5-2015

Development of Optimal Experimental Design Parameters for Pseudo Ambient Vibration Testing of Bridges

David Samudio Castillo
University of Arkansas, Fayetteville

This thesis is approved.

Thesis Advisor:

Kirk A. Grimmelsman, Ph.D., P.E.
Digitally signed by Kirk A. Grimmelsman, Ph.D., P.E
DN: cn=Kirk A. Grimmelsman, Ph.D., P.E., o, ou, email=kirk.grimmelsman@gmail.com, c=US
Date: 2015.04.20 22:06:43 -04'00'

Thesis Committee:

W. Micah Hale
Digitally signed by W. Micah Hale
DN: cn=W. Micah Hale, o, ou=University of Arkansas, email=micah@uark.edu, c=US
Date: 2015.04.21 09:02:13 -05'00'

Eric Fernstrom
Digitally signed by Eric Fernstrom
DN: cn=Eric Fernstrom, o, ou, email=efernstr@uark.edu, c=US
Date: 2015.04.27 11:27:06 -05'00'

Development of Optimal Experimental Design Parameters for Pseudo Ambient Vibration Testing of Bridges

An Undergraduate Honors College Thesis

in the

Department of Civil Engineering

College of Engineering

University of Arkansas

Fayetteville, AR

By

David Samudio C.

Abstract

The United States of America is facing an infrastructure crisis that is characterized by aging and deteriorating structures, a significant backlog of maintenance and upgrades for existing infrastructure, limited funding and lack of practical and effective tools for identifying and prioritizing the most pressing infrastructure needs. The American Association of Civil Engineers (ASCE) qualifies America's infrastructure with a D+(ASCE Report Card). This rating reflects the general state of infrastructure that is unlikely to improve dramatically in the short-term, yet the situation costs the nation billions of dollars annually due to losses in economic efficiency and productivity, and in some cases can needlessly expose communities to safety risks that would be considered unacceptable for other industries. There is a clear need for the development of better tools for assessing the condition of existing aged and deteriorated structures to support more timely and effective infrastructure maintenance management and planning decisions.

The focus of this research is to improve upon an existing test method that is widely used for characterizing the performance of in-service bridges and other civil infrastructure systems. The specific characterization method explored here is known as ambient vibration testing (AVT). It involves measuring a structure's vibration responses due to environmental and/or operating loads in order to quantitatively identify its dynamic characteristics and to evaluate its structural properties, performance and condition. The identified dynamic properties are mathematically related to the physical characteristics of the structure can be compared to a baseline characterization to identify and evaluate structural damage and deterioration. In AVT, the structure vibrates due to unmeasured

dynamic forces from natural sources and operating traffic, and because these inputs are unknown, their characteristics must be assumed. Researchers at the University of Arkansas are trying to improve upon ambient vibration testing by using multiple low-cost shakers to provide known and controlled dynamic forces to the structure thereby reducing the uncertainty in this approach. Establishing the optimal test design parameters for this new vibration testing approach represents a critical need for improving the cost, reliability, and testing time requirements for this novel experimental method.

Introduction

High quality bridges are necessary infrastructure for the nation's development. The American Society of Civil Engineers grades the United States' bridge infrastructure with a C+. Twenty percent of bridges are considered functionally obsolete or structurally deficient. On a regular day, around two hundred million trips are taken over bridges that are catalogued as deficient. In 2012, one in every nine bridges was classified as structurally deficient (ASCE, 2013). With time, bridges deteriorate and are not as safe as they were initially designed to be. Federal Highway Administration (FHWA) calculated that 30 percent of bridges have exceeded their 50-year design life. The average age of bridges in the U.S. is 42 years (ASCE, 2013). It is imperative to decrease the number of structurally deficient and functionally obsolete bridges in the years to come to ensure public safety.

To better test in service bridges, two approaches are being used by civil engineers: forced vibration testing and ambient vibration testing. In forced vibration testing, a known input such as a mass, shaker devices, or impact hammers are used to dynamically excite the structure. In ambient vibration testing, the input is uncontrolled and the structure is excited by environmental sources such as but not limited to: wind, microtremors, waves, and by operating service loads. These sources of dynamic excitation are assumed to be Gaussian white noise and spatially well-distributed. The two methods, force vibration testing and ambient vibration testing, measure the output to perform a Modal Analysis (Carreiro, et al., 2013). The types of modal analyses that have been used in the past could be deterministic, stochastic, or combined. The deterministic modal analysis approach corresponds to Experimental Modal Analysis (EMA), which consists of applying a measured dynamic excitation to a structure and measuring its response. The stochastic modal analysis corresponds to Operational Modal Analysis (OMA), which consists of having randomness as an input and measuring its response. The combined deterministic-stochastic modal analysis, as described by the name, consists of having a mixture of stochastic and deterministic approach (Guillaume, et. Al, 2007). Assuming linear structural dynamics, the several modal parameters can be computed from the response such as: natural frequencies, mode shapes, modal flexibility and damping ratios of the structure (Fernstrom and Grimmelsman, 2014).

