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Dynamic Excitation Related Uncertainty in Ambient Vibration Testing of a Truss Bridge

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Dynamic Excitation Related Uncertainty in Ambient Vibration Testing of a Truss Bridge

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Department of Civil Engineering
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By

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ABSTRACT

The aging and deteriorating state of bridges in the US, along with the many limitations of the visual inspection data that is used for assessing and evaluating their condition, have provided motivation for research on experimental methods to quantitatively describe and evaluate their in-situ performance and condition. Ambient vibration testing is one such global characterization approach that has been widely explored due to its low cost and ease of implementation for in-service bridges. The testing is used to identify the modal properties of the structure, typically the natural frequencies, mode shapes, and damping ratios. Although ambient vibration testing has been used for many structural identification and health monitoring applications with bridges, the measurements are subject to uncertainty from a number of different sources that can limit the reliability and effectiveness for many practical objectives. One possible source of uncertainty that is particularly challenging to quantify and evaluate relates to the actual nature of the uncontrolled and unmeasured dynamic excitation of the bridge that leads to its measured vibration responses. The uncontrolled dynamic excitation in an ambient vibration test comes from natural environmental inputs and operating traffic loads, and is assumed to be spatially distributed on the structure and to have broadband, uncorrelated Gaussian white noise characteristics. Presently, variations to this assumed character have only been evaluated analytically or indirectly from the measurement results. Both of these approaches are subject to limitations that only permit qualitative assessments of the excitation related uncertainty.

This paper describes a study that was designed to experimentally evaluate the characteristics of the ambient dynamic excitation on the identified modal parameters for a full-scale truss bridge in a direct manner using controlled excitation from a spatially distributed network of dynamic exciters attached to the bridge. This novel and low-cost dynamic excitation system was developed by Dr. Grimmelsman and enabled the research team to apply controlled dynamic excitation to the bridge that was consistent with the characteristics normally assumed for ambient vibration testing and for known

variations to these characteristics. The modal parameters identified from these controlled excitation cases were compared with those identified from uncontrolled ambient dynamic excitation of the bridge. The results showed that the effective bandwidth of the uncontrolled ambient excitation was relatively narrow, and that most consistent and reliable identification could be obtained when spatially distributed, broad band white noise excitation was supplied to the bridge using the dynamic excitation system. The dynamic excitation system was also observed to lead to bridge vibrations that were substantially larger than those induced by ambient natural sources demonstrating that it could be an effective tool for characterizing and evaluating excitation related uncertainty in ambient vibration testing for other short to medium span length bridges.

INTRODUCTION

The aging and deterioration of U.S. bridges is a serious problem. In a recent review by American Society of Civil Engineers (ASCE) 12.1% of the 600,905 bridges in the U.S. were categorized as structurally deficient and another 14.8% are considered functionally obsolete (ASCE, 2009). Deterioration of bridges along with limitations of current assessment and evaluation methods have served as motivation for much research on alternative approaches for quantitatively characterizing and evaluating the performance of bridges. Ambient vibration testing is one such alternative characterization method that has received considerable interest since it is practical and relatively inexpensive to implement, especially compared to other full-scale testing methods. In ambient vibration testing, the bridge is subject to uncontrolled and unmeasured dynamic excitation from various sources, and the resulting vibration responses of the structure are measured and analyzed using output-only system identification techniques. The goal of the test is to identify the dynamic properties of the structure, namely its natural frequencies, mode shapes, and damping ratios.

The dynamic properties are directly related to the mass and stiffness characteristics of the bridge and can be considered to be system properties that characterize the in-situ state of the structure. Structural identification is one approach in which this characterization data is used for constructed systems. Structural identification is a framework that integrates analytical modeling, experimental measurements, and data analysis techniques to produce a quantitative description of the bridge. (Catbas et al. 2013) This approach limits many uncertainties that come from unknown information or idealizations of the structural behavior because it takes in account existing defects, damage, and deterioration of the structure from measurements of its in-situ behavior. Changes in the dynamic properties can be evaluated to identify damage or deterioration to the structure. The success of structural identification and many damage detection methods is largely dependent on the reliability of the characterization measurements, and uncertainty in these measurements will impact their utility for these and other applications.

