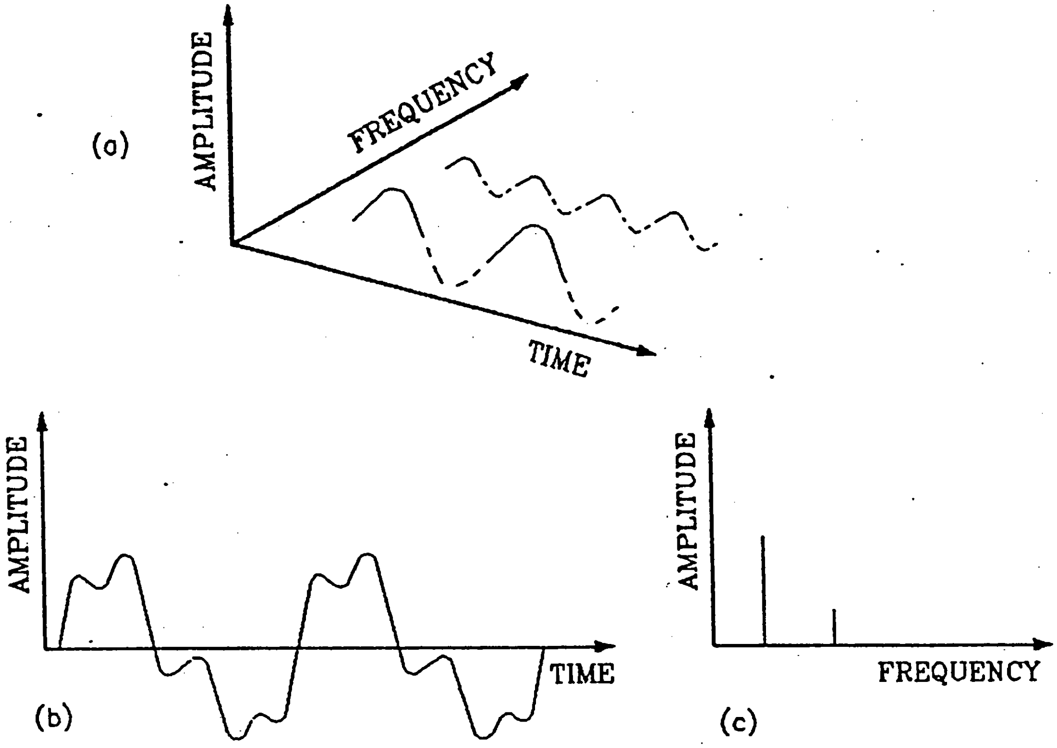


Figure 4. (a) 3-D View of Time and Frequency Domains.

(b) Time Domain View. (c) Frequency Domain View.

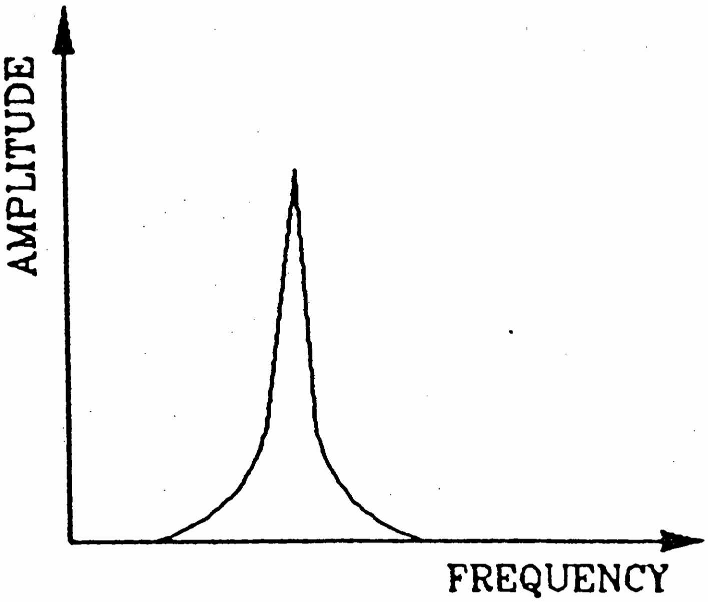


Figure 5. Transient Frequency Response.

The main problem associated with the time signal is noise. A few types of noise apparent to the monitoring system are: background noise, acoustical noise, and 60-cycle noise. Each affects the time signals and ultimately, the spectra in different ways. Each can either appear randomly or be inherent to the system. Fortunately, because most sources of noise are random, there are mathematical techniques to remove them. This ultimately enhances the development of a signature.

SPECTRAL REFINEMENT

Many techniques have been developed to help clean up the signals and spectra. However, some care must be taken when using such techniques because they may actually be detrimental to the spectra. These are reviewed briefly in the following, with a more thorough discussion in Reference (1).

Averaging - This is one of the most common techniques for reducing noice in a frequency spectrum. In general, it is based on calculating the mean amplitude for each corresponding frequency from a series of time periods and using that mean amplitude for the averaged spectrum. Since the noise normally is random, averaging any number of spectra should diminish the noise and make the resonant peaks more apparent. This flattening of the noise is beneficial. The resonant peaks then become more prominent, which enhances their determination and, thus, the development of the bridge's signature.

One concern is that a resonant peak is not automatically excited in each run. One spectrum may have a very large resonant peak at some frequency while another spectrum may have no resonant peak at the same frequency. Averaging the two spectra would reduce that large peak. But, because the noise levels are normally so much smaller than the resonant peaks, this scenario is not usually a problem. In fact, the averaged spectrum is often squared in order to make the resonant peaks more prominent. Therefore, the consistent recurrence of the resonant peaks will keep these peaks prominent relative to the noise levels. Resolution of the system also determines whether averaging will have an effect on the resonant peaks.

Windowing - The Fourier Transform, from which the FFT is an approximation, is an integral taken over infinite time. Even with the most elaborate data acquisition devices, it is impossible to sample over infinite time. Therefore, because our time signals are finite in length, the FFT takes the finite time signal and assumes it repeats itself throughout time. Then, the FFT is computed using that assumed infinite time signal. This does not pose a problem when dealing with time records that have a smooth joint between repeats or with functions that are periodic. (A periodic record is one that exactly repeats itself after a discrete amount of time.) The result is still a sharp peak in the frequency spectrum. However, when dealing with irregular joints between repeats or non-periodic functions, the frequency spectrum will have a widened peak. This widening of the peak is referred to as leakage. This leakage may cause closely spaced resonant peaks to smudge together resulting in misinterpretation of the natural frequencies associated with the system.

If one could multiply the time signal by a function that is zero at the end and large in the central region, the FFT can concentrate on the center of the signal. This is established by using a windowing function. There are many windowing functions, including hanning windows, hamming windows, and kaiser windows.

Because the monitoring system can collect data at any random point in time and because the user has no idea what the vehicular loading is at that time, the time signal may have large activity at the very beginning of the record and little activity in the center region. For this time signal, the windowing function can actually wipe out any low amplitude frequencies that may be occurring during that first four seconds. If the system is set to arrange the time signal so that the largest excitation always occurs in the center portion of the record, windowing is a resourceful way of minimizing FFT leakage without losing pertinent information to the signature.

Curve-fitting - Resolution capabilities of data acquisition equipment can pose problems not related to noise or leakage. If resolution capabilities are too coarse, small changes in resonant frequencies will go undetected. These difficulties that arise from coarse resolution capabilities are compounded by the fact that most data analysis software use linear interpolation between measured data points to plot frequency spectra. An alternate method of plotting the frequency spectra from measured data points is to use a curve-fitting scheme. This should better define the actual resonant frequency which should increase the stability of the peak.

