Evaluation of the Quality of Ambient Vibration Monitoring Data from the Henry Hudson Bridge

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Abstract: The quality of test data is an important consideration in conducting field experiments on civil infrastructure. In addition to possible errors due to the experimental setup, the uncertainties due to incomplete knowledge of a structure's behavior and its interactions with the natural environment greatly affect the reliability of the system identification results. This paper discusses the uncertainties related to ambient vibration testing of a long-span steel arch bridge and possible ways to mitigate them. The consistency of the identified parameters is examined through statistical analyses.

Keywords: Ambient vibration; Noise removal; Stationarity; Frequency bandwidth; Variability

1. INTRODUCTION

Ambient vibration testing, as a practical tool for the evaluation of large civil engineering structures, has been widely conducted in recent years. Applications of the ambient vibration testing include system identification (Abdel-Ghaffar and Scanlan 1985 a, b; Feltrin 2001; Ren, Blandford and Harik 2004; Ren, Zhao and Harik 2004), condition assessment (Brownjohn and Xia 2000) and damage detection (Catbas et al. 1998; Catbas and Aktan 2002). This is because a properly designed and executed field experiment or instrumented monitoring application is expected to objectively provide the in-situ characteristics and behavior of the structural system under consideration.

The performance of civil infrastructure systems is usually governed by a number of factors, including the actual operating and loading environments, complex interactions between structural members and systems, and defect, deterioration and damage mechanisms. On the other hand, the implementation of an ambient vibration testing application is also subject to various systematic and random errors and other mechanisms of uncertainty (Zhang and Aktan 2005; Grimmelsman and Aktan 2004), although some of the errors may be identified and mitigated through the design and calibration of the sensing system. Thus, in order to obtain reliable results from the ambient vibration testing, measures should be taken to identify mechanisms of uncertainty and to mitigate their effects on the extraction of model parameters.

The writers conducted an ambient vibration monitoring for system identification of the Henry Hudson Bridge, a long-span steel arch bridge located in New York City, with the objective of improving the reliability of a seismic retrofit investigation for this structure. This paper describes the design, execution and analysis of the ambient vibration testing, and presents selected results from measurements on the arch span. The errors encountered in the measurement data and the methods used for their mitigation are discussed. The uncertainty related to the ambient vibration testing of this bridge is examined by analyzing stationarity and the effects of bandwidth on the identified frequencies. The uncertainty related to the stability of the identified frequencies is also examined by comparing statistics for the time of day in which the measurements were collected and the quantity of data included for analysis.

2. DESCRIPTION OF THE BRIDGE

The Henry Hudson Bridge is a major long-span steel arch bridge located in New York City. The bridge spans the Harlem River and connects northern Manhattan to the Bronx. The bridge was opened in 1936 and is currently owned and operated by the MTA Bridge and Tunnel Authority.

The main span of the bridge (Figure 1), consists of a 256 m long fixed plate girder arch that provides a vertical clearance of 44 m. The arch span is flanked at its northern end by a steel tower structure, a 91 m long viaduct and an 82 m long approach, and at its southern end by a steel tower structure, a 91 m long viaduct, and a 125 m long approach. .The viaducts at the northern and southern ends are supported by steel bent structure of various heights at every 18 m.

