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Evaluation of the Effects of Dynamic Excitation Characteristics on Ambient Vibration Test Results for a Multi-Girder Bridge

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EVALUATION OF THE EFFECTS OF DYNAMIC EXCITATION CHARACTERISTICS ON AMBIENT VIBRATION TEST RESULTS FOR A MULTI-GIRDER BRIDGE

An Undergraduate Honors College Thesis

In the

Department of Civil Engineering
College of Engineering
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Fayetteville, AR

By

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Abstract

The bridge population in the US is currently aging and deteriorating rapidly. More than 30% of the bridges across the country have already exceeded their expected design life. Therefore, it is important to develop more timely, reliable and quantitative alternatives to the qualitative visual inspection approach that is currently used to evaluate these structures. One experimental approach that has been researched extensively for quantitatively characterize bridges is Ambient Vibration Testing (AVT) also known as Operational Modal Analysis (OMA). In this approach, the vibration responses of a structure due to unmeasured and uncontrolled ambient dynamic excitation are measured and analyzed to identify the modal parameters of the structure. Modal parameters (which generally include the natural frequencies, mode shapes, and damping ratios) are system properties that are directly related to the mass and stiffness characteristics of a structure. Changes in the modal parameters will reflect changes in the mass and stiffness of a structure due to damage or deterioration. Although there are many advantages in obtaining a quantitative description of a structure's in-situ condition, especially for supporting more rational and reliable management decisions, there are many potential sources of uncertainty associated with AVT that can limit the utility of the characterization for such purposes. Furthermore, since the dynamic excitation used in AVT testing is unmeasured, it is difficult to quantify and evaluate these uncertainties.

This paper presents a research study that was designed to evaluate the effects of uncertainty in the unmeasured ambient dynamic excitation on the identified modal parameters of a multi-girder bridge. A novel dynamic excitation system was used in this study to provide controlled dynamic excitation to the bridge that was consistent with the

assumed nature of ambient dynamic excitation. A number of controlled variations to the assumed nature were also evaluated. The modal parameters for these excitation cases are compared to results from uncontrolled ambient vibration and those obtained from traffic crossing the bridge.

The experimental results clearly indicated that the characteristics of the dynamic excitation had a significant impact on the identified modal parameters for the bridge. The dynamic excitation of this relatively short span bridge due to natural environmental sources was the least effective for identifying the modal parameters. Traffic related excitation permitted more modes to be identified, but the results reflected some degree of interaction between the vehicles and the structure. The dynamic excitation provided by the tactile transducers that most closely matched the assumed characteristics of uncontrolled and unmeasured dynamic excitation provided the most reasonable modal parameter results of the cases evaluated. Although traffic excitation on top of the full band controlled white noise excitation yielded the most modal parameters of any case evaluated, these modal parameters exhibit more uncertainty due to the interactions between the vehicles and structure than the same parameters identified from the full band controlled excitation case without traffic crossing the structure. Considering the results obtained from each dynamic excitation case, the modal parameters identified for full band white noise excitation (with no traffic crossing the bridge) provided the most reasonable results.

Introduction

Assuring the safety, performance and health of the nation's aging and deteriorating bridges is an ongoing challenge for engineers and managers of these critical transportation structures. A report on the condition of various infrastructure systems in U.S. published in 2013 by the American Society of Civil Engineers assigned bridges a grade of C+ (ASCE, 2013). Bridges, like other civil structures, suffer deterioration and damage over time due to defects created during their fabrication and construction, direct exposure to the environment, and the physical loads applied to them on a daily basis. The effects of deterioration and damage are additive and continue to degrade the safety and performance of a structure as it ages. Currently, there are over 600,000 bridges across the country of which 11% are considered structural deficient and around 14% are considered functionally obsolete (ASCE, 2013). The Federal Highway Administration (FWHA) also notes that more than 30% of the existing bridges in the U.S. have exceeded their design life (ASCE, 2013).

Structural identification is a system identification technique that integrates various analytical, numerical, and experimental techniques to provide a description of the in-situ characteristics and performance of a bridge (Catbas et al., 2013). This description can be used as a baseline of future testing for health monitoring purposes. Structural identification relies on experimental characterizations of a structure. Such characterizations may be obtained by measuring structural responses to dynamic excitation. The use of uncontrolled dynamic excitation to experimentally characterize in-service bridges is a popular approach referred to as ambient vibration testing. This method has become very common due to its cost and logistical advantages over other global characterization methods (Carreiro et al, 2013).

There are many potential sources of errors and uncertainty that can be encountered when applying ambient vibration testing to bridges. Furthermore, identifying and quantifying them is critical for the success of the experimental characterization program and for ensuring the reliability and utility of the results. The principal sources of errors and uncertainty in ambient vibration testing have been discussed extensively in the literature (Brownjohn et al., 2011; Moon and Aktan, 2006; Zhang et al., 2013). The common sources of these errors and their resulting uncertainties can generally be grouped into one of the following categories: (1) Design, execution, and analysis of experiment; (2) Characteristics of the sensors, data acquisition hardware, signal conditioning, sensor cabling, interference, and other similar factors related to the experimental hardware; (3) Structural complexity and dynamic interactions between structural components; (4) Structure-environment interaction (humidity, wind, and temperature); (5) Dynamic interactions between the structure and traffic dynamic (damping, mass loading, etc.); and (6) The actual characteristics of the dynamic excitation.