When curve-fitting, lower- and upper-bound frequency limits must be carefully chosen around a resonant peak in order to have an accurate curve-fit. These limits should contain enough measured data points so that the resonant peak is well defined. If two resonant peaks lie close together, selecting too large a band width would cause the curve-fit to try and fit one curve for the two resonances, producing erroneous results.

Unfortunately, with coarse resolution capabilities, usually only a few data points define the resonant peak. A weighting factor is then necessary. For this study a curve-fitting routine developed by Mazurek (3) was used. This routine uses a least squares approach, along with the Newton-Raphson method. A weighting factor is employed to place greater emphasis on measured data points closest to the resonance. This insures that the fitted curve is not governed by data points away from the actual resonance if a large band width bounding that particular resonance is chosen.

Offset Removal - A close look at a frequency spectrum obtained from the monitoring system often shows a large magnitude at zero frequency. This is referred to as the offset. This offset is due to a DC voltage from the electronic equipment in the monitoring system. The only obvious effect the offset has on the spectrum is the large value at zero frequency. Though the offset had a negligible effect on the frequency spectrum, it must be considered for other time signal calculations (i.e., phase relationships, deflections, etc.).

Moving Average - Noise is consistently present in any time signal throughout the entire range of frequencies. Noise levels at high frequencies can easily be removed with a moving average. The purpose of a moving average is to attempt to smooth a signal by averaging around each point. This is done with most commercial data processing software. The time signals with the moving average become smoother with an increased number of moving averages. Also, more of the high frequency noise is removed with an increased number of moving averages. Unfortunately, using this moving average technique can be dangerous. Increasing the number of moving averages begins to diminish the resonant peak, and it might even completely disappear. Thus, when the location of the resonant peaks is unknown during the developmental stages of establishing the signature, removing this high frequency response may remove peaks important to the spectrum.

CHAPTER 3

DEVELOPMENT OF BRIDGE SIGNATURE FROM SPECTRA

INTRODUCTION

The fundamental vibration components of a structure are comprised of the natural frequencies, mode shapes, and damping ratios. Since damping ratios have been found to be an unreliable source for monitoring purposes, the development of the bridge's natural frequencies and mode shapes is critical to the establishment of the bridge's base signature. Changes to the bridge's base signature should correspond to changes in the bridge's structural integrity.

NATURAL FREQUENCIES

As discussed previously, natural frequencies of a vibrating system are displayed as peaks in a frequency spectrum plot. An example spectrum is shown in Fig. 6. Significant peaks, associated with natural frequencies, are shown at approximately 2.0 Hz, 2.4 Hz and 4.1 Hz. As noted later, the peaks at higher frequencies are not readily definable as part of the signature.

MODE SHAPES

Natural frequency peaks are associated with a particular mode of vibration. A mode of vibration or mode shape is the discrete shape that the bridge assumes at that particular frequency of vibration. One mode shape type is a flexural or bending mode shape. This mode shape has major variations in displacement over the longitudinal direction of the bridge. The first four flexural modes for the bridge studied are shown in Fig. 7. Torsional mode shapes have variations in displacement over the transverse direction of the bridge, as well as in the longitudinal direction. The first four torsional modes are shown in Fig. 8. Natural frequencies can be verified by plotting the mode shape corresponding to that natural frequency.

O'Leary (25) has shown that the acceleration level of a natural frequency peak at a specific location is proportional to a normalized displacement at that location. Therefore, the plot of the acceleration levels for the natural frequency in question at different locations along the bridge corresponds to the mode shape for that particular natural frequency.