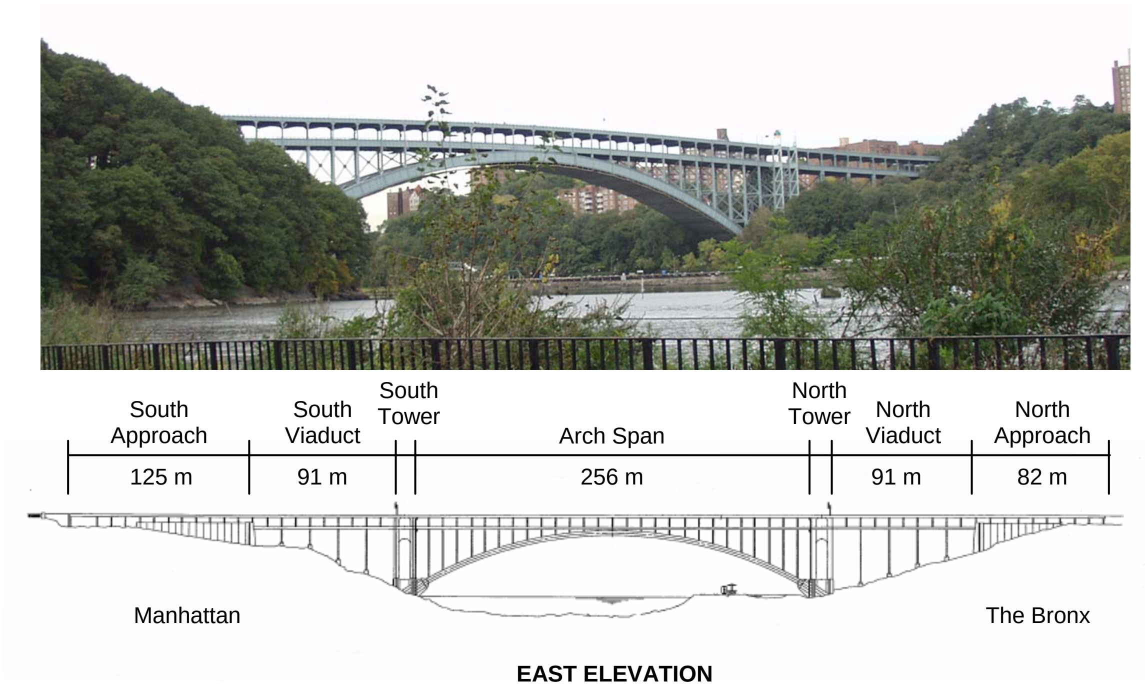

Figure 1 the Henry Hudson Bridge

The bridge normally carries a total of seven lanes of traffic on two levels, with three lanes devoted to northbound traffic on the upper level and four lanes devoted to southbound traffic on the lower level. The traffic using the bridge consists mainly of light vehicles since commercial truck traffic is prohibited. The bridge was in the process of being re-painted while the ambient vibration testing was being performed, and the contractor periodically had temporary lane closures on the upper and lower levels and heavy equipment on the spans.

3. AMBIENT VIBRATION TEST

Ambient vibration test was performed on the Henry Hudson Bridge in order to identify its dynamic properties (frequencies, mode shapes, and damping ratios) for further condition assessment of the bridge. The scope of the testing included measuring the vibrations of the arch span, the towers, the viaducts and their interaction under traffic and environment induced ambient excitation sources.

The arch span, viaducts, and towers were tested in two stages. In the first test stage, a total of 36 accelerometers were installed on the north-half of the arch span, the north tower and the north viaduct. The south-half of the arch span, the south tower and the south viaduct were tested in the second test stage using a total of 40 accelerometers. Among them, seven accelerometers on the bridge spans remained at the same locations during both test stages and were used as reference sensors in the data processing.

Multiple data sets were recorded during each test stage. The vibration measurements were recorded during each test stage using a number of different sampling frequencies. The sampling rates used ranged fro 20 Hz to 800 Hz, but the majority of the measurements were sampled at 200 Hz for intervals of 900 seconds. The multiple sample rates were used to permit the effect of bandwidth on identified frequencies to be evaluated.

3.1. Instrumentation scheme

At each stage of the test, stationary instrumentation scheme was used instead of a roving instrumentation scheme. Thus the vibration responses at all accelerometer locations on the bridge can be measured simultaneously. The stationary instrumentation also makes it possible for long-term ambient vibration monitoring. On the other hand, the limited number of sensors and data acquisition channels may lead to spatial aliasing, which can hamper the extraction of the mode shapes from the data.

In order to capture the vertical, torsional and lateral vibrations of the bridge, vertical and transverse accelerometers were installed on the east side of the upper level deck and on the west side of the lower level of the arch span respectively. Additional transverse sensors were placed on the arch girder of the arch span and the upper and lower level of the towers and viaducts. The detailed sensor layouts are shown in Figures 2 and 3.