Ambient vibration testing is a very popular dynamic characterization method in research and industry because it is very cost-effective. Often, it is the only method available to analyze large structures (Brincker, et al., 2003). Regardless of the multiple advantages that AVT provides for researchers and professionals, it is an output-only testing method. Characteristic of output-only testing methods, it cannot obtain mass normalized modal vectors. In addition, uncertainty is generated from the unknown and unmeasured dynamic excitation. In contrast, mass normalized modal vectors can be obtained from input-output testing methods, and uncertainty can be reduced as well (Dorvash et al., 2013). Higher degrees of uncertainty limit the reliability of any testing results, preventing engineers from making a correct assessment of civil infrastructure.

There have been prior attempts at using hybrid vibration testing approaches in order to enhance reliability and effectiveness vibration testing results. One of the most well-known examples of a hybrid vibration testing approach is Operational Modal Analysis in the presence of eXogenous Inputs (OMAX) testing (Guillaume et al., 2007). For OMAX testing, the input is a deterministic dynamic excitation plus an uncontrolled stochastic excitation from the environment. Reynders et al. (2010, 2011) implemented the OMAX approach to evaluate two footbridge structures. They compared the use of a drop hammer, an impact hammer, and a pneumatic artificial muscle (PAM) actuator for providing the deterministic part of the input. They found the hybrid vibration testing approach to be more accurate than conventional ambient vibration testing, but the deployment of the devices used for excitation resulted in single input, multiple output (SIMO) and multiple input, multiple output (MIMO) for deterministic and stochastic excitation, respectively.

For this research, the writers propose a novel hybrid dynamic that could be described as a MIMO test, it uses controlled and uncontrolled stochastic excitation sources. The novelty of the proposed approach is the means of providing the stochastic excitation of the structure: the writers use a network of low-cost, small-scale tactile transducers. The operation and performance of tactile transducers has been developed and studied in previous research by performed by Carreiro et al. (2013). Furthermore, the dynamic excitation system has been adapted for experimental modal analysis (EMA) (Carreiro et al., 2013), and has also characterized and evaluated the excitation of uncertainty in conventional ambient vibration testing (Fernstrom et al., 2014).

The proposed approach is described as a pseudo ambient vibration testing because it attempts to use provide controlled dynamic excitation similar to the characteristics of ambient vibration testing (stationary and uncorrelated Gaussian white noise). The advantage of this pseudo ambient vibration testing approach is that the dynamic excitation provided by the tactile transducers is known, but the dynamic excitation forces that are supplied to the structure remain unmeasured. The reason is to simplify the data processing and avoid additional expenses related to the deployment of transducers to measure actual input forces. This permits that the data processing be limited to output-only approaches that are commonly used in research and practice. Transitioning from conventional ambient vibration testing into the proposed pseudo ambient vibration testing approach avoids many of the logistical challenges that are usually encountered when installing devices like drop hammers, impact hammers, or large scale shakers. The excitation system developed using 16 individually controlled tactile transducers and has a cost of about $6,000 to construct.

The testing of the proposed pseudo ambient vibration testing approach was performed on a large-scale steel grid structure. Several cases vibration cases varying from conventional ambient vibration cases to different variations of controlled input were performed. An output-only analysis was performed to identify the modal parameters for all the test cases. All the results are compared to evaluate the effectiveness of the proposed pseudo ambient vibration test.

Objectives and Scope

The effects of dynamic excitation characteristics of bridges in a controlled environment are to be obtained with a low-cost multi-shaker dynamic excitation system are to be discussed in this paper. A systematical evaluation of a pseudo ambient vibration testing approach to evaluate the suitability for characterizing civil infrastructure was done. The controlled evaluation of a large scale steel grid model structure allows the researchers to determine the exact input that shakers are applying to the structure with known properties. The ten (10) different cases that were studied allowed a comparison between one pure ambient vibration test (as a baseline) and nine force vibration tests with input induced by tactile transducers. Several parameters were determined, like the number of inputs and the spatial distribution between them, the bandwidth of excitation, by looking at the modal parameters and their consistency. The research attempts to establish the design parameters for pseudo ambient vibration testing method: (1) optimal number excitation locations, (2) optimal excitation location on the structure, (3) optimal accelerometer location to measure vibratory responses, and (4) optimal duration of measurements.

Experimental Program

Experimental Equipment

To perform this investigation, the following experimental equipment was utilized: tactile transducers or shakers and their supporting hardware, accelerometers to measure dynamic input, a laptop with data acquisition software to collect the data generated by the accelerometer, and a laptop which sent the input signal to the tactile transducers. There were 15 tactile transducers used in this experiment, which provided dynamic excitation to the grid. Tactile transducers are compact, inexpensive, and capable of producing excitation forces within the frequency range (5- 200Hz) of the grid. Furthermore, his range of 5-200Hz is also compatible with the modes of short and medium span bridges. Since the tactile transducers are not commonly used for dynamic excitation of structures, the testing and evaluation is described in Fernstrom et al. and in Carreiro et al.

To measure the excitation produced by the tactile transducers, there were 21 uniaxial accelerometers installed on the bridge to measure vertical displacement of the structure at the given excitation scenario. The accelerometers used were Model 393C sensors from PCB Piezotronics Inc. with a nominal sensitivity of 1 V/g and a peak measurement range of +/-2.5 g. Then, the vibrations were recorded with National Instruments Model 9234 dynamic signal acquisition modules. Various uncorrelated Gaussian white noise excitation signals were generated in the computer and sent to each tactile transducer installed on the structure for the various test cases.