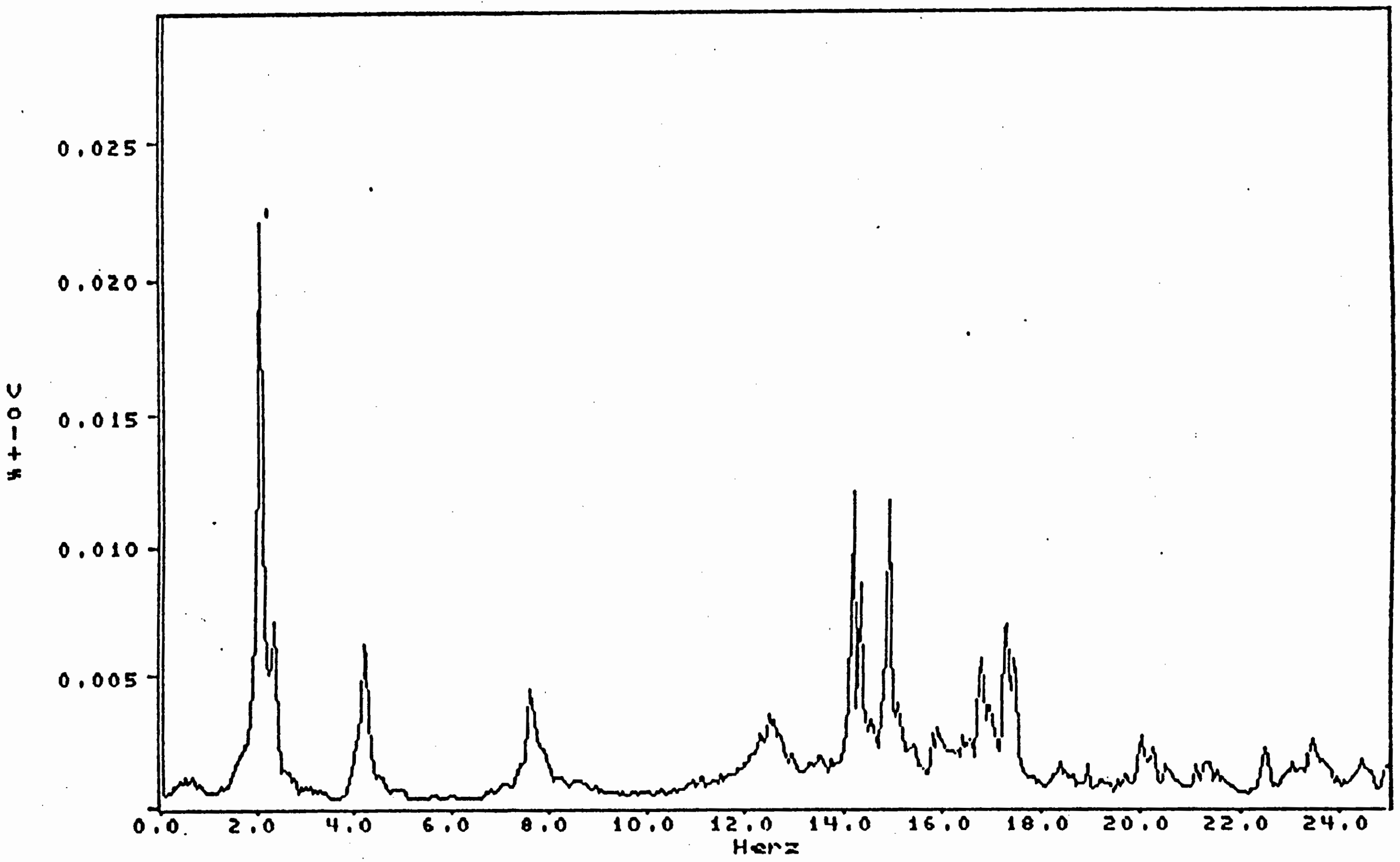
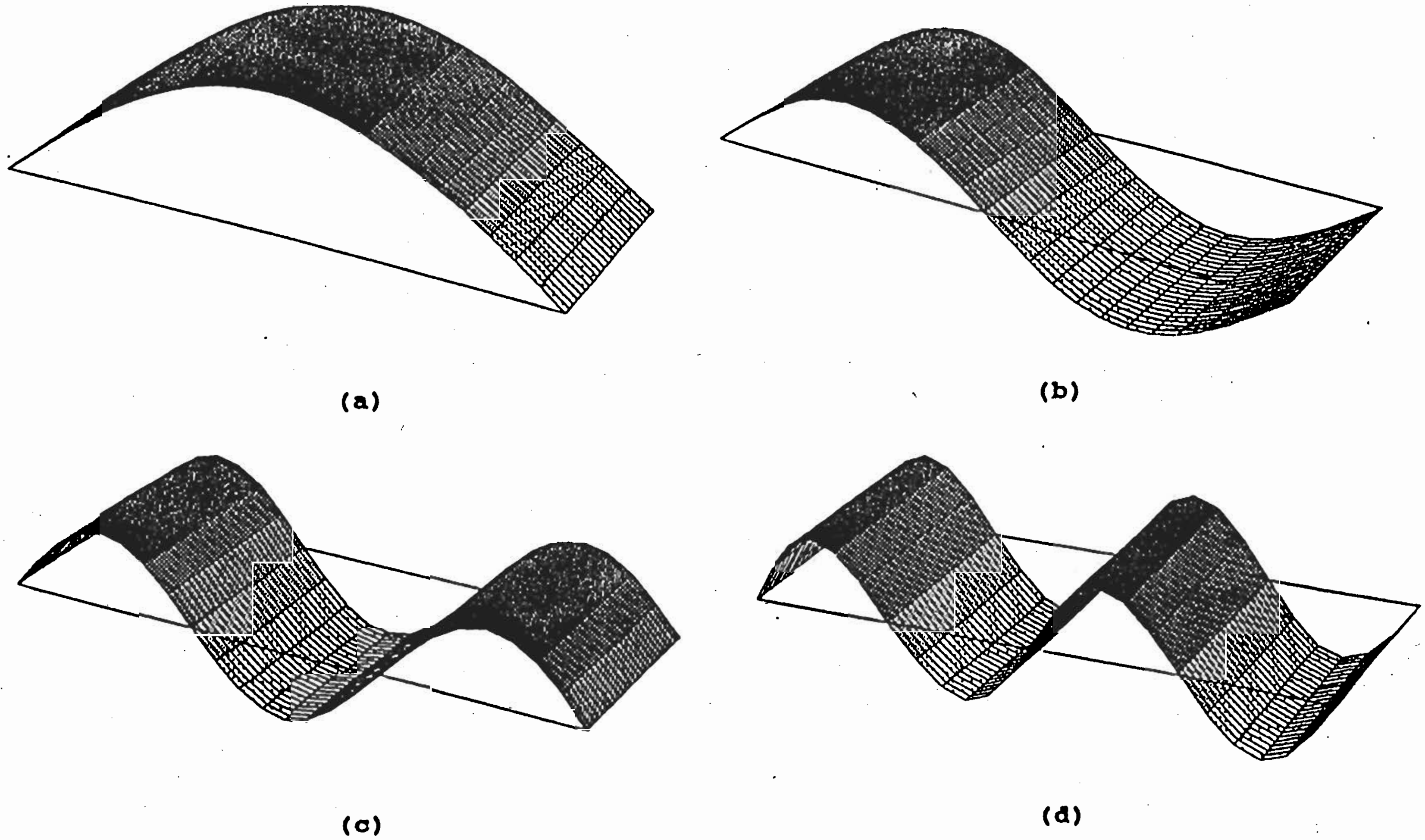


Figure 6. Typical Response Spectrum from Station #8.



(a) (b) (c) (d)

Figure 7. Three-Dimensional Flexural Mode Shapes.

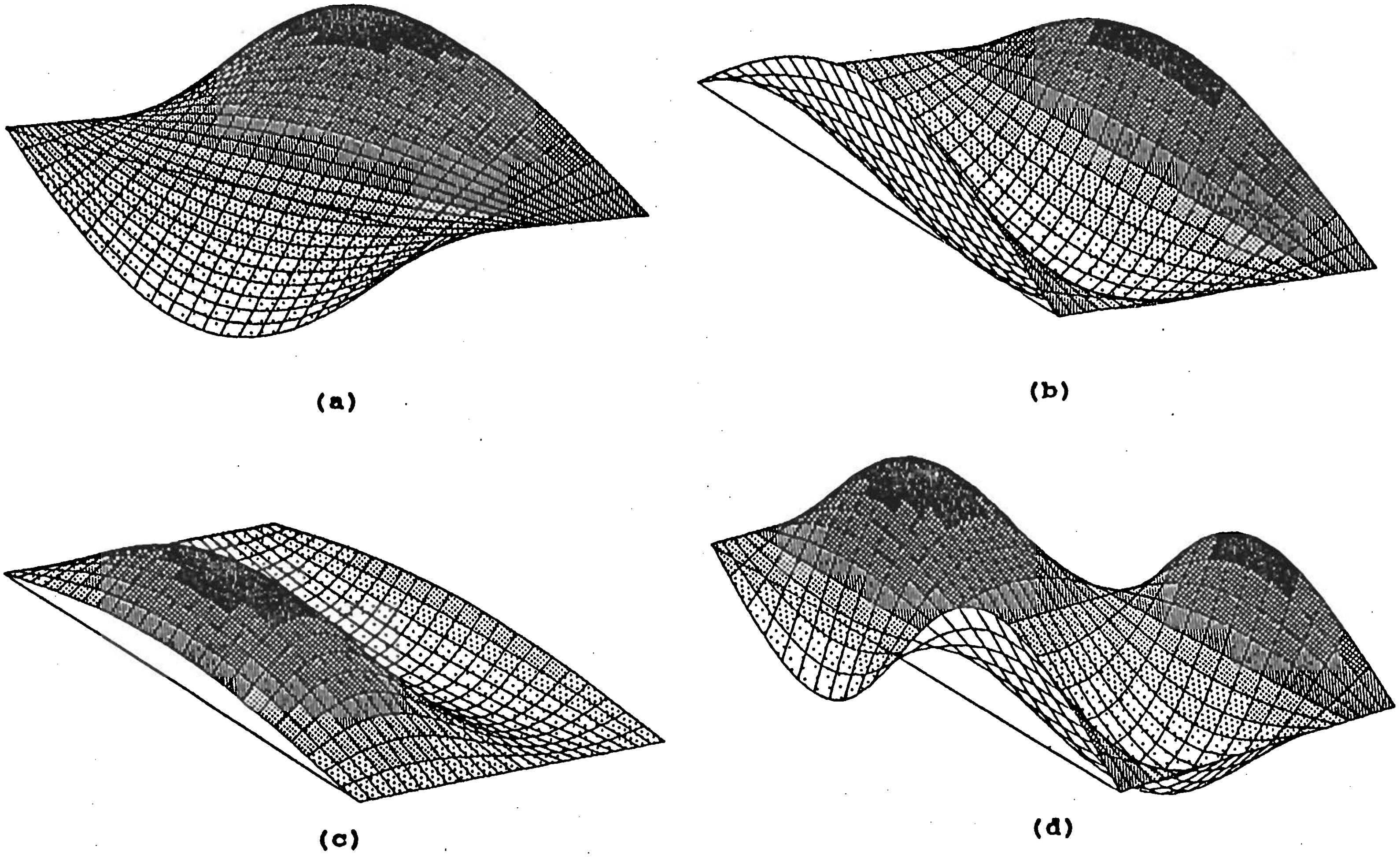


Figure 8. Three-Dimensional Torsional Mode Shapes.