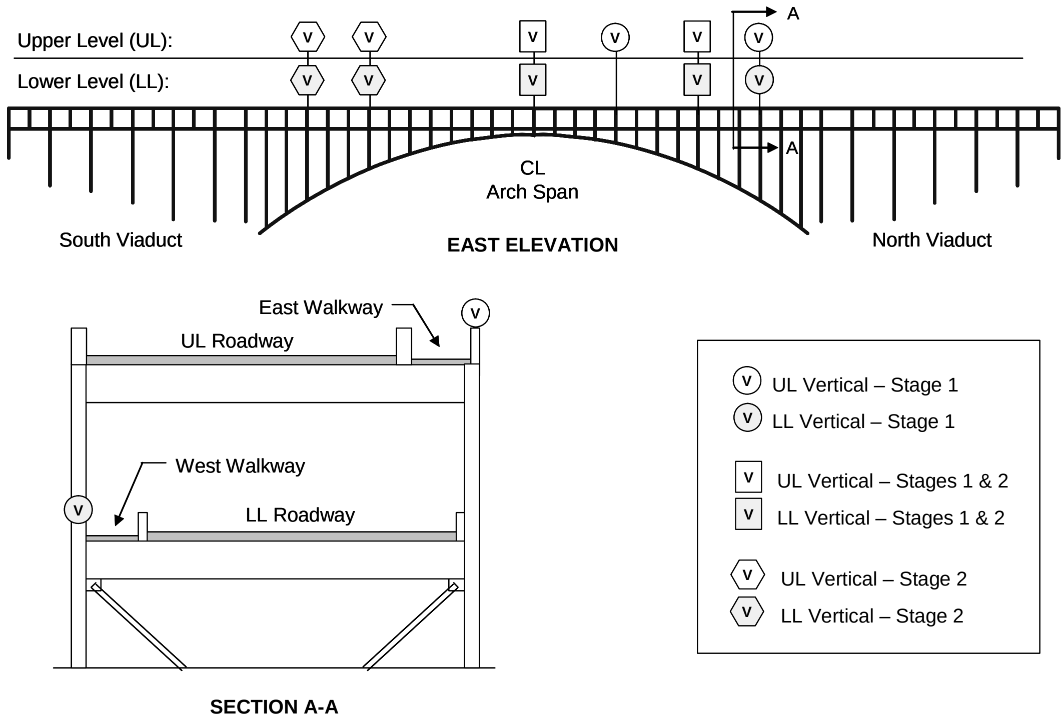

Figure 2 Accelerometer locations for measuring vertical and torsional vibrations

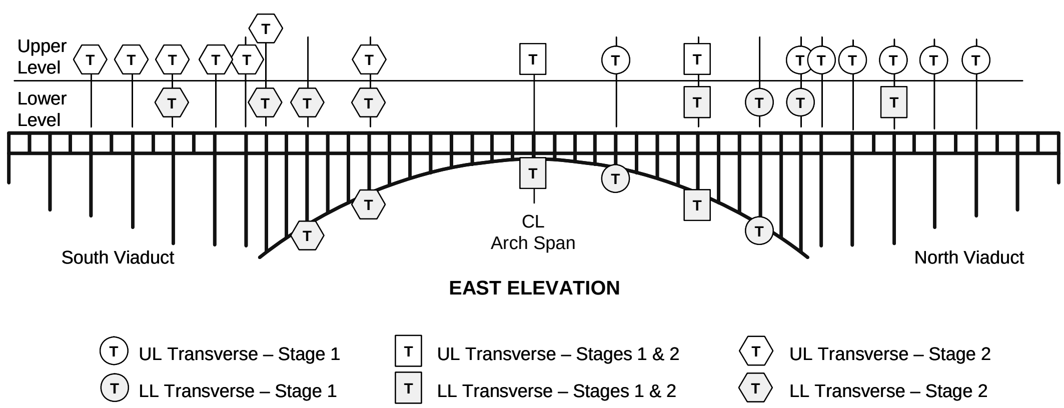

Figure 3 Accelerometer locations for measuring transverse (lateral) vibrations

3.2. Test equipment

The accelerometers used to measure the vibrations of the arch span and viaducts were Model 393C seismic accelerometers from PCB Piezoelectronics. These are uni-directional sensors that have a nominal sensitivity of 1 Volt/g, a peak measurement range of 2.5 g, a frequency range of 0.025 to 800 Hz, and a broad band resolution of 0.0001 g. The factory supplied calibration value for each accelerometer was verified in the laboratory using the back-to-back calibration method and a shaker device before the accelerometers were deployed in the field.

The data acquisition system consisted of a Hewlett Packard Model 8401A VXI mainframe with Model 1432A input modules, Model 481 signal conditioners from PCB Piezoelectronics, and a laptop computer. The data acquisition system was setup and removed daily during the ambient vibration testing.

4. DATA PROCESSING AND ANALYSIS

The measurement data from a field experiment or monitoring application are usually subject to various systematic and random errors and other mechanisms of uncertainty (Zhang and Aktan, 2005). Some of the errors may be identified and mitigated through the design and calibration of the sensing system. However, it is impossible to identify, characterize and control the mechanisms of uncertainty associated with field measurements. The following sections discuss some of the possible sources of the uncertainty in the field test and their effects on identified modal parameters.

The data processing scheme consisted of two stages, the pre-processing and the post-processing. During the pre-processing stage, the quality of the measurements is qualitatively assessed and sensing errors are identified and mitigated. Since most parameter estimation algorithms for ambient vibration tests are based on the assumption of stationarity of the measurements, stationarity testing is performed to verify the validity of the assumption. The effect of frequency bandwidth on the identified modal parameters is also evaluated through the data sets recorded with different sampling frequencies.

Then in the following post-processing stage, the dynamic properties are determined and the variability of the identified modal parameters due to different level of traffic and different finite length of record is evaluated. There are many available methods for identifying the dynamic properties from experimental vibration data. These approaches can be classified as either time domain or frequency domain methods. The results of a benchmark evaluation using many of these methods for identifying the dynamic properties of a bridge from ambient vibration data have been previously reported by Peeters and Ventura (2003). The dynamic properties of the Henry Hudson Bridge were identified by peak picking in the frequency domain as outlined in Bendat and Piersol (1980). In this approach, the natural frequencies are determined from the locations of peaks in the autospectra (PSDs) of the accelerometer channels. The PSDs were computed using Welch's method, which averages the discrete fourier transforms (DFTs) to obtain smoothed spectra. Each segment of time domain data was also pre-multiplied with a Hanning window before each DFT was computed to minimize leakage errors. It should be noted that this method is only applicable for lightly damped structures with modes that are well separated.

In this paper, the scope of the data processing and analyses is limited to examining the frequencies for the north-half of the symmetric arch span using the measurement data from the first test stage. The data processing was performed using the computer program MATLAB.