Of the various categories of errors and uncertainties listed above, perhaps one of the most difficult to characterize and evaluate for ambient vibration testing of bridges is the uncertainty related to the dynamic excitation characteristics. This is mainly due to the fact that the ambient dynamic excitation is uncontrolled and difficult to measure. Since the actual dynamic excitation cannot be measured and characterized, it is not practical to quantify the uncertainty that results if the actual excitation characteristics differ from those normally assumed for this type of testing. This difficulty is further reflected by the limited papers in the literature related to this topic. The effects of the excitation characteristics on the dynamic properties of a bridge identified by ambient vibration testing have primary been evaluated through analytical studies, laboratory studies or by analyzing the measurements from full-scale field tests on bridges and other structures.

Most of the analytical studies available in the literature have been focused on comparing and evaluating the capabilities of different modal parameter identification techniques. For example, Peeters (2000) evaluated the capabilities of different algorithms for processing output-only dynamic measurements. Various types and levels of noise were added to simulated measurement data to represent the effects of errors and uncertainties from all of the various categories described previously. Some researchers have also attempted to characterize the effects of traffic excitation, including dynamic interactions and mass loading, on the dynamic properties of bridges identified from ambient vibration testing. De Roeck et al. (2002) conducted finite element simulations of traffic crossing a bridge to evaluate its effect on the dynamic responses of the structure. While analytical studies such as these are convenient and useful for identifying and understanding the mechanisms by which traffic excitation may influence the dynamic response of bridges in an ambient vibration test, they are unlikely to faithfully reflect the actual dynamic excitation environment for a given bridge and often incorporate incomplete knowledge and idealizations about the structure and the traffic that add uncertainty to the evaluation results.

Other researchers have attempted to evaluate the effects of the dynamic excitation characteristics on the dynamic properties identified through ambient vibration testing of physical models in the laboratory. For example, Ciloglu (2006) and Ciloglu et al. (2012)

discuss the effects of different excitation characteristics on the ambient vibration results for a steel laboratory model. The dynamic properties identified from dynamic excitation from the ambient environment in the laboratory were compared with those obtained by providing broad-band random excitation from a single shaker located at different positions on or near the structure, random tapping on the structure, and multiple-reference impact testing. Although studies such as this automatically incorporate the experimental sources of uncertainty in way that is difficult to accomplish with purely analytical studies, they still suffer the limitations of not being able to fully control and characterize the nature of the ambient dynamic excitation supplied to the structure and that the implemented dynamic excitation schemes may not adequately represent the complexities of dynamic excitation from the environment and operating service loads for a bridge.

Some researchers have also examined the effects of excitation characteristics on the ambient testing results for bridges through the analysis of results from full-scale field vibration testing. Farrar et al. (1997) evaluated the effects of different excitation characteristics on the dynamic properties identified for a bridge by comparing the ambient vibration test results obtained for different environmental conditions and for different levels of traffic with those obtained for the bridge by forced-vibration testing. Similarly, Peeters et al. (2001) compared the effects of different dynamic excitation characteristics and environmental changes on the dynamic properties identified for the Z24 Bridge. In this study, two linear mass shakers were placed in two different spans of the bridge and band-limited noise excitation was input to the structure. The identification results from that test were compared to the results obtained from uncontrolled ambient dynamic excitation and from broad-band excitation from a drop hammer. Although this study did utilize controlled noise excitation, the number and spatial distribution of the inputs was still very limited. Zhang et al. (2002) compared the root-mean-squared accelerations and modal parameters identified from ambient vibration testing of a cable-stayed bridge under different levels of traffic. Grimmelsman et al. (2007) compared the modal parameters identified by ambient vibration testing of a long-span arch bridge during periods of light and heavy traffic usage to evaluate the impact of different excitation characteristics. Dorvash and Pakzad (2013) evaluated the modal parameters identified by ambient vibration testing of a steel bridge over a one year period to investigate the effects of different environmental conditions and traffic levels. Li et al. (2010) investigated the effects of different wind speeds and temperatures on the modal parameters identified for a bridge by ambient vibration testing.

These and similar studies from the literature have helped to illustrate that the characteristics of the unmeasured and uncontrolled dynamic excitation do have an effect on the dynamic properties of bridges identified by ambient vibration testing, and further, that the effects also depend on the type of bridge being evaluated, most of these studies represent an attempt to characterize the dynamic excitation related uncertainty through the indirect approach of evaluating the measured vibrations responses of bridges for dynamic excitation conditions that are often only qualitatively characterized or by comparing them to results obtained using controlled dynamic excitation that does not fully reflect the dynamic excitation characteristics assumed for ambient vibration testing. The inability to produce controlled and spatially distributed dynamic excitation for full-scale bridge structures in a practical and cost-effective manner is most likely the reason why these studies were implemented in such a manner.

Objectives and Scope

The effects of dynamic excitation characteristics on the dynamic properties of bridges identified by ambient vibration testing have been studied by numerous researchers using analytical methods, laboratory studies, and full-scale field tests. These studies have all been limited, however, by the inability to accurately simulate and impose dynamic excitation that is consistent with the characteristics normally assumed for the excitation in ambient vibration tests. Fellow researchers from the University of Arkansas have developed a low-cost multi-shaker dynamic excitation system that allows the effects of dynamic excitation characteristics on the ambient vibration test results to be evaluated in a controlled manner. The multi-shaker system permits controlled input of dynamic excitation with known characteristics to be applied to full-scale bridges. No similar studies of the effects of excitation characteristics using a similar approach could be found in the existing literature.