The limitation of this method is that because the acceleration levels in a frequency spectrum are always plotted positive, some guess work is necessary to determine the sign of the normalized displacement. An alternative is to use the comparison of phase information between two accelerations at different locations. If the two accelerometers in question are moving in the same direction, the accelerometers are said to be in-phase. If the accelerometers in question are moving in the opposite directions, the accelerometers are said to be out-of-phase. A cross-correlation function is also used to compare the two time signals. This measures the similarity between two non-identical time signals. If the same frequency sine wave is present in both time signals, it will be reinforced in the cross-correlation routine, while any random noise present in the time signals will be reduced. Software packages are readily available to perform this correlation. The approach is discussed in Reference (1).

GENERAL PROCEDURE

A general procedure was developed to identify other natural frequencies of the bridge, along with the corresponding mode shapes. The steps are:

1) Locate a peak common to a majority of the 16 accelerometers for an averaged run. Is this peak normally excited and is it stable?;

2) Use the time signals from these stations to obtain phase information. Is this phase information consistent?; and,

3) Plot mode shapes along the girders and across centerspan. Are the mode shapes consistent?

Finite element studies can also be used to locate possible natural frequencies and for further verification.

CHAPTER 4

SIGNATURE FROM FIELD RESULTS

INTRODUCTION

If the natural frequencies, mode shapes, and related vibrational information are stable over normal operating conditions, a baseline signature can be developed. This baseline signature can be used to evaluate the structural integrity of the bridge. Changes in this baseline signature would correspond to changes in the structural integrity of the bridge.

If the natural frequencies and mode shapes are not stable, variables contributing to this instability must be defined. Variables, such as resolution capabilities, excitation source, and environmental conditions were evaluated to determine their effect on the baseline signature. A means of defining the difference between a shift in frequency due to a structural defect and a shift in frequency due to these variables is necessary to allow an adequate establishment of the baseline signature.

NATURAL FREQUENCIES

In order to determine a natural frequency, the excitation source must be reliable enough to excite the peak under normal traffic conditions. Because a peak excitation is a function of the energy induced into the structure, a specific natural frequency may not be apparent for every data set or at all accelerometer locations. The energy required to excite the higher order modes is larger than the energy required to excite the lower order modes. Furthermore, a peak must be excited to a level greater than the system noise levels.

Single run frequency spectra were collected over a 10-month period, first for a frequency resolution of ±0.11 Hz and then for a frequency resolution of ±0.005 Hz. Fifty data sets for the ±0.11 Hz resolution and forty data sets for the ±0.055 Hz resolution were compared for the following. The four previously identified natural frequencies (4) at ±2.0 Hz, ±2.4 Hz, ±4.1 Hz, and ±8.6 Hz were evaluated to determine what percent of the time these peaks were sufficiently excited. The station corresponding to the maximum acceleration for that natural frequency was selected to evaluate that peak.

The following table shows the results from this evaluation. As expected, the higher order modes are sufficiently excited less frequently than the lower order modes.

Table 1. Consistency of Peak Excitation.

Natural Frequency	Resolution = ±0.11 Hz	Resolution = ±0.055 Hz
	% of time excited	% of time excited
±2.0 Hz	92%	97%
±2.4 Hz	84%	93%
±4.1 Hz	58%	63%
±8.6 Hz	52%	60%

A statistical study was conducted to determine the effect the resolution has on the variability of the natural frequencies. The results for the frequency resolutions of ±0.11 Hz and ±0.055 Hz, are given in Tables 2 and 3.

Table 2. Natural Frequency Stability, Resolution = ±0.11 Hz.

Mode Type	Mean Value	Standard Deviation	Maximum Value	Minimum Value
Bending 1	2.10 Hz	0.078	2.20 Hz	1.96 Hz
Torsion 1	2.41 Hz	0.050	2.52 Hz	2.30 Hz
Torsion 2	4.13 Hz	0.077	4.31 Hz	4.03 Hz
Torsion 4	8.60 Hz	0.072	8.78 Hz	8.50 Hz

Table 3. Natural Frequency Stability, Resolution= ± 0.055 Hz.

Mode Type	Mean Value	Standard Deviation	Maximum Value	Minimum Value
Bending 1	2.01 Hz	0.034	2.09 Hz	1.92 Hz
Torsion 1	2.37 Hz	0.036	2.52 Hz	2.30 Hz
Torsion 2	4.16 Hz	0.043	4.23 Hz	4.07 Hz
Torsion 4	8.58 Hz	0.051	8.68 Hz	8.51 Hz

The following observations apply to the stability of these frequencies:

1) As expected, the standard deviation results show that the finer resolution has a better natural frequency stability than the coarser resolution.

2) For the ±0.055 Hz resolution, the results show that lower frequencies exhibit smaller variations.

3) The maximum and minimum values fall outside of the standard deviation for every test. This would suggest that these maximum and minimum values occur infrequently.

An interesting problem did occur when defining the natural frequency peaks for the spectra collected using the ±0.055 Hz resolution. For a number of data sets, it was difficult to identify the natural frequency peak because other peaks were branching off of the main peak. This situation was not limited to any particular natural frequency. Interestingly enough, the mode shape for the branching peak was identical to the mode shape for the main peak.

The previously studied natural frequency peaks were all obtained by linear interpolation between measured data points. The curve-fit routine developed by Mazurek (2) was also used for this study. Table 4 represents the statistical results from this study. Some conclusions are:

1) One would expect the curve-fitting scheme to lower the standard deviation for the coarser resolution because it can better define the peak. Except for the 1st torsional mode, the decrease in the standard deviation was extremely small;

2) Curve-fitting had no effect on the mean frequency for either resolution; and,

3) Overall, curve-fitting made an insignificant difference to the linear interpolation scheme.

Averaging is often a useful technique for removing unwanted noise from a frequency spectru. Mathematically, the technique is based on the mean amplitudes of any number of frequency spectrum. Although the technique may be useful for removing unwanted noise, care should be used so that resonant frequencies important to the bridge's signature are not affected.

Averaged spectra for the ±0.055 Hz resolution were evaluated for 3, 5, 10, 15, 20, and 25-averages. Six separate tests were collected for each number of averages. As shown earlier, an increase in the number of averages will increase the amount of noise removed. Unfortunately, increasing the number of averages

Table 4. Curve-Fit Stability, Resolution = ±0.055 Hz.

Mode Type	Inter. Scheme	Mean Value	Stand. Dev.	Max. Value	Min. Value
1st Bending	Linear Inter.	2.01 Hz	0.034	2.09 Hz	1.92 Hz
	Curve Fitted	2.01 Hz	0.037	2.10 Hz	1.93 Hz
1st Torsion	Linear Inter.	2.37 Hz	0.036	2.52 Hz	2.30 Hz
	Curve Fitted	2.37 Hz	0.020	2.49 Hz	2.30 Hz
2nd Torsion	Linear Inter.	4.16 Hz	0.043	4.23 Hz	4.07 Hz
	Curve Fitted	4.15 Hz	0.046	4.24 Hz	4.07 Hz
4th Torsion	Linear Inter.	8.58 Hz	0.051	8.68 Hz	8.51 Hz
	Curve Fitted	8.59 Hz	0.045	8.66 Hz	8.51 Hz

increases the processing time necessary to obtain the averaged spectra.