4.1. Noise removal

Since some noise spikes were found to dominate in portions of the recorded data through a visual inspection, the first step in data pre-processing is to remove them in the measurements, which is a critical consideration for minimizing the uncertainty of the ambient test results. Noise spikes occurred due to many possible reasons such as malfunction of the data acquisition system and their existence can lead to low signal-to-noise ratios and erroneous identification results. In the long-term ambient vibration monitoring project on the arch dam of Mauvoisin, 41% of a total of 360 recorded samples were rejected thus.

In our pre-processing procedure, the measured vibration responses are first plotted in the time and frequency domains channel by channel so that unreliable or non-functioning channels could be identified. The DC component of the measurement signals was filtered from the spectra since this was coupled with temperature changes, and the locations of any spurious spikes in the time domain data were removed. This direct noise removal was tested to prove that it will not distort the resulting signals. An example of a typical spike found in the time domain signal is the time domain response is shown in Figure 4. The inset shown in Figure 4 is a representative of response that is free from sensing errors. The source of this measurement error could not be identified, but this type of error was periodically observed for many of the accelerometer channels and often occurred multiple times in a given data set. Figure 5 shows the frequency content for the signal shown in the previous signal before and after the spike was removed. Such spikes were removed from the measurement channels in order to salvage as much of the signals as possible for the data post-processing stage.

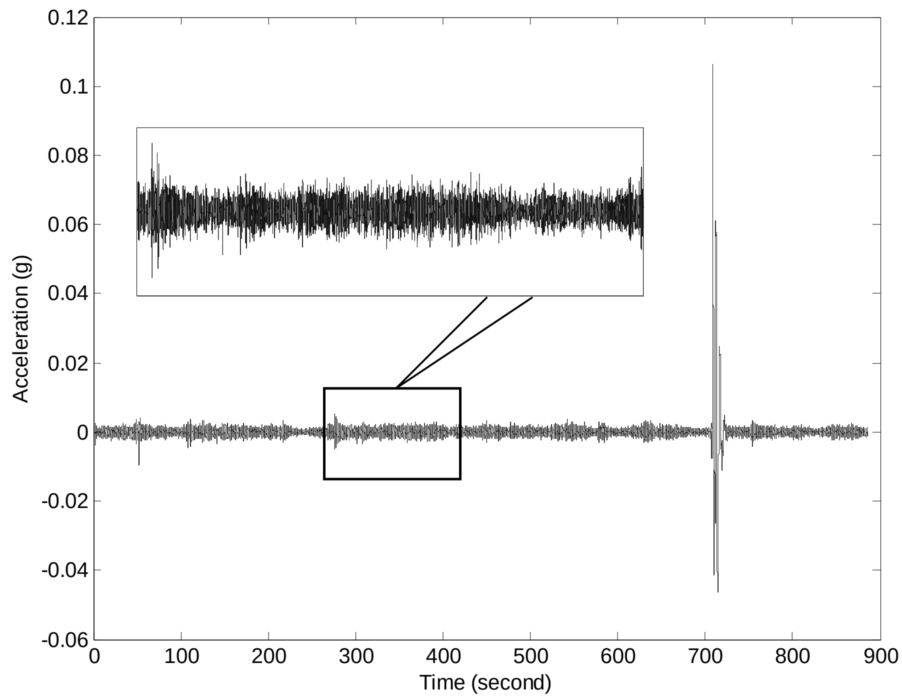

Figure 4 Spurious spike in the time domain acceleration response

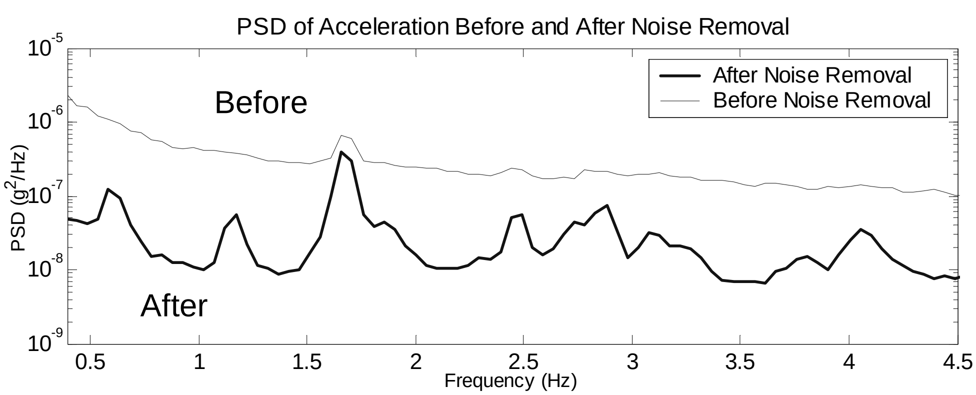

Figure 5 PSD of acceleration data before and after removal of spurious spike

4.2. Stationarity testing

The data measured in an ambient vibration test is generally assumed to be stationary, Gaussian random data. The methods used to analyze and interpret the vibration data are directly influenced by these characteristics. Various statistical analysis methods can be used to test whether these assumptions are valid. According to Bendat and Piersol (2000), two assumptions are required in order to test the stationarity of recorded data based on individual samples: (1) any sample record will properly reflect the nonstationary character of the random process in question and (2) any sample record is long enough compared to the lowest frequency component in the data, excluding a nonstationary mean.