The key objective of this research project was to evaluate the results of the AVT of a full-scale in service multi-girder bridge for ambient dynamic excitation, traffic input excitation, and the simulated excitation cases with the different known input characteristics from the multi-shaker system. The different cases created from the data obtained in the field were analyzed and the modal parameters were obtained and evaluated in this project. Also the Root-Mean-Squared (RMS) accelerations, which serve to characterize the level of the bridge's vibration response for a given dynamic excitation, are also evaluated for each excitation case considered in this study.

Multi-shaker Dynamic Excitation System

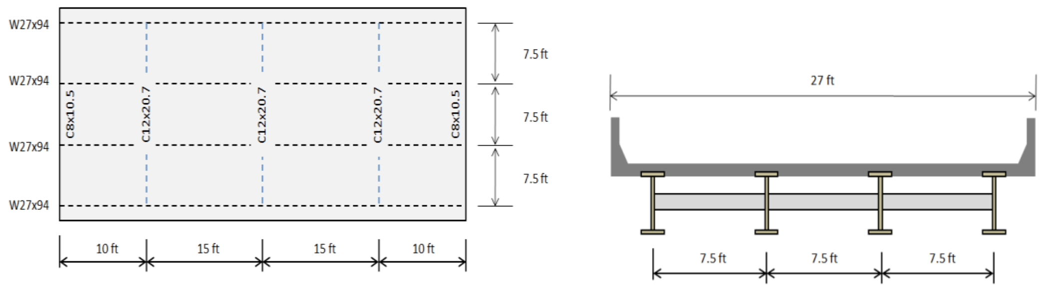
A novel multi-shaker dynamic excitation system was used to provide controlled and spatially distributed dynamic excitation to the bridge evaluated in this study. The multi-shaker dynamic excitation system was developed by Dr. Grimmelsman at the University of Arkansas and employs low-cost and very portable tactile transducers to provide the dynamic excitation. Tactile transducers or shakers are devices that are more conventionally used for home entertainment, gaming and amusement park applications. Tactile transducers provide user feedback of the normally inaudible and low frequency audio signals through induced vibrations. These devices are capable of producing random, harmonic or impulsive dynamic excitation forces depending on the type of experiment being performed. Since the tactile transducers are designed for use in dynamic testing of structures, several versions of the devices were systematically characterized in the laboratory to determine their operating and performance characteristics (Fernstrom et al., 2013). The laboratory evaluation results indicated that the tactile transducers were compatible with controlled dynamic excitation of short to medium span bridges (Carriero et al., 2013). A prototype dynamic excitation system was developed using these devices that featured 16 independently controlled excitation inputs and was ruggedized for field testing. This excitation system was the key enabling technology for the research described herein.

Experimental Program

Bridge Description

The bridge evaluated in this project is a concrete deck on steel beam bridge located in Fayetteville, AR. The bridge is named the Hancil "Tiny" Hartbarger Bridge which its construction dates from 1987 and carries two lanes of traffic over the White River. The bridge consists of 10 identical simply-supported spans each having a 50 ft span length. The superstructure consists of an 8-inch thick reinforced concrete deck that is composite with four W27x94 rolled steel beams that are spaced at 7.50 ft from center to center. The bridge deck has a width of 27 ft (24 ft curb to curb). Figure 1 shows schematics of the plan view and cross section of the superstructure.

This bridge was selected for use in this research project due to its close proximity to campus and because the superstructure can be easily instrumented from the underside without the need for special access equipment or lane closures. The bridge design is also representative of a large number of structures in the US bridge inventory. The bridge is subject to a moderate level of traffic use and, as a result, the dynamic testing results could be evaluated for purely natural dynamic excitation in addition to dynamic excitation due to operating traffic loads. This particular bridge has also been tested extensively by a number of different dynamic testing methods providing a good baseline of characterization results for comparison with this research. The specific bridge span evaluated in this project was the third span located from the west end of the crossing.



(a) (b)

Figure 1. Bridge span representation and dimensions for (a) plan view and (b) cross sectional view

Experimental Equipment

The primary experimental equipment used for the research included tactile transducers and their supporting hardware, accelerometers for measuring the bridge vibrations, and data acquisition hardware and software for recording the measurements. A video camera was also installed on the bridge to record vehicle crossings during testing. The video recordings of traffic crossing the bridge were later used to assist in isolating and separating the bridge vibration measurements that were due to natural excitation, traffic and the tactile transducers. A total of 24 uniaxial accelerometers were installed on the bridge girders to measure the vertical vibration responses of the structure. The accelerometers used were Model 393C sensors from PCB Piezotronics Inc. which have a nominal sensitivity of 1 V/g and a peak measurement range of +/- 2.5 g. The accelerometers were attached to the underside of the top flanges of the steel beams using magnets, and were distributed among six locations on each of the four beams. A total of 16 tactile transducers were also used for the testing. The tactile transducers were distributed evenly between the four beam lines and were spatially well-distributed across the span. The tactile transducers were clamped to the bottom flanges of the beams to provide dynamic excitation of the bridge in the vertical direction only. The measurement data were recorded at a sampling rate of 1.652 kHz and was resampled by a factor of four by the data acquisition software to provide an effective sampling rate of 413 Hz. This sampling rate yields an effective frequency band for the recorded vibration measurements of DC to 206.5 Hz. Figure 2 shows the positions of the accelerometers and the tactile transducers on the bridge superstructure. Figure 3 shows the equipment set up under the bridge span where the shaker and accelerometer placement can be observed