The following observations were made from the resulting spectra:

1) Averaging verified that no consistent resonant peaks occur at frequencies greater than ±20 Hz;

2) Averaging 3 to 5 spectra produced reasonably clean spectra and a reasonably low processing time; and,

3) Using 10 to 25-averages showed no noticeable increase in cleanliness. In fact, too many averages seemed to increase the distortion between the resonant peaks at ±2.4 Hz and ±4.2 Hz.

Additional information is contained in Reference 1.

ACCELERATION LEVELS

Recent studies by Lauzon (29) have shown that acceleration levels change significantly as a structural imperfection is induced into a bridge. Acceleration levels are a function of excitation source. In the case of a bridge, the vehicular mass, speed, and location contribute to the excitation level. Although this parameter is largely dependent on the excitation source, acceleration patterns can be defined to establish a baseline pattern. Acceleration trends exceeding the baseline pattern may signify a structural defect.

A statistical analysis was performed in an attempt to define the baseline acceleration patterns. The spectrum corresponding to the maximum acceleration for that particular natural frequency in question was used in the statistical analysis. Table 5 shows the results for the frequency resolutions of ±0.055 Hz. The accelerations are shown in volts, which is the value obtained from the accelerometer. The actual acceleration is directly proportional to this voltage value.

Table 5. Acceleration Levels, Resolution = ±0.055 Hz.

Mode Type	Average Acceleration	Standard Deviation	Maximum Acceleration
Bending 1	.039V	.042	0.171V
Torsion 1	.034V	.043	0.188V
Torsion 2	.031V	.030	0.089V
Torsion 4	.018V	.019	0.079V

Some interesting observations can be made:

1) The first bending mode has the largest average acceleration. This is expected since the lower order modes are usually easiest to excite;

2) The fourth torsional mode has the smallest average acceleration. This is expected because the higher order modes require more energy for excitation; and,

3) Maximum accelerations are always outside of the standard deviation value for all modes. This would suggest that these large accelerations are infrequent.

A graphical representation of the acceleration trends for the ±0.055 Hz resolution is shown in Figures 9 through 12. These figures represent the number of times a natural frequency's acceleration falls within a specified range.

MODE SHAPES

Another important element of the vibrational signature is the mode shape. If this mode shape is stable under normal operating conditions, baseline mode shapes can be developed to determine if the mode shape has changed. For this report the mode shape stability will be evaluated for the ±0.055 Hz resolution.

The 1st bending and 4th torsional modes were examined for stability along a girder while the 2nd and 3rd torsional modes were examined for stability across centerspan. These locations were examined because the mode shapes for these respective modes are most prominent at these locations. Five single run data sets were chosen at random to evaluate their mode shape stability. The mode shapes were normalized with respect to the maximum displacement for that frequency in question.

Figure 13 represents the mode shape stability of girder #3 for the 1st bending mode at 2.01 Hz. This mode shape shows a high degree of stability along this girder (approximate 10% difference in displacement).

Figure 14 represents the mode shape stability across centerspan for the 1st torsional mode at 2.37 Hz. This figure shows a larger variability in mode shape (approximate 30% difference in displacement).

Figure 15 represents the mode shape stability across centerspan for the 2nd torsional mode at 4.16 Hz. This mode shape shows a high degree of stability across centerspan (approximate 10% difference in displacement).

Figure 16 represents the mode shape stability of girder #3 for the 4th torsional mode at 8.58 Hz. This mode shape shows approximately a 20% difference in displacement.

VARIATIONS

Another variable that may influence the frequency stability is the environmental conditions.

The first environmental condition examined was temperature. Prior to the actual field testing, the temperature effect on the

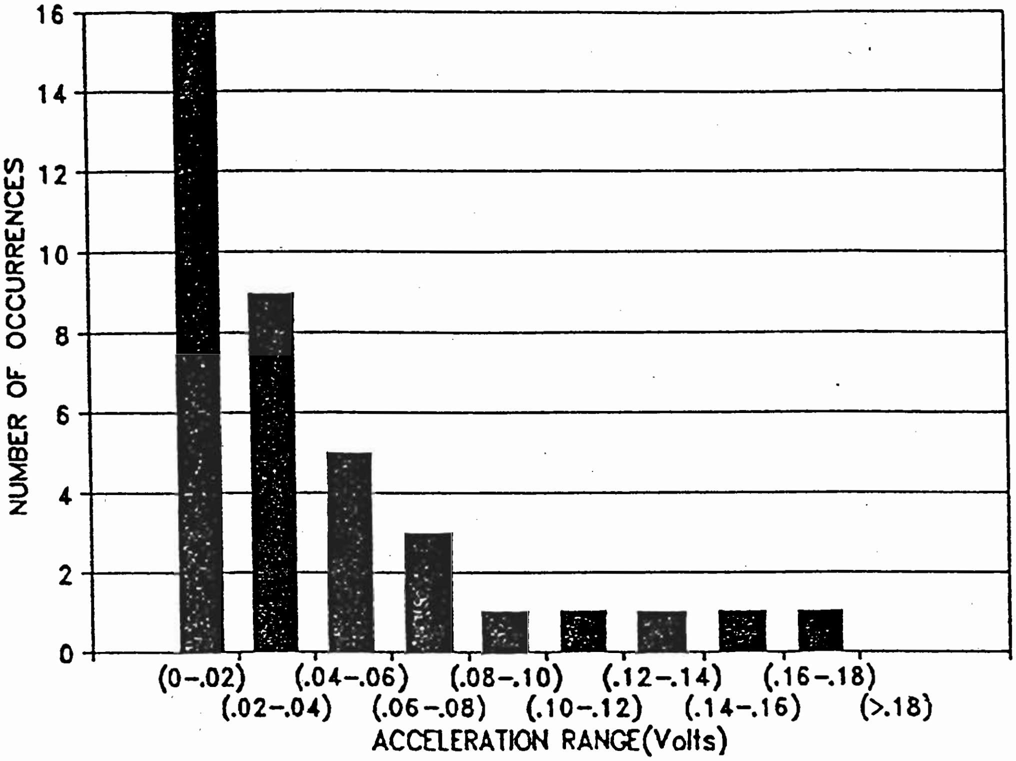


Figure 9. Occurrence vs. Acceleration Range, 2.01 Hz.