The dynamic excitation in ambient vibration testing is generally provided by the natural environment and operating service loads on the structure. Although this dynamic excitation is uncontrolled and unmeasured, it is assumed to have a very specific nature for system identification purposes. The dynamic excitation must be assumed to be stationary and uncorrelated Gaussian white noise (GWN). Since GWN is a broadband input, a structure's modes of vibration that lie within its effective bandwidth can be identified from the output measurements. The dynamic excitation is also assumed to be spatially well-distributed over the entire structure, effectively making ambient vibration testing a multiple-input, multiple-output (MIMO) dynamic test.

The degree to which the assumptions related to the dynamic excitation are valid is difficult to assess from the resulting measurements. Furthermore, the uncertainty that results in the identified dynamic properties when these assumptions are only loosely valid is not clear. There are only limited examples from the literature where the effects of dynamic excitation characteristics on the identified modal parameters of bridges have been studied. Some of these evaluated the identified dynamic properties for different levels of operating traffic (Grimmelsman et al. 2007, Dorvash and Pakzad 2013). Ciloglu et al. (2012) studied this issue using a large scale laboratory model. In all of the examples found in the literature, the effects of the unmeasured dynamic excitation characteristics were never evaluated against results obtained from controlled dynamic excitation of a similar nature. This is not unreasonable given the practical limitations and high cost associated with providing controlled dynamic excitation to many locations on a structure simultaneously. However, these and similar studies only provide a limited and subjective insight to the effects of the dynamic excitation characteristics on the identified dynamic properties in ambient vibration testing. The research described in this paper attempts to accomplish this through the use of a novel dynamic excitation system.

OBJECTIVE AND SCOPE

The motivation for this study was the general lack of information related to the effects of the dynamic excitation characteristics on the dynamic properties identified for bridges by ambient vibration testing. The study presented in this paper represents a first attempt to evaluate this uncertainty by comparing the dynamic properties identified for an in-service truss bridge by unmeasured and uncontrolled ambient dynamic excitation with those identified for controlled dynamic excitation with characteristics normally assumed for such testing. Several additional excitation cases are considered in which the effective bandwidth of the input is limited and the resulting dynamic properties are compared to those from the uncontrolled and controlled excitation cases.

The multi-shaker excitation system used for this study uses tactile transducers as input devices. These devices normally are used for home entertainment, amusement parks, and gaming applications. Tactile transducers enhance the user experience by producing feedback of normally inaudible sounds through induced vibration. These devices are small and unobtrusive and can produce virtually any type of excitation signal, whether random or deterministic, needed for vibration testing of bridges. In a previous study, the dynamic force, frequency range, and operating characteristic of the devices were evaluated to assess their capabilities for dynamic testing of full-scale bridges (Fernstrom et al. 2013b, Carreiro et al. 2013). While both their performance and operating characteristics were found to be not as good as those obtained from a more conventional linear mass shaker specifically intended for dynamic testing, the multi-shaker system does have the capability to be easily deployed in large numbers on a bridge for a fraction of the cost of deploying a single unit of a more conventional shaker. The prototype system used for this study can provide 16 simultaneous and controlled dynamic inputs to a structure, and the total cost for construction of the excitation system was approximately $6,000. A more conventional linear mass dynamic shaker can cost upwards of $14,000 for a single input location. The components of the multi-shaker dynamic excitation system are shown in Figure 1.

Figure 1. Components of the multi-shaker dynamic excitation system.