Grid Structure Description

The testing program was implemented with a large-scale, steel grid structure that was located in a laboratory at the University of Arkansas Engineering Research Center. The grid is relatively simple structure and is not subject to many of the sources of experimental and structural uncertainty routinely encountered in the field. This particular structure and its location within a controlled laboratory environment enabled the research to focus primarily on evaluating the nature of the dynamic excitation and its effects on the vibration test results. Although the grid structure is not generally subject to operating loads in the laboratory, it is subject to low level and uncontrolled ambient dynamic excitation from various sources such as the HVAC system, doors opening and closing in the building, and by people walking in and moving materials and equipment around in the hallways and laboratory rooms near the room where the grid structure was located.

The grid is a doubly symmetric, single span, and simply supported on rollers. The grid has bolted joints at all diaphragm lines. To prevent noise from within the structure, all 712 bolts are tightened. The bridge is supported by six columns. Figure 1 shows a graphical representation of the grid.

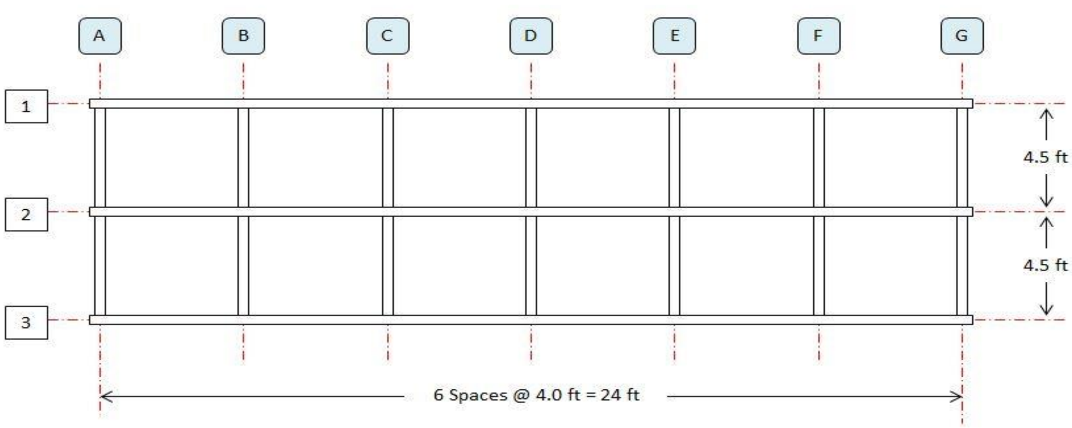

Figure 1. Framing plan of the steel grid model structure.

To perform the study, a grid model was used. To collect data from the grid, 21 accelerometers were installed at different locations throughout the grid to measure the structural vibration responses in the vertical plane. The setup of the accelerometers is as described in the following Figure 2. Accelerometers are located two feet away from each other, with the exception of rows B – C and E – F, where they are separated by a distance of four feet. No accelerometers were placed on the supports which are located at rows A and G.

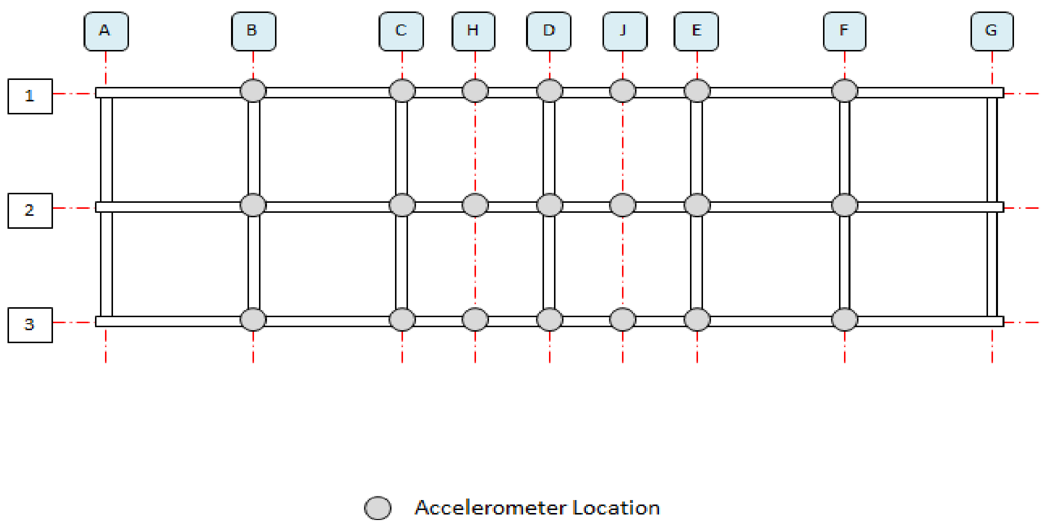

Figure 2. Accelerometer locations for the grid structure.

In addition, to compute the Modal Assurance Criterion (MAC), a theoretical model was developed. Throughout the study, 14 mode shapes were evaluated, and each one of them occurred at a particular frequency. The summary of images and frequencies is shown in Figure 2.