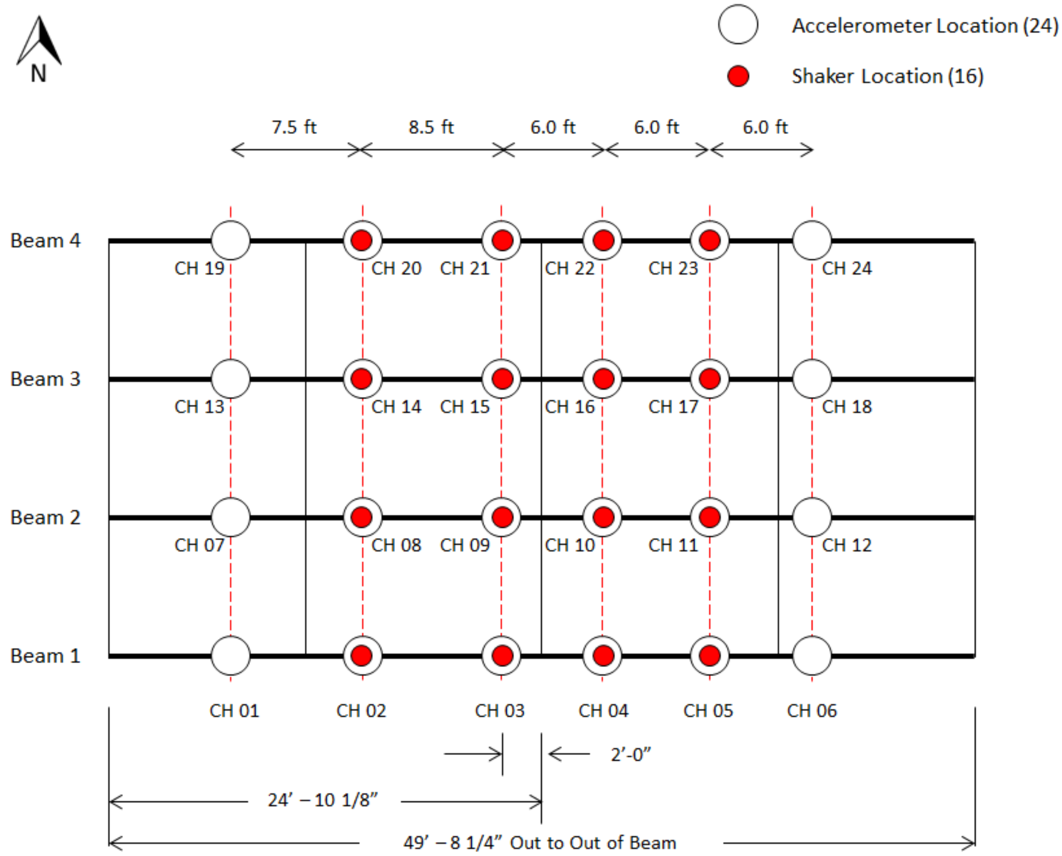


Figure 2. Accelerometer and shaker locations.

Figure 3. Equipment set up under the bridge span being analyzed.

Dynamic Excitation Cases

The bridge vibrations were measured for several hours under different dynamic excitation conditions and a total of eight distinct excitation cases were considered for the dynamic analysis. All of the dynamic excitation cases are based on the assumption that the dynamic excitation is uncorrelated Gaussian white noise. The positions of the shakers and the accelerometers were kept constant for all excitation cases. The specifics of each dynamic excitation case considered in this study are further described in the following.

Case 1 represents pure ambient (natural) dynamic excitation of the bridge; therefore, no input from the tactile transducers was used for this case. Vibrations of the bridge due to traffic excitations were also removed from the measurements for this case. The characteristics of the dynamic excitation in this were uncontrolled and are assumed to be uncorrelated, stationary, and spatially well-distributed Gaussian white noise. Case 2 represents the forced and free vibrations of the bridge due to traffic crossing the structure. These measurements were separated from the raw vibration data that contained a mix of natural and traffic excitations in MATLAB using information from the video recordings and visual inspection of the time domain measurement records. The testing program was designed to obtain an equal amount of vibration measurements due to ambient natural sources and traffic crossings. Case 3 consists of vibration measurements recorded for a mix of ambient natural excitation and traffic related excitation. This case represents the dynamic excitation that is typically used in operational modal analysis of in-service bridges, and is assumed to have broadband, white noise characteristics.

The remaining excitation cases utilized the tactile transducers to provide Gaussian white noise dynamic excitation to the bridge. The effective frequency band of this excitation was controlled for some of these cases to evaluate how the modal identification results would compare to the other excitation cases. In Cases 4, 5, and 6, broadband excitation that was filtered at 6 Hz and 80 Hz limits was provided to the bridge using the tactile transducers. These cases were deemed Full Band (FB) cases since the frequency band of the dynamic excitation covered the full range of the global vibration modes of interest for the bridge. The bridge measurements were recorded under a combination of tactile transducer input and traffic, so the same approach described previously was used to isolate and separate the bridge vibration measurements due to the tactile transducers from those due to traffic on the bridge. Case 4 represents the vibrations due to FB input from the tactile transducers only. Case 5 includes only the forced and free vibrations of the bridge due to traffic crossing events. FB input from the tactile transducers is also contained in these traffic crossing events. Case 6 represents a random mix of FB excitation from the tactile transducers and excitation from traffic crossing the bridge.