EXPERIMENTAL PROGRAM

The experimental program for this study included ambient vibration testing for an in-service truss bridge. A total of four different dynamic excitation cases were implemented and evaluated. The first case consisted of unmeasured and uncontrolled ambient dynamic excitation from the natural environment. The remaining three cases consisted of spatially distributed Gaussian white noise with different characteristics produced by the multi-shaker dynamic excitation system. The dynamic excitation in these remaining cases were treated as though it was uncontrolled and unmeasured ambient excitation in order to compare the results from these cases directly with those obtained by actual ambient dynamic excitation of the structure.

Bridge Description

The bridge chosen for this research was a Parker pony truss bridge that was constructed in the 1930's and is located near Fayetteville, Arkansas. The bridge is open to traffic and has three simply-supported truss spans that are each 100 feet long. Each of the trusses has 10 panels spaced at 10 feet. The bridge carries two 10 feet wide lanes across the West Fork of the White River. The width of the bridge is 22.3 feet measured from center-to-center of the trusses. The maximum height of the trusses is 14 feet at the midspan point. The individual truss members consist of rolled and riveted built-up steel sections. The eight inch thick reinforced concrete deck is supported by I-beams that span transversely between the two trusses. A photograph of the bridge is shown in Figure 2.

One reason this particular bridge was selected for this research project was because the daily traffic usage of the bridge is very minimal. This meant that the measured vibration responses of the bridge would only be due to the natural environment or due to the multi-shaker system. The study is also benefited by the minimal traffic over the bridge because the effects of the dynamic interaction between the bridge and any vehicles could be excluded from the data analysis and interpretation. The bridge had also been dynamically tested in several earlier studies, and the modal parameters of the structure were already known with a good degree of confidence (Wank et al. 2012, Fernstrom et al. 2013a). For this particular study, only the west end span of the bridge was evaluated.

Figure 2. Photograph of the truss bridge that was tested.

Instrumentation, Data Acquisition, and Signal Generation

A total of 18 accelerometers were placed throughout the tested span of the bridge to measure its vertical vibration responses for each dynamic excitation case. The accelerometers included Model 393C and Model 393B05 accelerometers from PCB Piezotronics, Inc. The 393C models have a normal sensitivity of 1 V/g with a range of +/- of 2.5 g. The 393B05 models have a normal sensitivity of 10 V/g with a range of +/- 0.5 g. The 393C accelerometers were located on the bridge where the vibration response were expected to be greatest. Magnets were used to attach the accelerometers on the steel structure. A PXI mainframe with 4472B dynamic signal acquisition modules from National Instruments was used to record the acceleration measurements. The measurements were sampled at a rate of 1 kHz and then resampled to a slower rate during the data analysis process. The excitation signals used by the shakers were generated independently from the PXI system using a multichannel analog output USB module connected to a laptop. From the analog module, an electrical excitation signal would be sent to the shaker amplifiers where then it would travel to its corresponding tactile transducer. A total of 14 shakers were used during this study and these were located at Panel Points L2 through L8 on the upstream and downstream trusses. Figure 3 shows the locations of the accelerometers used for the vibration testing. Figure 4 shows the experimental equipment as it was installed on the bridge during the field test.