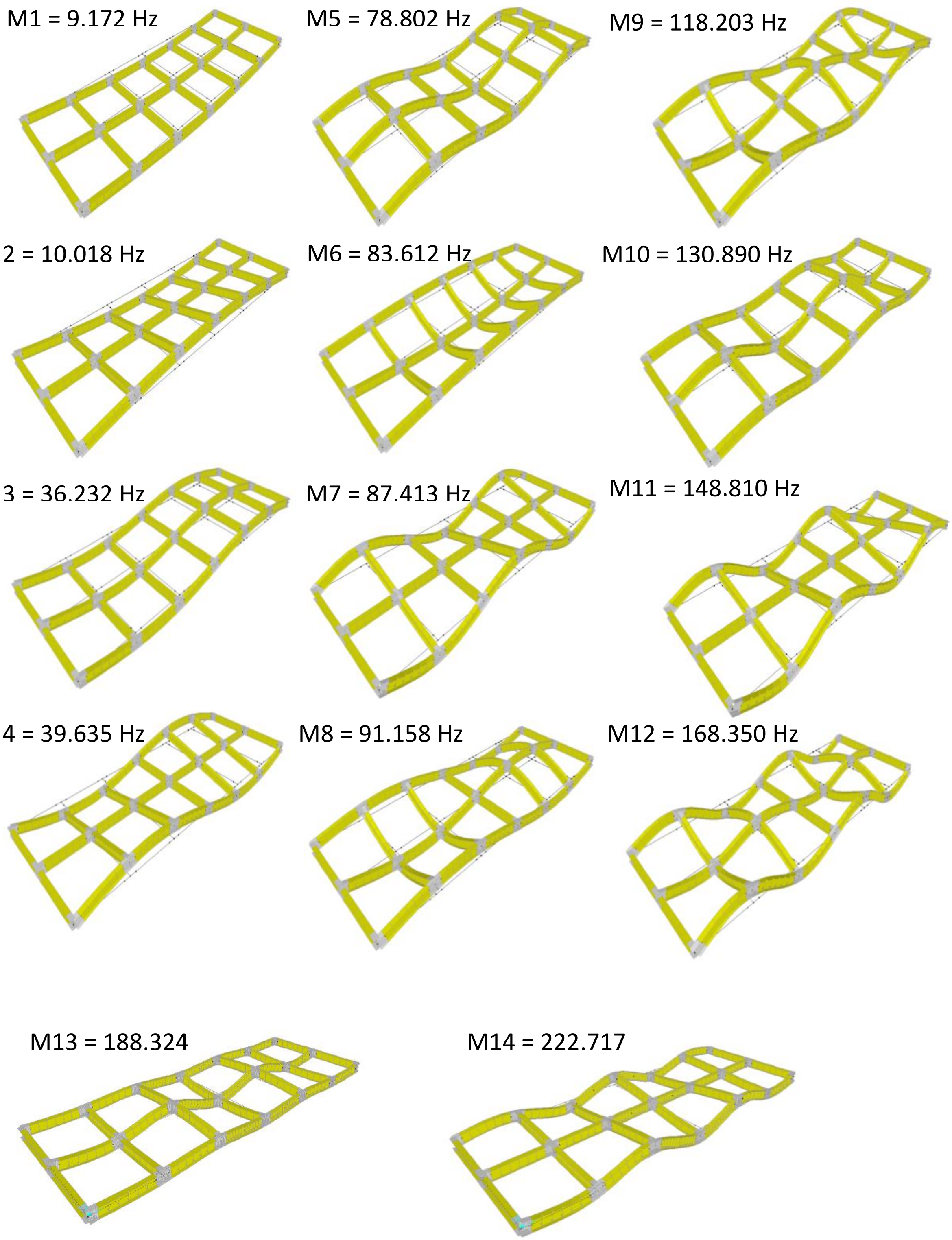

Figure 2. Mode shapes generated using SAP2000 and their respective natural frequencies.

Dynamic Excitation Cases

Ten different excitation cases were tested for further analysis with the following variables: number of shakers running, band measured, and force level input. The shakers and accelerometers remained installed throughout the entire testing period. The dynamic excitation that the structure is subject to is assumed to be uncorrelated Gaussian white noise. The dynamic excitation cases are further described below.

Case 1 represents a no-input or pure ambient dynamic excitation of the bridge, which means that the shakers remained installed but unused. Since the laboratory is not sound-proof and the accelerometers are highly sensitive, footsteps and doors opening provided input in this case. Case 2 through Case 6 correspond to the total amount of shakers installed and running throughout the testing period. The location of installation for these cases is shown in Figure 3. Since the structure's weight is a value used to determine the modal characteristics of the structure, the 15 shakers were installed and left in place during Case 1 as well, even though they were not utilized in this particular case.