If the above assumptions are made, the stationarity of the random data can be tested for a single time domain record using the following procedure (Bendat and Piersol 2000): (1) divide the data record for each channel into a number of equal length segments (N), each of which can be regarded as independent; (2) compute RMS values (mean values, mean square values, standard deviations or other similar parameter estimates also work equally well) for each segment and align these values in a time sequence; (3) test the sequence of RMS values for a nonstationary trend. The reverse arrangements test is a widely-used method to test for a nonstationary trend. After the total number of reverse arrangements in the sequence is found, a hypothesis can be made that the data is stationary. This hypothesis would be accepted at a certain level (α %) of significance if the reverse arrangements (A) produced by the sequence of N measurements fall between $A_{N;1-0.5\alpha}$ and $A_{N;0.5\alpha}$. Otherwise, the hypothesis of stationarity is rejected at the α % of significance, and the data are identified as being nonstationary. Similar procedure was utilized by Kijewski and Kareem (1999) for ambient vibration measurements from a tall building.

A data set with a duration of 60 minutes and a sampling frequency of 200 Hz was used to test stationarity. The 720000 data points contained in this record for each accelerometer channel were divided into 30 segments of 24000 data points. Each of these 30 segments corresponded to a 2 minute interval. The RMS accelerations were computed for the 30 segments from the 18 channels of arch span accelerations. The reverse arrangements test revealed that only 3 channels failed to pass the stationarity test for a 1% level of significance. The three channels that did not pass the stationarity test included a vertical accelerometer that was located on the lower level at midspan, a transverse accelerometer that was located on the arch girder at midspan, and a transverse accelerometer located on the upper level at close to midspan. This analysis indicates that the stationarity assumption for the acceleration data measured on the arch span is generally valid for short intervals of two minutes.

4.3. Frequency bandwidth analysis

In the past ambient vibration testing/monitoring applications, sampling frequency was usually chosen subjectively and some researchers have chosen frequencies of up to 1000 Hz (Ren, Zhao and Harik 2004). The objective of the frequency bandwidth analysis was to evaluate if the frequency bandwidth had any significant effect on the frequencies identified from the acceleration data when using the methods described in the previous section. The frequency bandwidth for the data is theoretically defined as one-half the sampling frequency. To perform this analysis, discrete time domain records that were collected on the same day using sampling rates of 100 Hz, 200 Hz, 400 Hz and 800 Hz were processed and the natural frequencies were identified. The length of the data segments contained within these records for which the DFT was computed was defined such that the same frequency resolution was obtained for each set. Because the size of the segments used to compute the DFT in the 800 Hz sampled data set must be large to obtain the same frequency resolution as the 100 Hz sampled data set, the number of averages used to generate each PSD is much smaller for the 800 Hz sampled data than for the 100 Hz sampled data.

The vertical and transverse frequencies identified from the discrete time domain data records measured using different sampling frequencies are summarized in Tables 1 and 2, respectively. The results indicate that the variations observed in the identified vertical and transverse frequencies are very small, and that for many frequencies no variation was observed. Furthermore, the very small variation that is observed for two vertical frequencies and two transverse frequencies is not significant enough that this difference can be directly attributed to the frequency bandwidth. The observed variation also does not appear to be directly related to the number of averages that were used to compute the PSDs from which the natural frequencies were identified.

Table 1 Vertical natural frequencies identified from single data records sampled at different frequencies.

Sampling frequency (Hz)	100	200	400	800	Mean	STD
No. of averages	97	49	21	13		
Frequency resolution (Hz)	0.024	0.024	0.024	0.024		
Frequencies (Hz)	0.732	0.732	0.732	0.732	0.732	0.000
	0.928	0.928	0.928	0.928	0.928	0.000
	1.465	1.465	1.465	1.465	1.465	0.000
	1.685	1.685	1.685	1.685	1.685	0.000
	2.441	2.441	2.466	2.466	2.454	0.014
	3.271	3.247	3.271	3.223	3.253	0.023

Table 2 Transverse natural frequencies identified from single data records sampled at different frequencies.