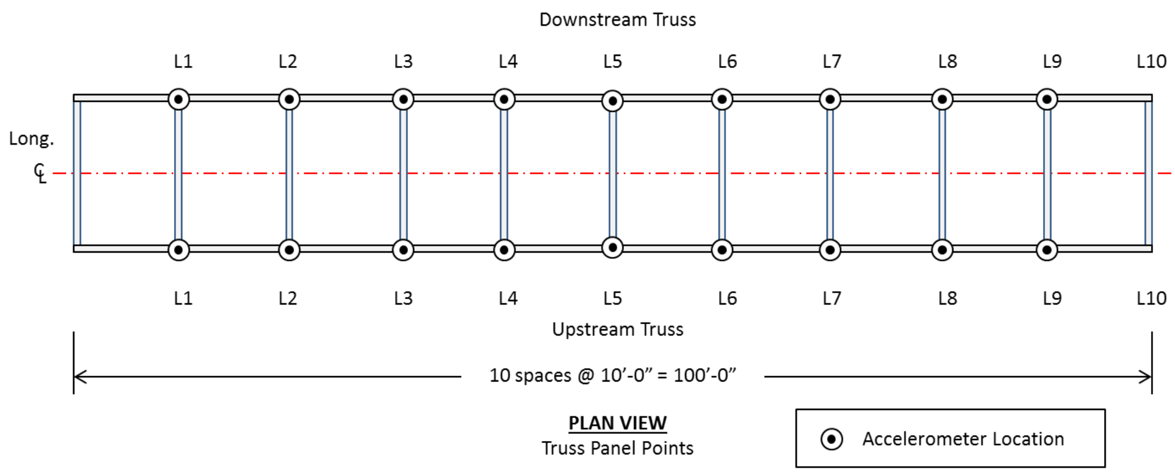

Figure 3. Schematic of the accelerometer locations on the bridge.

Figure 4. Experimental equipment installed on the bridge during vibration testing.

Dynamic Excitation Cases

The Parker Pony Truss Bridge was evaluated for four different dynamic excitation cases. A total of 28 minutes of vibration response data was recorded from each of these excitation cases. The first excitation case, “Pure Ambient”, used unmeasured and uncontrolled ambient dynamic excitation provided by the natural environment. This dynamic excitation is assumed to have stationary and uncorrelated Gaussian white noise characteristics, and to be spatially distributed across the truss span. The second case, “Full Band”, used all 14 shakers with each supplying uncorrelated Gaussian white noise that was band pass filtered to create an effective frequency band for the excitation of 3.5 Hz to 150 Hz. The frequency band of interest for the bridge’s vertical and torsion vibration modes are in the range of 4 Hz to 40 Hz. The third excitation case, “Low Band”, was the same as the second case except that the white noise excitation signals were first low pass filtered with a cutoff frequency of 50 Hz before being sent to the shakers. This produced an effective frequency band for excitation of 3.5 Hz to 50 Hz. This excitation case was designed to evaluate the uncertainty of the modes that are above this band and compare them relative to the “Pure Ambient” and “Full Band” excitation cases. The last case that was considered, “High Band”, used the same type of excitation signals as “Full Band”, but the signals were high pass filtered at 25 Hz limit of the frequency to produce an effective bandwidth of 25 Hz to 150 Hz. This case was intended to document the uncertainty of the modes that are located below this frequency band and compare them relative to the “Pure Ambient” and “Full Band” excitation cases.

DATA ANALYSIS

The measured vibration responses for each case were recorded in the time domain. An output-only data analysis approach was used to identify the natural frequencies, mode shapes, and percent damping of the structure for each excitation case. As was stated previously, 28 minutes of vibration data were recorded from each excitation case. The 28 minute measurement records were then divided into 4 minute long intervals and analyzed to evaluate the stationarity of the identification results with time. A four minute long segment of measurements is enough time to provide for approximately 1000 oscillations of the lowest vibration mode of the bridge. One accelerometer channel malfunctioned during the field test and its measurements were excluded from the subsequent data analysis stage.

In order to compare the overall level of bridge vibration that resulted from each excitation case evaluated, root-mean-squared (RMS) accelerations were computed for each accelerometer location in the time domain. These accelerometer RMS values were then added together to produce a single value that was termed the "Total RMS Acceleration" for each excitation case. The Total RMS Acceleration is a single global index value that describes the overall vibration level for the structure and includes the spatial effects of this response. The Total RMS Acceleration was computed for all seven of the four minute segments of vibration measurements recorded for each excitation case. The mean and standard deviation of the Total RMS acceleration were computed for the seven data sets evaluated in each case to evaluate how stationary the input excitation was in each excitation case. The mean values of Total RMS Accelerations obtained for each excitation case were also normalized with respect to the mean Total RMS Acceleration computed for the Pure Ambient excitation case. This permitted the bridge vibration levels induced by the shakers to be compared with the bridge vibration produced by purely natural ambient dynamic excitation sources.