Case 7 is a bandlimited dynamic excitation case. The effective frequency band of the excitation provided by the tactile transducers was limited by digital filtering in this case between 30 Hz and 80 Hz. This case was termed a High Band (HB) case since it is limited to the frequency range for the higher global vibration modes of the bridge. Traffic crossing events were removed from these measurements using the procedure described previously, so this case consists of excitation from the tactile transducers only. Case 8 is also a bandlimited excitation case in which the input band was filtered between 6 Hz and 30 Hz. This frequency band covers only the lower global vibration modes of the structure and was termed a Low Band (LB) excitation case. As with Case 7, all traffic related vibrations were removed from the measurements before subsequent analysis of the data. Table 1 summarizes the characteristics for the 8 different dynamic cases evaluated.

Table 1. Dynamic Excitation Cases

Excitation Case	Description	High Pass Filter (Hz)	Low Pass Filter (Hz)	Record Duration (min)
1	Pure Ambient	-	-	10
2	Pure Traffic	-	-	10
3	Ambient and Traffic	-	-	10
4	FB Shakers	6	80	10
5	FB Traffic	6	80	10
6	FB Shakers and Traffic	6	80	10
7	HB Shakers	30	80	10
8	LB Shakers	6	30	10

Data Analysis

The vibration measurements recorded from the various excitation cases described previously were analyzed in time domain to evaluate the excitation characteristics and to identify the modal parameters for the bridge. The first analysis stage consisted of computing Root-Mean-Squared (RMS) acceleration amplitudes from each output sensor (channel) on the bridge span. The RMS values of each channel were then summed up to obtain a single index value or total RMS value that was later compared for the different excitation cases. The total RMS value represents the overall level of vibration response measured from the spatially distributed accelerometer locations on the bridge span and can be used as a global parameter describing the vibration responses for each excitation case. The RMS values were calculated using MATLAB. The total RMS computed for each excitation case was also normalized with respect to Case 1, the purely natural ambient excitation case, to compare and evaluate the resulting bridge response levels for the other dynamic excitation scenarios considered.

The modal parameters were determined using an SSI (Stochastic Subspace Identification) algorithm (Van Overschee and De Moor, 1996) that was implemented in MATLAB by a graduate student working with the research group. SSI is a time domain identification algorithm that is commonly used for the output only identification of modal parameters from AVT testing of bridges and other civil structures (Brincker and Andersen, 2006). The natural frequencies, damping ratios and mode shapes for the bridge were evaluated from each excitation case. Modal Assurance Criterion (MAC) values were also computed between the experimentally identified mode shapes and corresponding mode shapes extracted from the modal analysis results from finite element model of the bridge for the specific sensor locations employed for the bridge. A MAC value of 1.0 indicates that two mode vectors are identical whereas a MAC value of zero indicates that two mode vectors are completely different (Allemang, 2002).

The SSI algorithm requires significant computational time and resources to implement. In order to streamline the data analysis stage for the different excitation cases, a 10 minute time duration of measurement data from each case was analyzed by the SSI algorithm in separate 5 minute long segments. The SSI code should be executed for a minimum order of 2N where N is the number of vibration modes estimated to be located within the measurement data, but generally requires a much larger order to obtain stable results. A number of different modal orders were attempted with the SSI code, and stable results were generally obtained when the code was run using a model order range of 100 to 120. The results of each run were evaluated using a stabilization diagram that was used to identify the consistency of the modal parameter results at each of the model orders considered for the SSI algorithm. In general, the modal parameter results obtained from this range were consistent for the two five minute segments of data evaluated for a specific excitation case.

Results

The in-field dynamic testing was performed in one day including instrumentation set up, data collection for each excitation case, and demobilization of the testing equipment. The measured data were inspected closely prior to subsequent analysis to verify that all of the accelerometer channels functioned properly and to assess the quality of the measurements. All 24 channels were deemed to have recorded reliable measurements and the data were subsequently separated into distinct excitation cases.

Data files containing ten minutes of measurements from each excitation case were assembled for subsequent analysis. The individual data sets were first analyzed to determine the RMS accelerations for each channel for the entire 10 minute duration. The RMS accelerations computed for each channel were added together within a given data set to obtain a total RMS acceleration for the bridge.

The total RMS acceleration computed for each excitation case was normalized with respect to the total RMS acceleration computed for the ambient excitation due to only environmental sources (Case 1) to enable the overall vibration response level of the bridge in the other dynamic excitation cases to be compared to a single baseline value. Table 2 summarizes the RMS accelerations computed for each sensor location and the total RMS accelerations for each dynamic excitation case evaluated.

Due to computational limitations with the SSI algorithm, the data sets were processed to identify the modal parameters in two 5 minute long segments.