Sampling frequency (Hz)	100	200	400	800	Mean	STD
No. of averages	97	49	21	13		
Frequency resolution (Hz)	0.024	0.024	0.024	0.024		
Frequencies (Hz)	0.610	0.610	0.610	0.610	0.610	0.000
	1.172	1.172	1.172	1.147	1.166	0.012
	1.563	1.563	1.563	1.563	1.563	0.000
	1.904	1.880	1.880	1.880	1.886	0.012
	2.344	2.344	2.344	2.344	2.344	0.000
	2.466	2.466	2.466	2.466	2.466	0.000

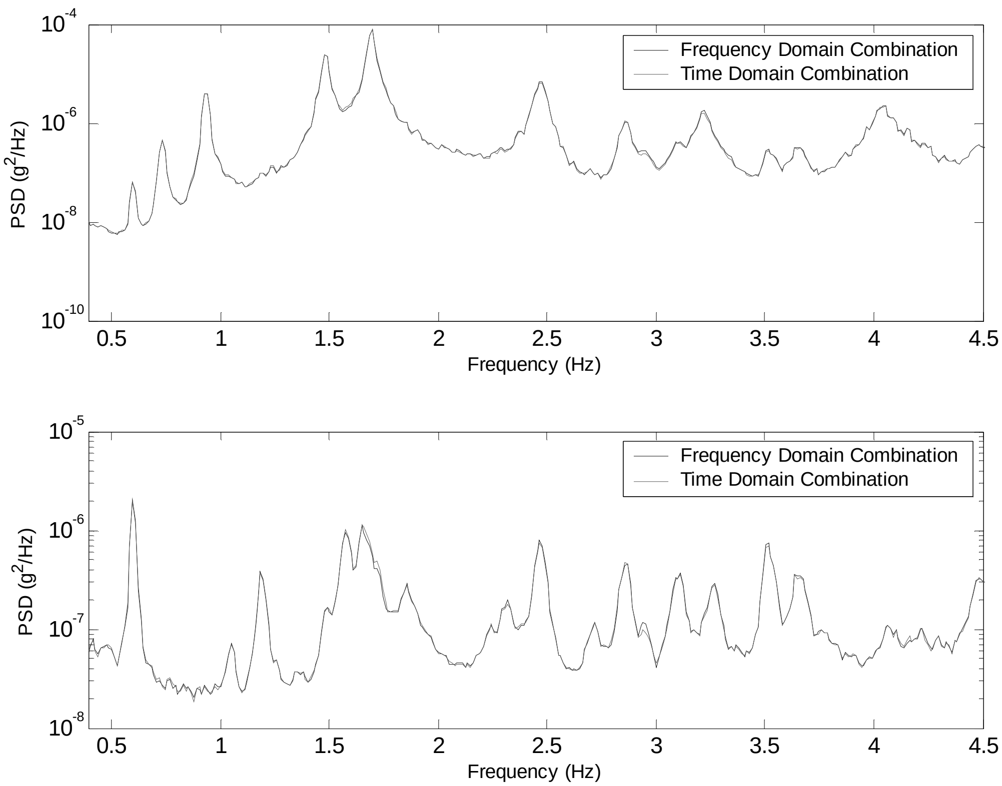

Figure 6 Resulting frequency contents of multiple measurement records combined together in the time domain and in the frequency domain

4.4. Variability analysis

Variability in the identified dynamic properties, especially that in natural frequency, has been repeatedly reported by many researchers. Farrar and Doebling (1997), based on the study of the dynamic properties determined from ambient vibration testing of a medium-span bridge, concluded that significant variability can result from changes in environmental conditions, changes in service conditions, and the data reduction method used for the measurements. Feltrin (2001) also identified the long term variations of eigenfrequencies induced by long term variations of temperatures from the one-year ambient vibration monitoring of the Romeo Bridge of the Obkirchen viaduct. He also pointed out that only low correlation was found between the daily variations of eigenfrequencies and temperatures. Halling et al. (2004) attributed the 0.9 to 4.1 percent of variations in the natural frequencies largely to testing procedures and not to temperature fluctuations in the ambient monitoring of the S-shaped steel plate girder bridge in Salt Lake City.

Considering the small temperature changes during our monitoring process, the variability of the identified frequencies was mainly evaluated as a function of the level of traffic on the bridge and as a function of the amount of data considered for the analysis, using discrete data sets collected over a period of several days and at a constant sampling rate of 200 Hz. The data was decimated to 50 Hz for this analysis, and the duration of each discrete data set was 900 seconds. The frequency resolution of the analysis was 0.012 Hz.

The level of traffic crossing the bridge was considered as a parameter for this analysis since it was generally moderate when the measurements were recorded before 15:00 hours (excluding the morning rush hour period) and was much heavier when measurements were recorded after 15:00 hours. The amount of data utilized for the modal parameter estimation was also considered as another possible source of variability since the random traffic and wind which provide the ambient excitation may not excite all of the frequencies all of the time. This is especially true if the excitation is not broad-banded as is usually assumed. Although ambient temperature was not recorded in conjunction with the ambient vibration testing, its effects are inevitably included in this analysis since the ambient temperature at the site also varied over the course of each day.