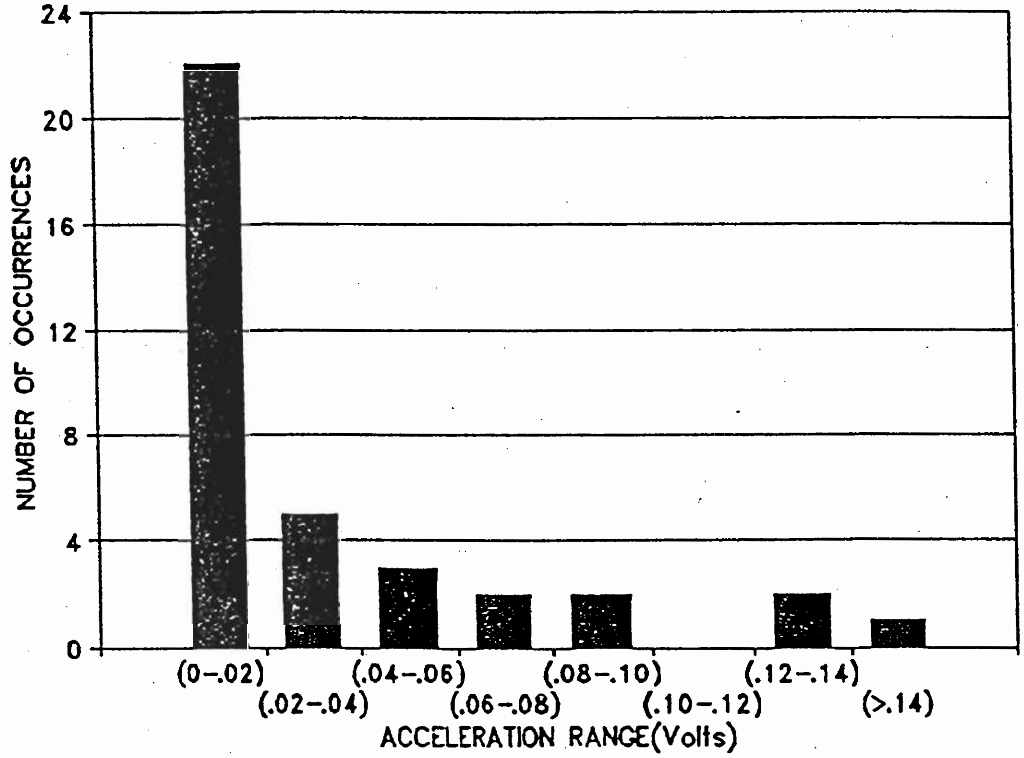


Figure 10. Occurrence vs. Acceleration Range, 2.37 Hz.

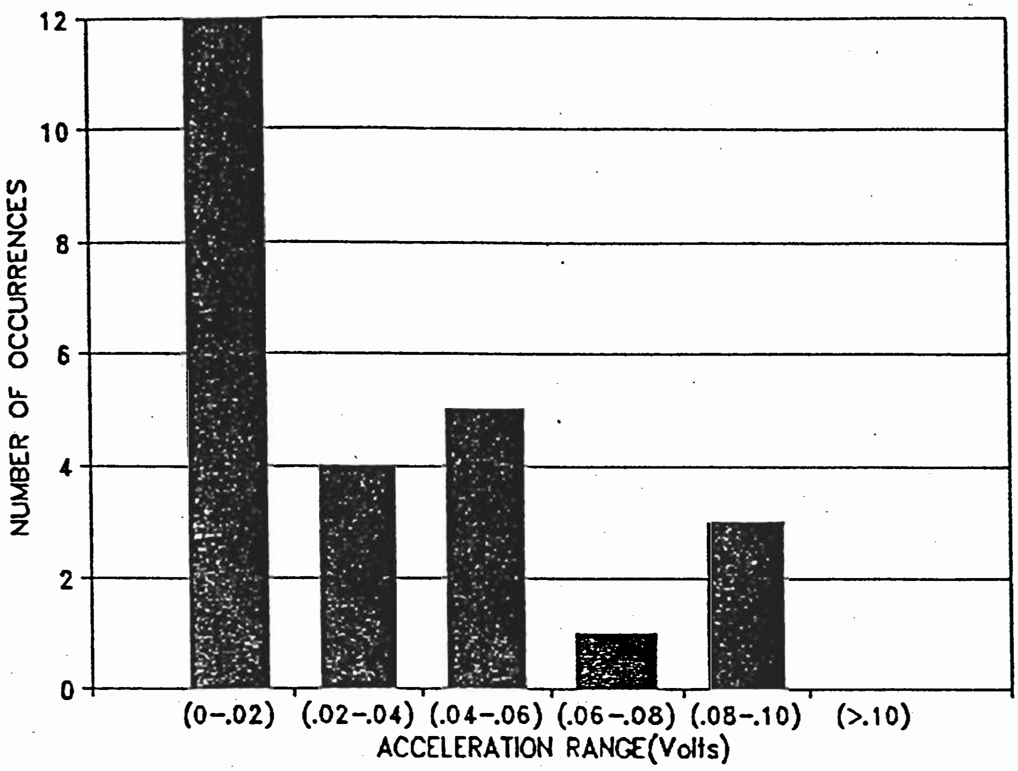


Figure 11. Occurrence vs. Acceleration Range, 4.16 Hz.

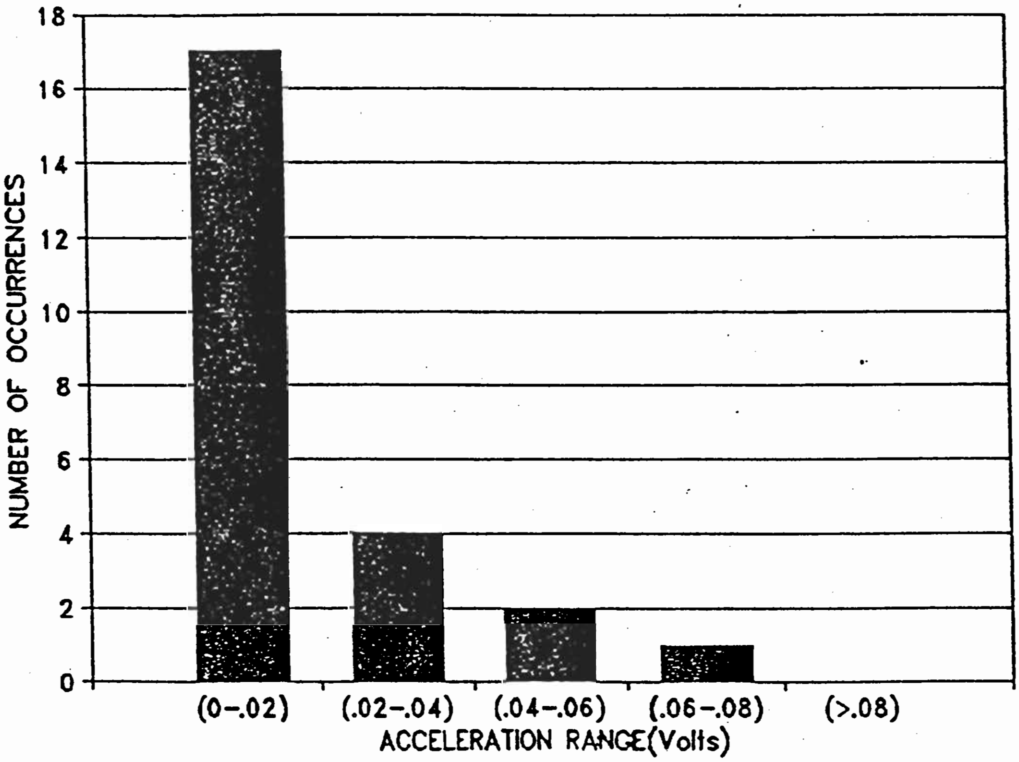


Figure 12. Occurrence vs. Acceleration Range, 8.58 Hz.