Table 2. RMS values obtained per channel for each case

Channel	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
1	6.9E-04	2.7E-03	2.0E-03	2.1E-03	4.1E-03	3.3E-03	2.4E-03	1.9E-03
2	6.5E-04	3.9E-03	2.7E-03	3.0E-03	5.8E-03	4.8E-03	3.4E-03	2.6E-03
3	4.9E-04	3.4E-03	2.4E-03	2.4E-03	5.1E-03	4.1E-03	2.7E-03	2.1E-03
4	4.4E-04	3.2E-03	2.2E-03	2.1E-03	4.7E-03	3.9E-03	2.2E-03	1.8E-03
5	2.2E-04	3.0E-03	2.2E-03	3.2E-03	5.3E-03	4.4E-03	4.5E-03	3.2E-03
6	8.9E-05	2.6E-03	1.8E-03	1.8E-03	4.0E-03	3.2E-03	1.8E-03	1.5E-03
7	1.1E-03	5.8E-03	4.0E-03	3.5E-03	7.7E-03	6.0E-03	3.9E-03	3.0E-03
8	4.8E-04	4.2E-03	3.0E-03	3.2E-03	6.4E-03	5.2E-03	3.1E-03	2.6E-03
9	4.7E-04	4.2E-03	3.0E-03	3.3E-03	6.5E-03	5.4E-03	3.2E-03	2.7E-03
10	3.0E-04	5.0E-03	3.5E-03	3.5E-03	7.4E-03	6.0E-03	3.5E-03	2.9E-03
11	2.8E-04	3.8E-03	2.7E-03	3.2E-03	6.0E-03	5.0E-03	3.3E-03	2.7E-03
12	2.7E-04	3.6E-03	2.5E-03	2.8E-03	5.6E-03	4.5E-03	2.9E-03	2.3E-03
13	8.1E-04	3.3E-03	2.4E-03	2.5E-03	5.0E-03	4.1E-03	2.5E-03	2.1E-03
14	7.4E-04	3.7E-03	2.6E-03	3.3E-03	5.9E-03	4.9E-03	3.3E-03	2.8E-03
15	4.9E-04	3.7E-03	2.5E-03	3.0E-03	5.7E-03	4.8E-03	2.9E-03	2.6E-03
16	4.2E-04	3.6E-03	2.5E-03	3.1E-03	5.8E-03	4.8E-03	2.9E-03	2.6E-03
17	4.8E-04	3.4E-03	2.4E-03	2.8E-03	5.4E-03	4.5E-03	2.7E-03	2.3E-03
18	2.6E-04	3.3E-03	2.3E-03	2.6E-03	5.2E-03	4.2E-03	2.8E-03	2.1E-03
19	8.4E-04	2.6E-03	1.9E-03	2.3E-03	4.0E-03	3.3E-03	2.3E-03	2.0E-03
20	7.0E-04	2.8E-03	2.0E-03	3.7E-03	5.2E-03	4.6E-03	3.9E-03	3.1E-03
21	4.6E-04	3.4E-03	2.3E-03	2.6E-03	5.2E-03	4.2E-03	3.0E-03	2.3E-03
22	4.3E-04	3.0E-03	2.1E-03	2.2E-03	4.7E-03	3.8E-03	2.3E-03	1.9E-03
23	4.0E-04	2.7E-03	1.9E-03	2.6E-03	4.5E-03	3.8E-03	3.0E-03	2.4E-03
24	2.6E-04	2.4E-03	1.7E-03	2.0E-03	3.8E-03	3.1E-03	2.0E-03	1.7E-03
Total RMS	**1.2E-02**	**8.3E-02**	**5.8E-02**	**6.7E-02**	**1.3E-01**	**1.1E-01**	**7.0E-02**	**5.7E-02**
Normalized RMS	**1.0**	**7.1**	**5.0**	**5.7**	**11.0**	**9.0**	**6.0**	**4.9**

The total RMS acceleration computed for the pure ambient vibration case (Case 1) is the lowest values for all of the excitation cases considered. This result is as expected since the short-span bridge is relatively stiff and the dynamic excitation from natural environmental sources is not expected to lead to significant vibration responses. The total RMS acceleration for Case 4, which has controlled full band white noise excitation is close to 6 times greater than for Case 1. Case 2 and Case 5 indicated relatively higher total RMS accelerations as these only contain dynamic responses to traffic occurrences which are higher in intensity than ambient vibration and the excitation provided by the tactile transducers. It is noteworthy that the total RMS acceleration for Case 4 is not significantly smaller than that for Case 2 in which the excitation was provided exclusively by vehicles. This demonstrates that the tactile transducers were capable of dynamically exciting the bridge to a level comparable to that due to traffic crossing the structure, but with known and controlled characteristics.

The natural frequencies, damping ratios, and mode shapes were then obtained from the five minute segments using the results from the SSI code from order 100 to 120. A finite element (FE) model was created for the bridge and modal analysis of this model provided analytical mode shapes for the structure that were compared to the experimentally identified mode shapes. Only vertical mode shapes from the FE model (global bending and torsion modes) were evaluated with the experimental results since the accelerometers only measured vertical vibrations. . A total of 31 analytical modes in the range from 0 Hz to 81 Hz were considered for this comparison. Modal Assurance Criterion (MAC) values were calculated by comparing all of the experimental mode shapes identified for a given excitation case to the 31 analytical mode shapes. Table 3 through Table 5 summarize the modal parameters and MAC values identified from dynamic excitation cases. The blank entries in these tables indicate that a particular mode could not be confidently identified from the measurement data.

Table 3. Modal parameters from ambient and operating load excitation cases (Cases 1- 3)

Mode	Case 1			Case 2			Case 3		
	f (Hz)	ζ (%)	MAC	f (Hz)	ζ (%)	MAC	f (Hz)	ζ (%)	MAC
M1	6.061	0.607	0.998	6.013	1.683	0.999	6.028	2.321	0.995
M2	7.219	3.094	0.934	7.052	1.011	0.984	7.052	1.047	0.985
M3	12.291	0.588	0.989	12.227	1.011	0.981	12.182	0.751	0.996
M4	29.708	0.131	0.836	21.651	1.993	0.977			
M5				22.018	0.010	0.940	21.974	0.011	0.921
M6							22.905	1.027	0.902
M7				25.416	2.059	0.990	25.225	2.170	0.987
M8				31.930	1.951	0.879	31.804	2.603	0.949
M9									
M10									
M11									
M12									
M13									
M14									
M15									