The following three cases were considered in this analysis: (1) vertical and transverse frequencies identified from a single data set recorded during periods of either moderate traffic levels (before 15:00 hours) or heavy traffic levels (after 15:00 hours) over a period of several days, (2) vertical and transverse frequencies identified from multiple data sets recorded during periods of either moderate or heavy traffic levels within a single day, and (3) vertical and transverse natural frequencies identified from the combination of all data sets (moderate and heavy traffic levels) collected during a given day. Combinations of discrete data sets are considered in the second and third cases. These data sets were combined in the frequency domain by calculating the mean PSD from the collection of data sets being considered. This method of combining the data sets was found to yield frequency results which were essentially equivalent to the frequency results obtained when discrete data sets are combined end-to-end in the time domain as shown in Figure 6 for the combination of 3 records of 900 seconds each.

The frequencies for vertical and transverse modes identified from single data sets sampled during moderate and heavy traffic, are summarized in Table 3 and Table 4, respectively. It is clear from these results that there was very little variation in the frequencies identified from single 900 seconds long data records collected before 15:00 hours or collected after 15:00 hours for different days of the week.

The percent differences between the vertical natural frequencies identified from single data records collected before and after 15:00 hours on September 24 are summarized in Table 5. The vertical frequencies identified from the combination of all data sets for September 24 and the percent difference between these values and those identified in Table 5 are summarized in Table 6. These results indicate a maximum of 1% difference between the identified frequencies for the cases considered.

Table 3 Vertical natural frequencies identified from single data sets sampled before and after 15:00 hours on different days

Date	**20-Sep**	**21-Sep**	**22-Sep**	**23-Sep**	**24-Sep**	**27-Sep**	**29-Sep**	**Mean**	**STD**
Time		**12:39**	**12:20**	**13:19**	**13:44**	**13:48**	**13:19**		
Frequencies (Hz) before 15:00		0.732	0.745	0.745	0.732	0.745	0.732	0.739	0.007
		0.940	0.940	0.940	0.940	0.940	0.940	0.940	0.000
		1.477	1.477	1.477	1.477	1.489	1.465	1.477	0.008
		1.697	1.697	1.697	1.685	1.697	1.697	1.695	0.005
		2.490	2.466	2.466	2.441	2.478	2.502	2.474	0.021
		3.235	3.271	3.235	3.271	3.247	3.235	3.249	0.018
Date	**20-Sep**	**21-Sep**	**22-Sep**	**23-Sep**	**24-Sep**	**27-Sep**	**29-Sep**	**Mean**	**STD**
Time	**17:54**	**17:03**	**17:30**	**17:26**	**15:22**	**17:30**			
Frequencies (Hz) after 15:00	0.732	0.732	0.745	0.745	0.732	0.732		0.736	0.006
	0.940	0.940	0.940	0.928	0.928	0.940		0.936	0.006
	1.489	1.477	1.477	1.465	1.477	1.477		1.477	0.008
	1.697	1.697	1.697	1.685	1.685	1.697		1.693	0.006
	2.478	2.490	2.454	2.478	2.454	2.441		2.466	0.019
	3.223	3.223	3.235	3.223	3.259	3.271		3.239	0.021

Table 4 Transverse natural frequencies identified from single data sets recorded before and after 15:00 hours on different days

Date	**20-Sep**	**21-Sep**	**22-Sep**	**23-Sep**	**24-Sep**	**27-Sep**	**29-Sep**	**Mean**	**STD**
Time		**12:39**	**12:20**	**13:19**	**13:44**	**13:48**	**13:19**		
Frequencies (Hz) before 15:00		0.598	0.610	0.610	0.598	0.610	0.598	0.604	0.007
		1.123	1.111	1.184	1.160	1.160	1.172	1.152	0.029
		1.587	1.575	1.550	1.575	1.575	1.575	1.573	0.012
		1.807	1.855	1.904	1.868	1.855	1.831	1.853	0.033
		2.344	2.295	2.319	2.307	2.307	2.307	2.313	0.017
		2.466	2.478	2.466	2.466	2.454	2.478	2.468	0.009
Date	**20-Sep**	**21-Sep**	**22-Sep**	**23-Sep**	**24-Sep**	**27-Sep**	**29-Sep**	**Mean**	**STD**
Time	**17:54**	**17:03**	**17:30**	**17:26**	**15:22**	**17:30**			
Frequencies (Hz) after 15:00	0.598	0.610	0.610	0.610	0.598	0.598		0.604	0.007
	1.196	1.135	1.135	1.172	1.160	1.160		1.160	0.023
	1.563	1.587	1.587	1.587	1.563	1.563		1.575	0.013
	1.855	1.831	1.831	1.904	1.868	1.892		1.864	0.031
	2.307	2.271	2.271	2.332	2.344	2.344		2.311	0.034
	2.466	2.466	2.466	2.478	2.478	2.454		2.468	0.009

Table 5 Comparison of vertical natural frequencies identified from single and multiple data records collected on September 24.