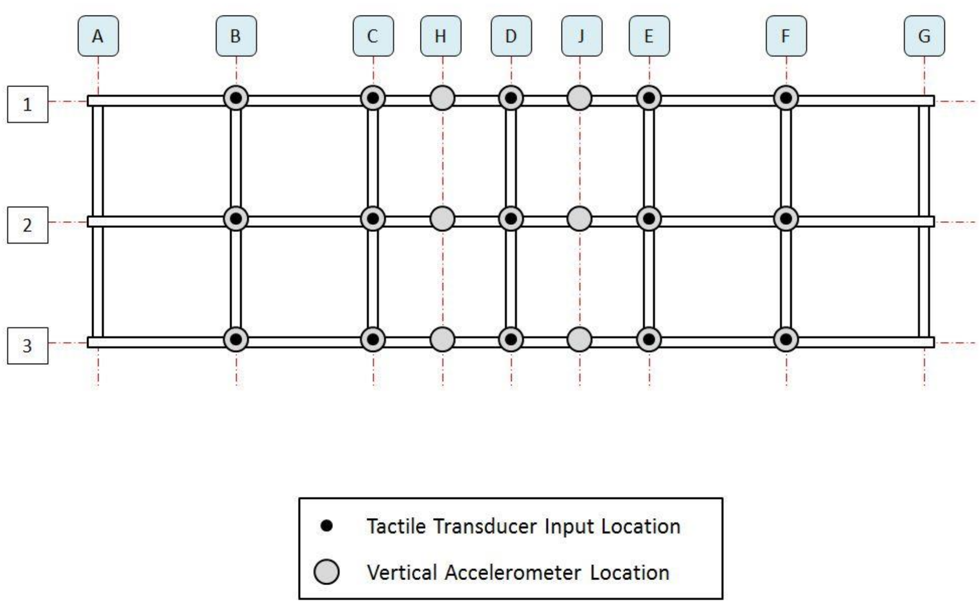

Figure 3. Location of tactile transducers in the grid structure for Case 2 through Case 6.

For Case 7 and Case 8, nine shakers were running in different locations shown below. Case 9 consisted of four shakers operating, and Case 10 consisted of three shakers operating. For the cases where less than 15 shakers were operating, the unused shakers remained installed in the structure to keep the mass of the grid consistent between different excitation cases. The locations of the tactile transducers on the grid for each excitation case are shown in Figure 4 and Figure 5.

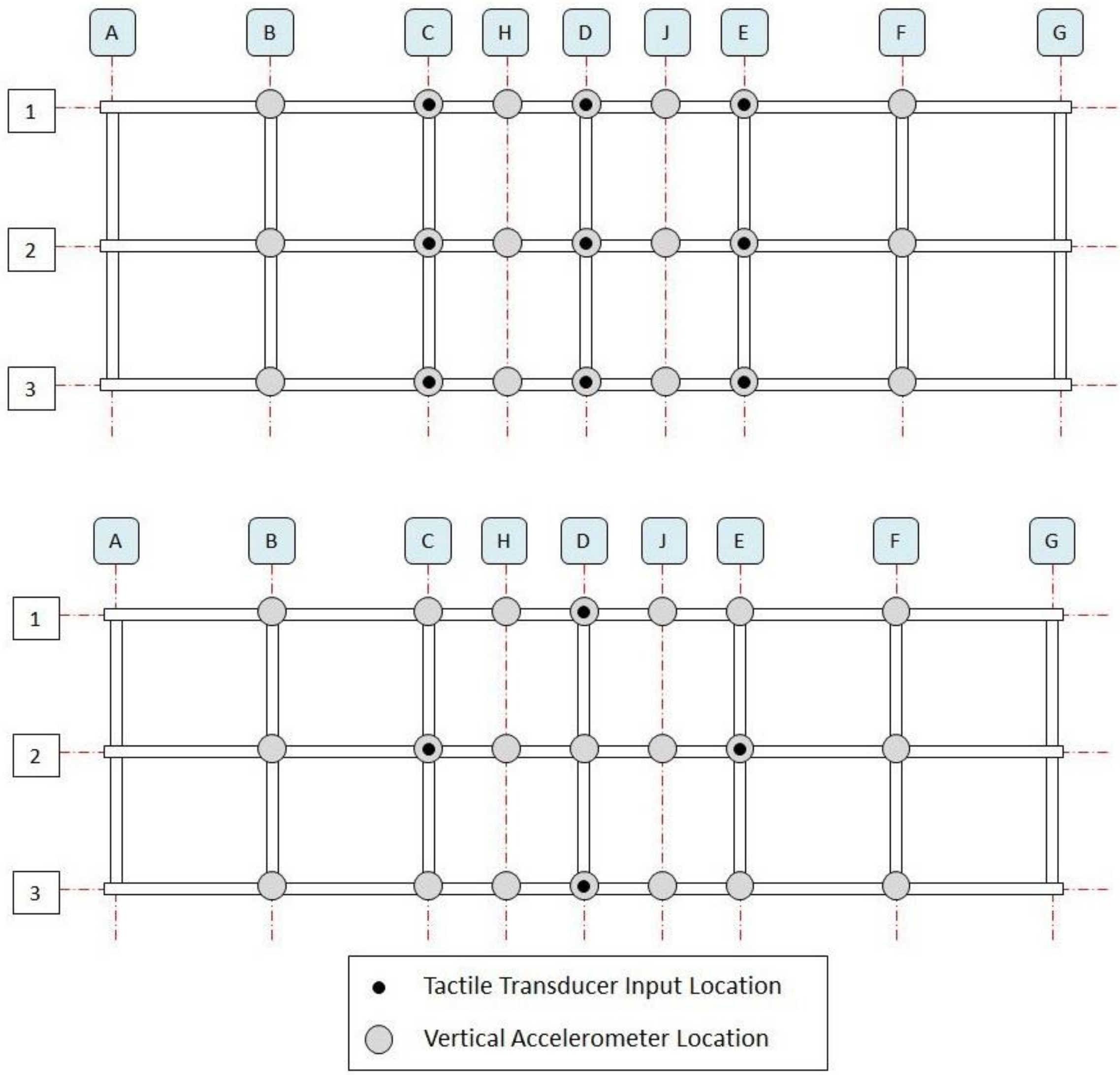

Figure 4. Active Shaker Locations for Case 7 (top), and Case 8 (bottom).