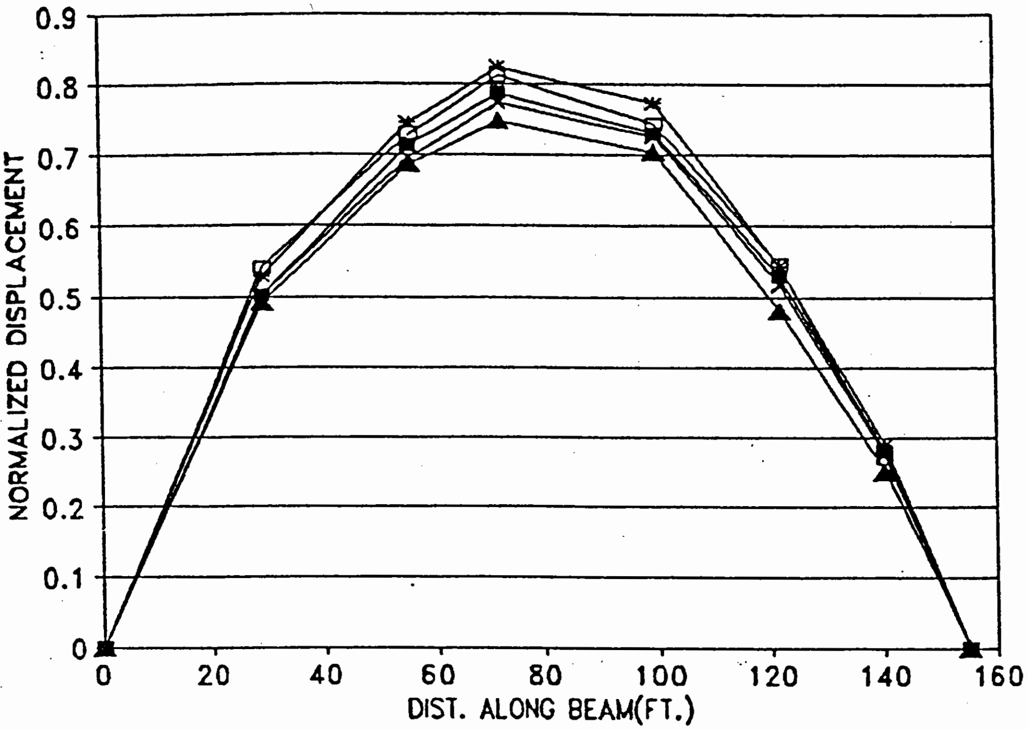


Figure 13. Mode Shape Stability, ±2.01 Hz.

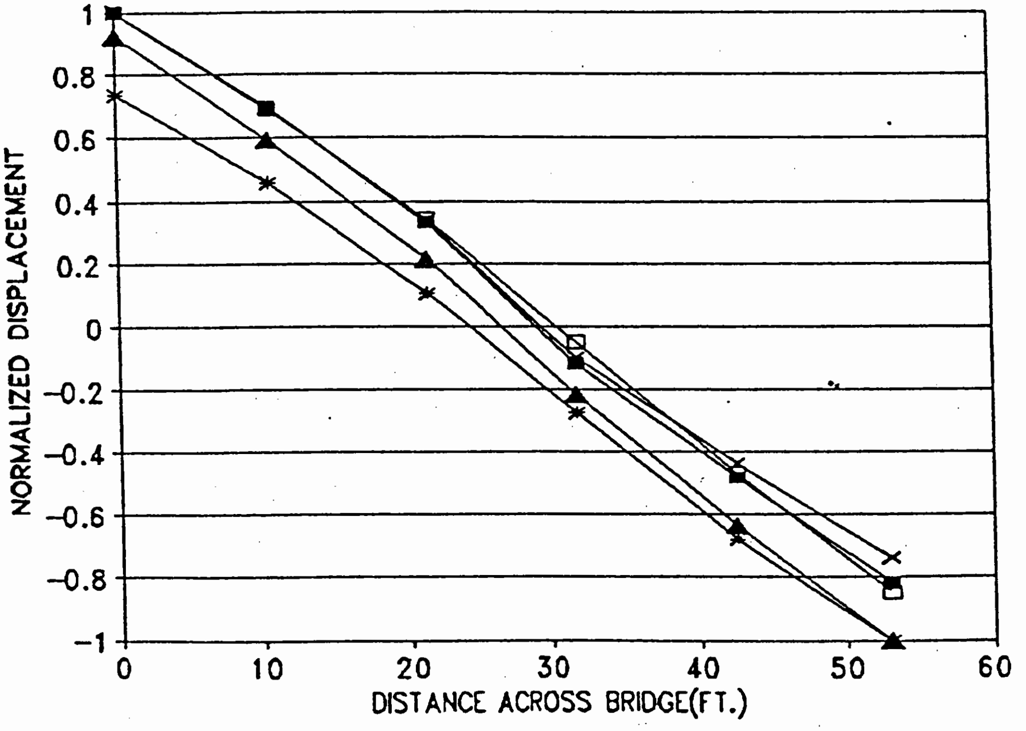


Figure 14. Mode Shape Stability, ±2.37 Hz.

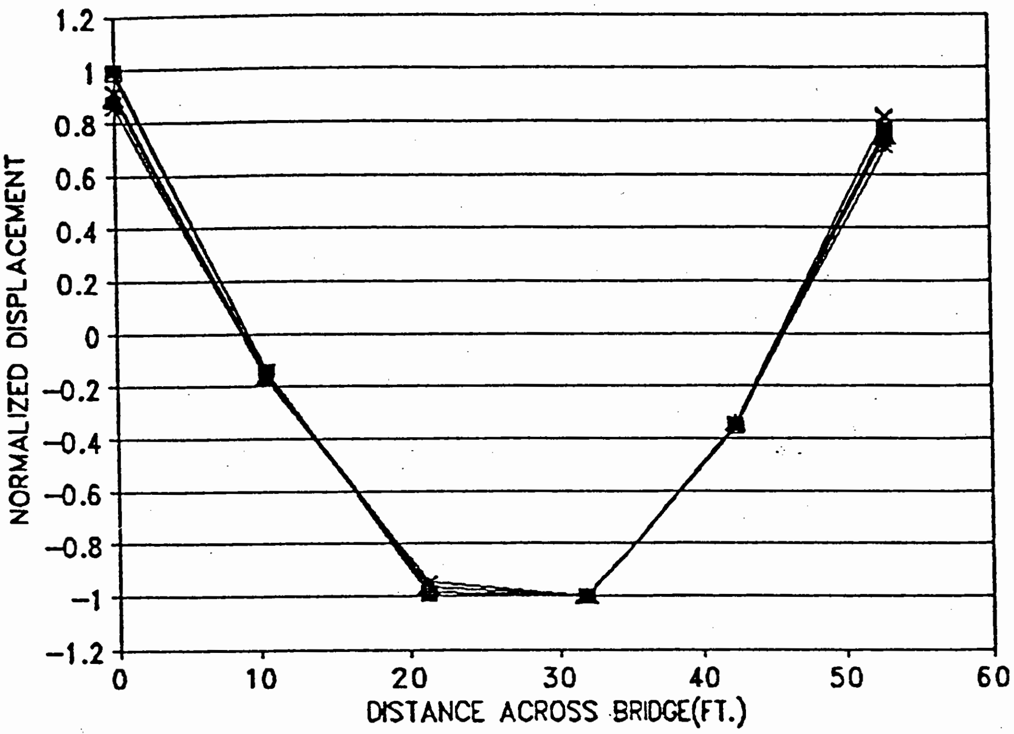


Figure 15. Mode Shape Stability, ±4.16 Hz.