Table 4. Modal parameters from full band excitation cases (Cases 4 - 6)

Mode	Case 4			Case 5			Case 6		
	f (Hz)	ζ (%)	MAC	f (Hz)	ζ (%)	MAC	f (Hz)	ζ (%)	MAC
M1	6.064	1.860	0.993	6.054	1.580	0.998	6.011	1.651	0.997
M2	7.006	3.005	0.994	6.984	1.305	0.998	6.949	1.661	0.955
M3	12.272	0.793	0.977	12.214	0.987	0.967	12.002	8.444	0.955
M4	21.784	2.131	0.736	21.792	2.320	0.924	21.761	2.078	0.924
M5	22.188	0.006	0.935	22.157	0.010	0.957	22.178	0.009	0.920
M6				22.890	1.735	0.936	22.485	2.594	0.949
M7	25.147	2.711	0.996	25.162	1.900	0.993	24.973	2.794	0.989
M8	31.792	0.817	0.979	31.678	1.694	0.976	31.657	2.524	0.933
M9	41.027	8.201	0.833	43.072	4.381	0.661	43.359	4.657	0.589
M10	45.404	0.843	0.932	44.954	2.205	0.818	45.543	2.555	0.853
M11	63.028	0.765	0.953	63.028	1.090	0.950	62.960	1.218	0.950
M12				70.394	3.567	0.790			
M13				70.903	1.623	0.606	71.061	1.397	0.663
M14							80.879	1.712	0.730
M15				89.445	2.877	0.672	88.608	2.074	0.694

Table 5. Modal parameters from bandlimited cases (Cases 7 - 8)

Mode	Case 7			Case 8		
	f (Hz)	ζ (%)	MAC	f (Hz)	ζ (%)	MAC
M1	6.093	0.510	0.994	6.144	1.824	0.995
M2				7.061	3.048	0.992
M3				12.377	0.724	0.993
M4				21.873	2.374	0.990
M5	22.704	0.017	0.933	22.453	0.007	0.974
M6				22.834	1.416	0.982
M7				25.346	2.666	0.993
M8	33.401	1.618	0.933	32.342	2.498	0.916
M9	41.267	9.088	0.612			
M10	45.943	1.586	0.840			
M11	63.728	0.564	0.952	63.671	2.020	0.917
M12						
M13	71.925	1.144	0.676			
M14						
M15						

Theoretically, there are 31 global vertical modes for this bridge in the frequency band from 0 Hz to 81 Hz, but only 15 of these modes could be located from the experimental results obtained from all of the dynamic excitation cases considered in this study. The MAC values for some modes are really close to 1.0 which indicates very good agreement between the experimental and FE mode shapes. On the other hand, a lower MAC value indicates poor agreement between the experimental and FE mode shapes. Figure 4 shows a graphical representation of the mode shapes obtained for the bridge from the experimental analysis.