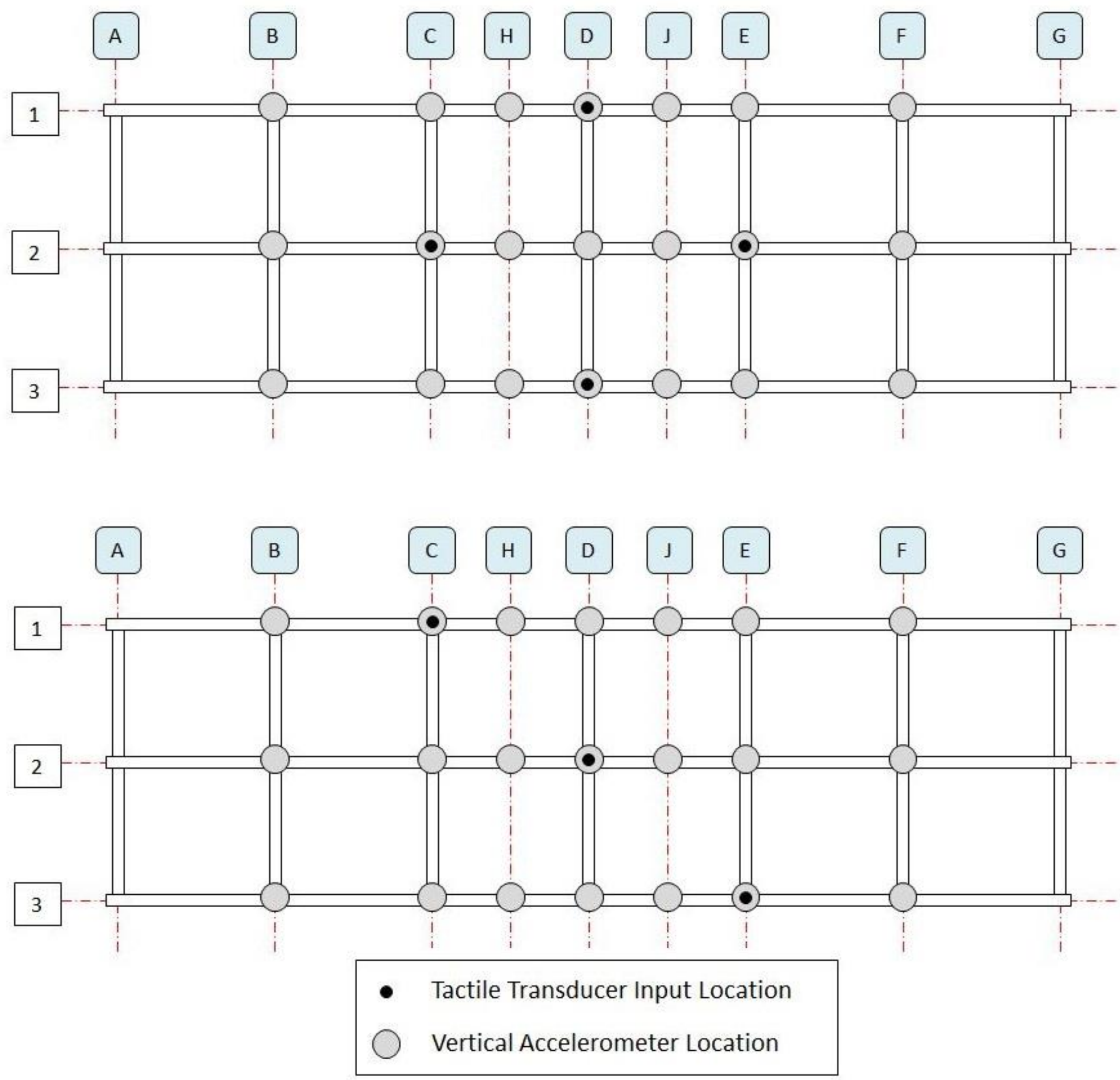

Figure 5. Active Shaker Locations for Case 9 (top), and Case 10 (bottom).

Broadband excitation varied throughout all the cases. The broadband range that covered from 5-180Hz is called Full Band (FB), since it covers the full range of modes. Case 2 through Case 10, were measured in full band (5- 180Hz), with the exception of Case 5 and Case 6. Case 5 and Case 6 were both bandlimited, which means that they did not cover the full band of 5-180Hz. Case 5 was measured using a Low Band (LB), which ranged from 5- 50Hz, and Case 6 was measured using a High Band (HB), which ranged from 50- 180Hz. Case 2 through Case 10 consist of full band bandwidth (5-180Hz), with the exception of Case 5 and Case 6, which are bandlimited. Case 5 is bounded by a Low Pass Filter (LPF) from 5-50Hz and Case 6 is bounded by a High Pass Filter (HPF) from 50-180Hz. In addition, the force level input varied throughout the cases, but was predominantly low force level. Case 1 through Case 10 had a low force level input, with the exception of Case 3, which had a high force level input. Furthermore, the excitation in Case 4 had a regenerated signal. Table 1 summarizes the cases described. A summary of the ten dynamic excitation cases evaluated is presented in Table 1.