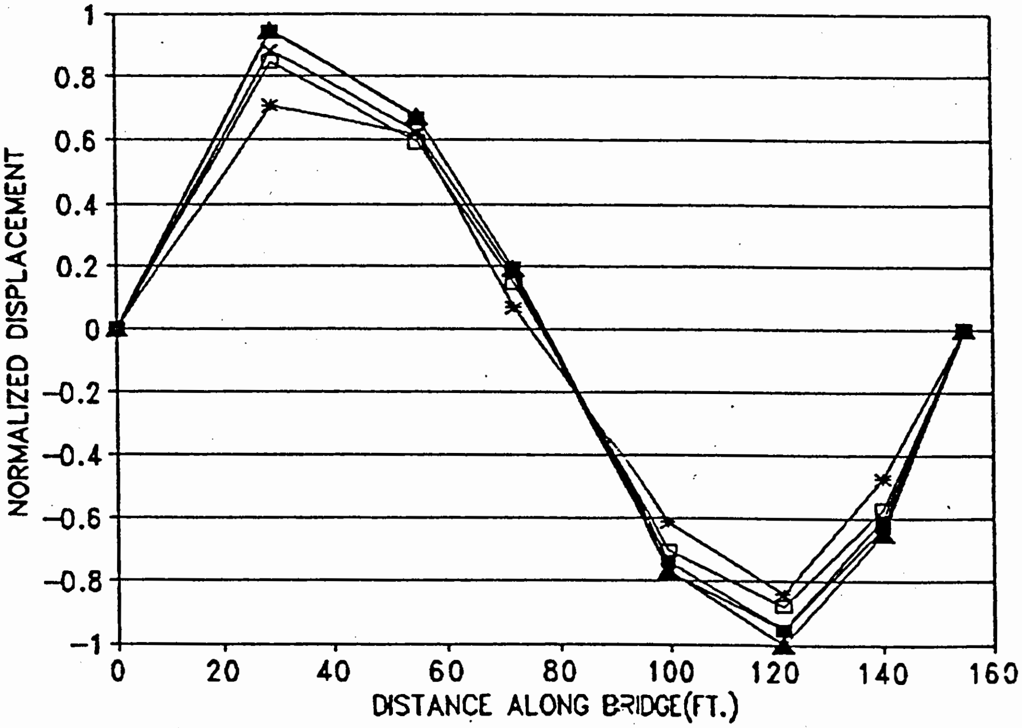


Figure 16. Mode Shape Stability, ±8.58 Hz.

natural frequencies was evaluated analytically by comparing the natural frequencies of a 155-foot beam before and after it thermally expands. These results showed that a change in temperature of 60° had a negligible effect on the natural frequency (less than 0.1% change).

The field results were evaluated with respect to temperature. Both frequency resolutions were evaluated. For the ±0.11 Hz resolution, single run data sets were collected for temperatures ranging from 37°F to 100°F, and for the ±0.055 Hz resolution, single run data sets were collected for temperatures ranging from 32°F to 74°F. The results are shown in Figs. 17 and 18. For each of these figures, a line based on linear regression is also plotted.

Some observations are:

1) Linear regression for these figures shows that the natural frequency is nearly constant over the temperature range; and,

2) Although the figures only represent the temperature effect for the first bending and first torsional modes, the second and fourth torsional modes rendered similar results.

Acceleration levels were also evaluated with respect to temperature changes. The colder month's acceleration patterns were compared to the hotter month's acceleration patterns. These temperature changes showed no effect on acceleration patterns.

The second environmental factor examined was humidity. Humidity was examined to make sure the electrical components of the monitoring system were not being affected during humid periods. Relative humidities ranging from 32% to 93% were examined. Figure 19 shows the humidity effect on the first bending mode for the ±0.055 Hz resolution. This figure shows that the relative humidity has no significant effect on the natural frequency. Similar plots for the other natural frequencies and for the coarser resolution also showed no effect.

Another important variable that may have an influence on the stability of the natural frequencies is time. Many structural properties of a bridge are a function of time: concrete creeps, structural steel corrodes, and bearings freeze. Single-run data sets were collected using the ±0.11 Hz resolution over an approximate seven-month period. Figure 20 represents the frequency versus time for the first bending mode for the ±0.11 Hz resolution. The linear regression shows a slight decrease in natural frequency over time. This decrease could be attributed to the instability of the coarser resolution. Unfortunately, these results may be misleading. The one-year period for which the bridge has been tested is much too short to safely conclude that time has no effect on the natural frequencies. In actuality, if time does have an influence on the signature, the signature may have to be slowly revised with time.

CHAPTER 5

CONCLUSIONS

The extensive testing and a statistical analysis have shown that natural frequencies and mode shapes remain relatively stable under varied traffic conditions. These form the bridge's baseline vibrational signature which can then be used to monitor the structural integrity of the structure. Statistical comparisons of acceleration trends may also be a possible indicator of structural change. While there is a large dependency on the excitation source, statistical comparisons can show changes when the structural integrity is changed.

Four peaks were identified as natural frequencies of the bridge, and the mode shapes were established for these. These natural frequencies were assumed to be suitable for monitoring purposes. Unfortunately, the other prominent peaks were unreliable for monitoring purposes. Typical problems that made identifying these peaks unsuccessful were:

1) Mode shapes were unrecogniable or unstable;

2) The peak had a typically small excitation level;

3) Many peaks were clustered in a very small band width; and,

4) Phase results for a peak were inconsistent.

These results indicated that the peak in question was either part of the system noise or a natural frequency unreliable for monitoring purposes. Part of the reason is that higher order natural frequencies require more energy. Further refinements in the system resolution could also facilitate determining higher order natural frequencies.

The determination of the bridge's baseline signature is necessary to be able to evaluate the bridge's condition. The procedure should include:

1) A windowing function to reduce FFT leakage;

2) An averaging scheme to reduce random noise. It was concluded that 3 to 5-averages sufficiently reduced the random noise while minimizing the data processing time;

3) The establishment of the bridge's natural frequencies and mode shapes under normal operating conditions; and,

4) The establishment of the acceleration patterns associated

with the natural frequency peaks. These patterns may be a possible indicator of a structural defect.

FUTURE WORK

Hardware - The frequency resolution should be increased to improve the natural frequency stability. Ideally, a user should be able to adjust the resolution and frequency range to best suit the bridge being tested.

Software - Continued software development is needed for: (1) automating the determination of natural frequencies, based on averaged frequency spectra with windowing techniques; (2) automating of phase information which is useful in determining the natural frequencies; and, (3) determination and evaluation of mode shapes.

A system of characterizing the bridge's vast vibrational data will then be needed for a functioning monitoring system. Vibrational information involves many variables, none of which would be adequate alone in predicting structural integrity problems. A total picture must be obtained, such as through application of a neuro-network approach in which all variables are continuously evaluated. Earlier attempts to apply vibrational techniques to determine structural deterioration in bridges was not successful because they based the effort on specific vibrational parameters only. They did not look at the whole picture.

Continued Testing - Future testing recommendations area: (1) long-term monitoring to further establish time and environmental effects; (2) relocating the monitoring system to a continuous bridge with increased complexity; (3) use of the system on an older bridge to evaluate the stability of the monitoring information; and, (4) investigation of using additional higher level vibrational techniques as a means to monitor a structure.

Destructive tests of real bridges will be necessary to fully establish the monitoring technique.

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