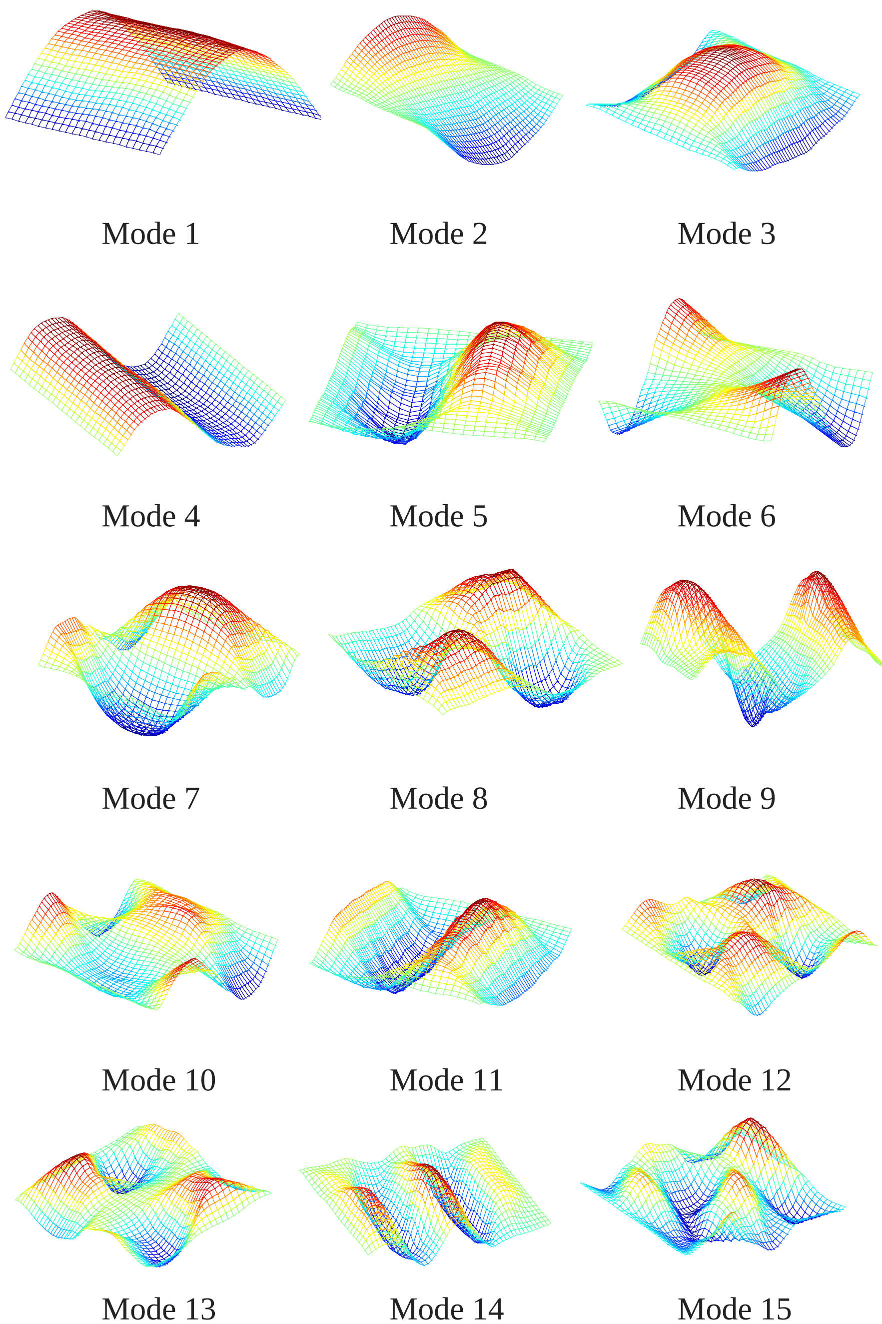


Figure 4. Mode shapes observed from data analysis

Several observations can be made from the modal parameter identification results. The unmeasured and uncontrolled dynamic excitation in Case 1 (pure ambient case) led to the identification of only the first 3 modes with confidence. A fourth mode was identified from this case, but this mode was inconsistent with the result obtained from other excitation cases and is deemed to be more uncertain. Cases 2 and 3 enabled some additional modes of the bridge to be identified; however, these modes are more inconsistent with the results obtained from other excitation cases. Since these cases represent the forced and free vibrations of the bridge due to traffic crossings, the inconsistencies observed are most likely due to dynamic interactions between the bridge and the traffic and mass loading of the structure from the vehicles. It is clear from these results that the dynamic excitation of the bridge from traffic is not consistent with a broadband white noise assumption. The results from Case 3, which was a random mix of excitation from natural sources and traffic which are very dependent on the time span of the segment of the data that was evaluated (it contained less traffic crossing events than Case 2).

For the full band excitation cases employing the tactile transducers (Case 4 – 6), more mode were identified for the bridge as compared to the cases where these devices were not used. The largest number of modes identified from any of the cases evaluated were found from Case 5 and Case 6, where traffic excitation was included with the controlled excitation from the tactile transducers. However, some of the damping ratios and mode shapes associated with these results were distorted which can be attributed to mass loading and dynamic interactions between the vehicles and the bridge. Case 8, which has a low frequency band excitation, yielded 8 modes in the frequency range of 6 Hz to 32

Hz and the results seem to be more consistent in terms of frequency, damping, and MAC values. On the other hand, Case 7, which used a high frequency band input, primarily found the modes in higher frequency range of 30 Hz to 80 Hz. The modal parameter results obtained from Cases 6 and 7 are generally consistent with the expected results for the frequency bands considered in each, and since the measurements were free of traffic excitation, the results do not indicate the same inconsistencies apparent in the results from the cases that included traffic effects.

Conclusions and Future Work

A study on the effects of different dynamics excitation cases using a novel multi-shaker system on a multi-girder bridge was performed. The modal parameters of the bridge were identified from these measurements using output-only analysis methods and compared for dynamic excitation cases that included the actual excitation due to ambient natural sources and operating loads, and for controlled dynamic excitation cases that were consistent with the character normally assumed for such unmeasured and uncontrolled dynamic excitation, and known variations to the normally assumed characteristics. The results obtained from this study support the following conclusions and recommendations for future work:

- The nature of the dynamic excitation of a structure in ambient vibration testing has a significant and observable effect on the modal parameters identified for the bridge evaluated in this study. It was clearly observed that cases with shaker and or traffic input were helpful to identify more mode shapes and frequencies than those cases that did not include traffic or shakers.

- The broadband white noise characteristics normally assumed for the uncontrolled and unmeasured dynamic excitation from natural sources and operating traffic loads for AVT do not appear to be reasonable for the bridge evaluated. The dynamic excitation provided by natural sources was extremely limited with respect to its effective frequency band, and the vibration responses of the bridge due to this excitation were generally very small. Furthermore, the results obtained from the cases that included operating traffic showed inconsistencies that were likely the result of mass loading of the bridge and dynamic interactions between the vehicles and the structure.
- The dynamic excitation due to operating traffic loads on the structure (with or without broadband excitation from the tactile transducers) enabled more of the vibration modes to be identified; however, the nature of these results indicates that the traffic excitation has an influence on them. Some of the natural frequencies, damping ratios, and mode shapes identified from these cases are inconsistent with results obtained when there was no traffic on the structure, thus these results would not be considered very reliable.
- The cases that incorporated controlled white noise excitation from the tactile transducers spatially distributed across the structure generally yielded the most consistent, reliable, and unaltered modal parameter results. Having a multi-shaker system, which allows control of input excitation and consistency of measurement of results, is clearly beneficial for reducing the level of uncertainty in the identified modal parameters.

- The amount of data evaluated in this research was limited by computational constraints associated with the SSI algorithm used to evaluate the modal parameters and by the experimental challenges associated with instrumenting and testing the bridge in a single day. Ideally, future studies of a similar nature should be performed on other types of bridges for longer periods of time to construct a more complete picture of how the dynamic excitation characteristics affect the modal parameters identified in AVT. A basic framework for conducting such studies was successively developed and implemented in this research that could be extended for other types of bridges.

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