Table 1. Dynamic Excitation Cases Evaluated

Case	Description	HPF (Hz)	LPF (Hz)	Duration (min)
1	Pure Ambient	-	-	60
2	15 Shakers (Low Force)	5	180	60
3	15 Shakers (High Force)	5	180	60
4	15 Shakers (Low Force)*	5	180	60
5	15 Shakers (Low Force)	5	50	60
6	15 Shakers (Low Force)	50	180	60
7	9 Shakers (Low Force)	5	180	60
8	9 Shakers (Low Force)	5	180	60
9	4 Shakers (Low Force)	5	180	60
10	3 Shakers (Low Force)	5	180	60

* = regenerated signal.

Data Analysis

The measurements obtained from the different excitation cases were analyzed in the time domain to identify modal parameters of the grid. The Root-Mean-Squared (RMS) acceleration amplitudes and its statistics were computed from each accelerometer. Each channel provided a different result. To obtain a total RMS value, all the individual RMS values were added up, which represents the total level of vibration obtained from the spatially distributed accelerometers. In addition, the mean, standard deviation, and 95 percent confidence interval were computed for the total and segments RMS. To obtain the

RMS values, MATLAB was used. All the values were normalized with respect to Case 1, which is pure ambient, to evaluate the bridge with reference to the dynamic excitation cases that were studied.

Stochastic Subspace Identification (SSI) algorithm (Van Overschee and De Moor, 1996) was utilized to find the modal parameters. This algorithm was developed by a graduate student and it was implemented in MATLAB. The results of this algorithm were the natural frequencies, damping ratios, and mode shapes for the grid. The results were computed for each dynamic excitation case. Furthermore, a comparison between the theoretical natural frequencies and the experimental natural frequencies was done, which as a result gives the Modal Assurance Criterion (MAC) values. A MAC Value of 1.0 indicates an identical resemblance, whereas a MAC value of zero, indicates no resemblance at all (Allemang, 2002).

Results

The measurements obtained from the different excitation cases were analyzed in the time domain to characterize the nature of the stochastic excitations. The Root-Mean-Squared (RMS) acceleration amplitude and its statistics were computed from each accelerometer. The total RMS acceleration amplitude is a simple global index used to evaluate and compare the unmeasured ambient dynamic excitation for each test case from the measured vibration responses (Grimmelsman et al., 2014). Each channel provided a different result. To obtain a total RMS value, all the individual RMS values were summed together, which represents the total level of vibration obtained from the spatially distributed accelerometers. These computations were implemented in MATLAB. In addition, the mean, standard deviation, and 95 percent confidence interval were computed for the total RMS values obtained for 15 segments of 4 minutes each and compared with the results obtained for the full 60 minute long data set.. All of the total RMSvalues were normalized with respect to Case 1, which is the pure ambient excitation case, in order to compare the pseudo ambient vibration cases with the pure ambient vibration case. The total RMS results for the 10 cases are summarized in Table 2.

Stochastic Subspace Identification (SSI) algorithm (Van Overschee and De Moor, 1996) was utilized to find the dynamic properties for the grid structure from the vibration measurements collected in each test case. This algorithm was also implemented in MATLAB by a graduate student working with Dr. Grimmelsman's research group.. The analysis provided the natural frequencies, damping ratios, and mode shapes for the grid structure. The results were computed for each dynamic excitation case and summarized in Table 3, Table 4, and Table 5, respectively.. Furthermore, a comparison between the analytical mode shapes the experimental natural frequencies was performed, which provides Modal Assurance Criterion (MAC) values. A MAC Value of 1.0 indicates an identical resemblance between the two modal vectors being compared, whereas a MAC value of zero indicates no resemblance at all (Allemang, 2002).

Table 2. Root-Mean Squared acceleration amplitudes (g's) for each case.

Segment	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
1	0.001	1.124	2.415	1.092	0.761	0.634	0.899	0.822	0.601	0.575
2	0.001	1.129	2.410	1.086	0.761	0.630	0.897	0.814	0.613	0.598
3	0.001	1.135	2.393	1.086	0.770	0.629	0.913	0.819	0.612	0.583
4	0.001	1.123	2.426	1.086	0.760	0.631	0.910	0.818	0.610	0.578
5	0.001	1.135	2.396	1.087	0.753	0.628	0.903	0.822	0.607	0.589
6	0.001	1.130	2.395	1.093	0.759	0.627	0.897	0.819	0.609	0.589
7	0.001	1.131	2.414	1.089	0.762	0.626	0.896	0.826	0.615	0.579
8	0.001	1.110	2.102	1.088	0.772	0.625	0.898	0.821	0.616	0.574
9	0.001	1.115	2.242	1.086	0.762	0.626	0.901	0.814	0.608	0.598
10	0.001	1.132	2.418	1.083	0.760	0.619	0.906	0.821	0.608	0.588
11	0.001	1.123	2.090	1.082	0.765	0.624	0.895	0.818	0.607	0.582
12	0.001	1.131	2.340	1.083	0.746	0.620	0.904	0.830	0.610	0.601
13	0.002	1.116	2.276	1.089	0.765	0.623	0.895	0.822	0.610	0.586
14	0.001	1.111	1.971	1.088	0.770	0.620	0.892	0.814	0.613	0.577
15	0.001	1.116	2.391	1.081	0.756	0.621	0.905	0.816	0.612	0.575
Total RMS (60 mins)	**0.001**	**1.124**	**2.316**	**1.087**	**0.762**	**0.626**	**0.901**	**0.820**	**0.610**	**0.585**
Mean (segments)	**0.001**	**1.124**	**2.312**	**1.087**	**0.761**	**0.626**	**0.901**	**0.820**	**0.610**	**0.585**
Std. Deviation (segments)	**0.0004**	**0.0087**	**0.1459**	**0.0035**	**0.0066**	**0.0043**	**0.0060**	**0.0044**	**0.0037**	**0.0089**
95% C.I.	**0.0002**	**0.0048**	**0.0808**	**0.0019**	**0.0036**	**0.0024**	**0.0033**	**0.0025**	**0.0021**	**0.0049**
Normalized Mean Total RMS	**1**	**1115**	**2293**	**1078**	**755**	**621**	**893**	**813**	**605**	**580**