The dynamic properties of the bridge were identified for each excitation case using an output-only identification approach that was implemented in MATLAB. As with the RMS analysis, the data from each excitation case were evaluated in four minute long segments. The mean and standard deviations of the natural frequencies and damping ratios identified from the seven data segments in each excitation case were used to evaluate the stationarity and uncertainty associated with these results. The basic approach used to identify the dynamic properties was a variation of the well established Frequency Domain Decomposition (FDD) technique. The implementation of this algorithm involved the following steps: (1) auto- and cross-correlation functions were computed between the measurements from each accelerometer channel to obtain estimates of the impulse response functions (IRFs), (2) the impulse response functions were transformed to frequency response functions (FRFs) by fast Fourier transform (FFT) and assembled into a FRF matrix of reference and output channels, (3) singular value decomposition (SVD) of the FRF matrix was performed at each frequency line and a plot of the largest singular values was created, (4) peaks in the singular value plot were identified as locations of possible structural vibration modes, (5) modal vectors were extracted from the left singular vectors corresponding to each identified peak, (6) the selected modal vectors were used to filter the FRF in the vicinity of each vibration mode producing an equivalent single degree of freedom (SDF) FRF, and (7) the damping ratio and undamped natural frequency were estimated from the SDF FRF using a least squares curve fit approach. The frequency resolution of the data analyzed in this stage was 0.122 Hz. The results obtained from these analyses are presented in the following section.

RESULTS AND DISCUSSION

The Total RMS Accelerations computed for each time segment, the mean Total RMS Acceleration, its standard deviation from the seven segments analyzed, and the Total RMS Acceleration normalized against the Pure Ambient result are summarized for each excitation case in Table 1. The Total RMS Acceleration results show that the multi-shaker excitation system induced a greater global vibration of the bridge than that produced by natural dynamic excitation sources. The Full Band shaker excitation case created a bridge vibration response that was nearly 15 times larger the response produced by Pure Ambient dynamic excitation. The High Band excitation case produced a response that was more than 18 times larger than the Pure Ambient case. The Low Band case produced a response that was 7 times larger than Pure Ambient case. The results largely corresponded to the operating characteristics of the shakers that were identified in an earlier study. The shakers are stroke limited at the lower frequencies and produce a much larger excitation force at higher operating frequencies (Fernstrom et al. 2013b). The standard deviation of the Total RMS Accelerations indicated that the ambient natural dynamic excitation was relatively stationary over the 28 minutes of testing; however, the responses from the multi-shaker excitation cases were even more stationary over the same amount of time. The Full Band case produced the most consistent global vibration responses of the bridge of all the shaker excitation cases. The Total RMS Acceleration results indicate that the multi-shakers excitation system excited the bridge to a higher degree and at a more consistent rate than the natural ambient excitation.

Table 1. Total RMS accelerations for each excitation case

	Total RMS Acceleration (g's)			
Time Segments	Case 1 (Pure Ambient)	Case 2 (Full Band)	Case 3 (Low Band)	Case 4 (High Band)
1	0.0045	0.0886	0.0452	0.1083
2	0.0059	0.089	0.0425	0.109
3	0.0104	0.0893	0.0433	0.1098
4	0.0095	0.0882	0.0435	0.1081
5	0.0035	0.0891	0.0431	0.1087
6	0.004	0.0893	0.0437	0.1092
7	0.0043	0.0899	0.0434	0.1094
Mean Total RMS	0.006	0.0891	0.0435	0.1089
Std. Dev.	0.0028	0.0005	0.0008	0.0006
Normalized Mean Total RMS Acceleration	1	14.8	7.2	18.1

The natural frequencies and the percent damping values identified from each excitation case are summarized in Table 2 and Table 3. A total of seven vibration modes could be identified from the complete analysis of the vibration data from all of the excitation cases. These natural frequencies of these modes ranged from 4.17 Hz to 32.36 Hz. There were some differences observed in the number of natural frequencies identified from the four minute segments of the different excitation cases, and in the identified frequency values for each mode. The standard deviations of the natural frequencies identified from each excitation case show that the Full Band case produced results that were the most consistent over the 28 minute duration of time considered.