Single record			Multiple records			% Diff from single record	
Freq (Hz)		% Diff from	Freq (Hz)		% Diff from		
Pre 15:00 record	Post 15:00 record	Pre 15:00 record	Pre 15:00	Post 15:00	Pre 15:00 records	Pre 15:00 records	Post 15:00 records
0.732	0.732	0	0.732	0.732	0	0	0
0.940	0.928	-1	0.940	0.928	-1	0	0
1.477	1.477	0	1.477	1.477	0	0	0
1.685	1.685	0	1.685	1.685	0	0	0
2.441	2.454	0	2.441	2.466	1	0	0
3.271	3.259	0	3.235	3.247	0	1	0

Table 6 Comparison of vertical natural frequencies identified from the combination of all data records with the single and multiple data records collected on September 24.

Full-day combination of records	% Diff from single record		% Diff from multiple records	
Freq (Hz)	Pre 15:00 record	Post 15:00 record	Pre 15:00 records	Post 15:00 records
0.732	0	0	0	0
0.940	0	-1	0	-1
1.477	0	0	0	0
1.685	0	0	0	0
2.441	0	0	0	1
3.247	1	0	0	0

The percent differences between the transverse natural frequencies identified from single data records collected before and after 15:00 hours on September 24 are summarized in Table 7. The transverse frequencies identified from the combination of all data sets for September 24 and the percent difference between these values and those identified in Table 7 are summarized in Table 8. These results indicate a maximum of 2% difference between the identified frequencies for the cases considered.

Table 7 Comparison of transverse natural frequencies identified from single and multiple data records collected on September 24.

Single record			Multiple records			% Diff from single record	
Freq (Hz)		% Diff from	Freq (Hz)		% Diff from		
Pre 15:00 record	Post 15:00 record	Pre 15:00 record	Pre 15:00	Post 15:00	Pre 15:00 records	Pre 15:00 records	Post 15:00 records
0.598	0.598	0	0.598	0.598	0	0	0
1.160	1.160	0	1.160	1.160	0	0	0
1.575	1.563	-1	1.563	1.563	0	1	0
1.868	1.868	0	1.855	1.855	0	1	1
2.307	2.344	2	2.332	2.344	1	-1	0
2.466	2.478	0	2.466	2.478	0	0	0

Table 8 Comparison of transverse natural frequencies identified from the combination of all data records with the single and multiple data records collected on September 24.

Full-day combination of records	% Diff from single record		% Diff from multiple records	
Freq (Hz)	Pre 15:00 record	Post 15:00 record	Pre 15:00 records	Post 15:00 records
0.732	0	0	0	0
0.940	0	0	0	0
1.477	1	0	0	0
1.685	1	1	0	0
2.441	-2	0	-1	0
3.247	0	0	0	0

5. CONCLUSIONS

This paper examined some of the possible errors and uncertainty related to ambient vibration testing of a long-span arch bridge. There were sensing related errors such as DC bias and spurious spikes observed in some of the acceleration records; however, these errors could be removed from the records and did not contaminate the identified dynamic properties. Sensing related errors, such as the types discussed in this paper are not uncommon in field experiments and these errors can have significant influence on the data quality and the subsequent analysis and interpretation of the results. This is particularly true in the case of ambient vibration testing of a long-span bridge since the measured accelerations generally are very small and therefore have very low signal-to-noise ratios.

Some of the more common sources of uncertainty were examined and found not to have a significant effect on the analysis and interpretation of the measurements for this bridge. The hypothesis of stationarity for the vibration measurements was tested by a reverse arrangements test, and only a small subset of accelerometer channels were unable to pass this test. The accelerations recorded from the first stage of ambient vibration testing performed on this bridge could be considered to be stationary even for a relatively short testing duration of about 1 hour. Stationarity of the measurements is an important consideration for determining how long the structure must be monitored in order to reliably identify its dynamic properties. This in turn influences the design of the testing and its cost.

The variability of the frequencies identified for the arch span was analyzed to determine if the amount of traffic flow on the bridge, the time of day the testing was performed, or the amount of measurement data considered in the identification process had any significant influence on the identified frequencies. The variability due to these factors and changes in ambient temperature, which was indirectly included in this analysis, was found to be minimal for this particular structure. The apparent lack of any significant ambient temperature related effects on the variability of the identified frequencies seems to contradict the findings from ambient vibration tests of many short to medium span bridges. It could be that the natural frequencies of some long-span bridges are not as sensitive to such influences as their short to medium span counterparts because of their size or structural configuration; however, analyses of vibration measurements conducted over a longer term than was done for this bridge would be required to verify this.

Finally, the frequency bandwidth of the measurements was not found to have any significant influence on the identified frequencies, provided that the bandwidth used was more than adequate to identify the frequencies in the band of interest for the structure. This is an important consideration since the sampling rate defines the frequency bandwidth. If data is sampled at a rate far in excess of what is necessary to reliably identify the dynamic properties, the duration of the measurements needs to be large in order to obtain an adequate frequency resolution. A long measurement duration coupled with a very fast sampling rate will lead to difficulties in data processing and storage.

ACKNOWLEDGEMENTS

The writers would like to acknowledge Terry Cullen from the MTA for his assistance and cooperation during the ambient vibration testing. The writers would also like to acknowledge the leadership and contributions to this effort from Parsons Transportation Group, the project engineer for the seismic retrofit investigation.

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