The tables also show that Mode 2 (Torsion 1) was only identified in one of the 4 minute segments during the High Band excitation case. Also, Mode 4 (Bending 3) was not identified in any of the 4 minute segments from the High Band. These results however are consistent with the effective frequency band of the white noise used in the High Band excitation case (25 Hz to 150 Hz), which is higher than the frequencies of Modes 2 and 4. The Low Band excitation case had the highest standard deviation of all cases for Mode 7 (Torsion 4). The natural frequency for this mode (32.3 Hz) is located somewhat above the upper frequency limit of the excitation used in this case (3.5 Hz to 25 Hz). The results also showed that the actual frequency band for the ambient excitation of the bridge produced by the natural environment is probably much less than 20 Hz given the higher standard deviations associated with Mode 6 and Mode 7 identified from this case. This indicates that the assumption of a broadband input with a flat spectrum for this type of excitation was only loosely valid for this bridge.

The percent damping results showed similar trends as were observed relative to the natural frequencies for the different excitation cases; however, these results also showed more variability in general for all excitation cases. The damping values identified from the shaker excitation cases were generally larger than those identified from the Pure Ambient case. Other researchers have observed that damping results identified from vibration testing are strongly influenced by the response level of the bridge. The high degree of uncertainty in damping estimates is frequently due to low vibration amplitudes that are generally measured in typical ambient vibration testing. Damping was noticeably larger in the excitation cases that utilized the multi-shaker excitation system, and the largest coming from the Full Band excitation case. Overall, the percent damping values identified are inconclusive because of the uncertainty in the data and its relationship to the dynamic excitation characteristics. Further experiments should be conducted where the amplitude of the white noise produced by the shakers is varied in order to gain more definitive insight on the uncertainty in the damping estimates relative to the dynamic excitation characteristics.

Table 2. Natural frequencies identified from the data segments for each excitation case

Mode	Type	Statistics	Natural Frequencies (Hz) Case 1 (Pure Ambient)	Case 2 (Full Band)	Case 3 (Low Band)	Case 4 (High Band)
1	Bending 1	Mean	4.1714	4.1723	4.1711	4.1573
		Std. Dev.	0.0268	0.0148	0.0208	0.0220
2	Torsion 1	Mean	6.6154	6.7457	6.7592	6.9350[a]
		Std. Dev.	0.1999	0.0429	0.0336	--
3	Bending 2	Mean	9.5608	9.5556	9.5562	9.5418
		Std. Dev.	0.0170	0.0039	0.0057	0.0103
4	Bending 3	Mean	13.1559	13.1138	13.1185	--[b]
		Std. Dev.	0.0439	0.1032	0.1377	--
5	Torsion 2	Mean	17.2190	17.2067	17.2149	17.2182
		Std. Dev.	0.0132	0.0050	0.0070	0.0060
6	Torsion 3	Mean	23.9659	23.6632	23.6662	23.6483
		Std. Dev.	0.4874	0.0367	0.0323	0.0366
7	Torsion 4	Mean	31.5652	32.3613	32.3032	32.1918
		Std. Dev.	0.5750	0.0378	0.9895	0.1354

Notes:

a. Mode 2 was identified in only one 4 minute segment from Case 4

b. Mode 4 was not identified in any of the segments from Case 4

Table 3. Percent damping identified from the data segments of each excitation case

			Damping (%)			
			Case 1	Case 2	Case 3	Case 4
Mode	Type	Statistics	(Pure Ambient)	(Full Band)	(Low Band)	(High Band)
1	Bending 1	Mean	0.8064	0.6768	0.9367	0.8944
		Std. Dev.	0.2231	0.2076	0.2539	0.3777
2	Torsion 1	Mean	0.7461	1.0922	0.8157	0.4501[a]
		Std. Dev.	0.2692	0.4125	0.2483	--
3	Bending 2	Mean	0.4449	0.3766	0.3148	0.3837
		Std. Dev.	0.2916	0.0948	0.0860	0.2247
4	Bending 3	Mean	0.7342	1.1617	1.1077	--[b]
		Std. Dev.	0.2235	1.6056	0.6052	--
5	Torsion 2	Mean	0.2068	0.2250	0.2210	0.2219
		Std. Dev.	0.0588	0.0593	0.0261	0.0286
6	Torsion 3	Mean	0.4235	0.7512	0.7394	0.7026
		Std. Dev.	0.2068	0.0544	0.0681	0.1519
7	Torsion 4	Mean	0.1964	0.9153	2.6702	1.0323
		Std. Dev.	0.0662	0.1515	2.7234	0.1522

Notes:

a. Mode 2 was identified in only one 4 minute segment from Case 4

b. Mode 4 was not identified in any of the segments from Case 4

CONCLUSIONS AND FUTURE WORK

This paper presents the results of a study that was designed to investigate the uncertainty in the dynamic properties of a truss bridge identified by ambient vibration testing due to the actual characteristics of dynamic excitation. A novel dynamic excitation system was used to facilitate this study, and controlled Gaussian white noise dynamic excitation was provided to the structure at multiple input locations simultaneously. Furthermore, the effective bandwidth of the controlled dynamic excitation was varied to evaluate its effect on the identified properties, and to estimate the likely bandwidth of the unmeasured and uncontrolled ambient dynamic excitation. The results obtained from this study support the following conclusions and recommendations for future work:

- The global response of the bridge as characterized by the total RMS accelerations plainly show that the multi-shaker excitation system was able to induce a larger and more consistent bridge vibration response than the dynamic excitation provided by the ambient environment. This study did not include operating traffic loads as a dynamic excitation source, but this factor could be evaluated using the same approach used in this study on a bridge subject to more traffic. This would enable the effects of the forced and free vibrations due to traffic crossings, including and vehicle-structure interactions and mass loading effects, to be compared to purely ambient and controlled shaker excitation.

- The Full Band excitation case most closely represented the assumed nature for ambient dynamic excitation and produced results which showed the least variability and uncertainty of the cases evaluated. This conclusion confirms that broadband, stationary, and spatially distributed excitation normally assumed for operational modal analysis will produce the most reliable results. The identified damping values were more variable than the natural frequencies for the different excitation cases and did not show a clear relationship to the excitation characteristics as the natural frequencies did. The damping values are often considered less reliable than other dynamic testing approaches when obtained from OMA. Future testing is recommended to evaluate the effects of excitation characteristics on this parameter more conclusively.

- The unmeasured excitation of the bridge provided by the ambient environment was reasonably stationary over the time duration that was evaluated. The modal properties found from this case indicate that the upper limit of the effective frequency band for this excitation case was probably less than 24 Hz. It is assumed in ambient vibration testing that the effective frequency band of the excitation will include the modes of interest for the given structure, but the actual effective frequency band is difficult to predict for different structures and different environmental and operating traffic conditions. The test results clearly showed that reliability of the results for certain modes were influenced by the frequency band of the excitation. Further study should be done for bridges under different environmental and operating conditions to better characterize and bound the resulting uncertainty in the identified dynamic properties.

- The multi-shaker dynamic excitation system did show promise as a tool for enabling similar studies in the future for other types of short to medium span bridges. The ability to produce spatially distributed and stationary dynamic excitation with this system could also prove to be useful for quantifying and evaluating effects of other sources of uncertainty in the identification results of an ambient vibration test of bridges and other constructed systems.

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