Table 3 (a). Natural frequency results (Hz) for cases 1 through 4.

	Case 1			Case 2			Case 3			Case 4		
Mode	n	Avg. Freq.	Std. Dev.	n	Avg. Freq.	Std. Dev.	n	Avg. Freq.	Std. Dev.	n	Avg. Freq.	Std. Dev.
1	15	8.891	0.021	15	8.712	0.018	14	8.635	0.063	15	8.780	0.017
2	15	10.134	0.013	15	10.066	0.037	15	10.072	0.052	15	10.050	0.006
3	15	33.523	0.949	15	32.780	0.017	15	32.747	0.023	15	32.717	0.005
4	15	36.433	0.542	15	36.988	0.020	15	36.838	0.044	15	37.010	0.013
5	15	67.640	0.115	15	67.869	0.036	15	67.542	0.093	15	68.090	1.204
6	10	73.047	0.642	15	73.698	0.039	15	73.869	0.114	15	73.571	0.015
7	15	76.923	0.188	15	78.162	0.031	15	78.000	0.109	15	78.190	0.027
8	5	80.527	0.688	15	82.191	0.036	15	82.148	0.066	15	81.971	0.013
9	3	106.862	0.390	15	106.358	0.207	15	105.720	0.628	12	107.031	0.353
10	14	110.242	0.523	15	110.365	0.225	15	110.166	0.229	15	110.258	0.055
11	13	117.204	0.329	15	130.949	0.356	15	131.351	0.631	15	131.309	0.052
12	2	151.587	0.602	15	155.397	0.162	15	155.368	0.342	15	155.590	0.153

Table 3 (b). Natural frequency results (Hz) for cases 5 through 8

	Case 5			Case 6			Case 7			Case 8		
Mode	n	Avg. Freq.	Std. Dev.	n	Avg. Freq.	Std. Dev.	n	Avg. Freq.	Std. Dev.	n	Avg. Freq.	Std. Dev.
1	15	8.655	0.012	0	NA	NA	15	8.785	0.010	15	8.685	0.006
2	15	10.035	0.014	0	NA	NA	15	10.088	0.015	15	9.950	0.012
3	15	32.778	0.018	15	32.614	0.023	15	32.673	0.012	15	33.078	0.016
4	15	36.930	0.022	15	36.745	0.032	15	36.819	0.019	15	37.394	0.013
5	15	67.768	0.035	15	67.798	0.041	15	67.491	0.031	15	68.146	0.037
6	15	73.529	0.030	15	73.054	0.032	15	73.605	0.027	15	74.460	0.055
7	15	78.007	0.045	15	77.956	0.024	15	77.482	0.018	15	78.181	0.032
8	15	81.971	0.039	15	81.347	0.071	15	81.381	0.030	15	82.787	0.034
9	15	106.491	0.227	15	105.500	0.142	9	103.273	0.330	15	106.155	0.197
10	15	109.982	0.134	15	109.890	0.062	15	110.151	0.076	15	109.975	0.044
11	14	130.730	0.193	11	131.269	0.100	12	130.502	0.102	15	130.189	0.109
12	15	155.094	0.102	15	154.840	0.095	15	154.770	0.207	15	153.031	0.211

Table 3 (c). Natural frequency results (Hz) for cases 9 and 10

	Case 9			Case 10		
Mode	n	Avg Freq	Std. Dev.	n	Avg Freq	Std. Dev.
1	15	8.801	0.009	15	8.839	0.009
2	15	10.081	0.011	14	10.100	0.007
3	15	32.612	0.013	15	32.627	0.011
4	15	36.621	0.012	15	36.794	0.015
5	15	67.463	0.031	15	67.481	0.039
6	15	73.276	0.024	15	72.955	0.022
7	15	77.529	0.019	10	77.335	0.036
8	15	81.103	0.041	15	80.899	0.030
9	1	107.180	NA	5	106.635	0.105
10	15	110.121	0.055	15	109.774	0.032
11	14	131.808	0.588	15	130.220	0.092
12	0	NA	NA	14	154.274	0.610

Table 4 (a). Damping ratios identified for Cases 1 through 4

Mode	Case 1			Case 2			Case 3			Case 4		
	n	Avg. Damp.	Std. Dev.	n	Avg. Damp.	Std. Dev.	n	Avg. Damp.	Std. Dev.	n	Avg. Damp.	Std. Dev.
1	15	0.010	0.002	15	0.018	0.002	14	0.036	0.009	15	0.017	0.001
2	15	0.007	0.001	15	0.023	0.003	15	0.032	0.004	15	0.019	0.000
3	15	0.010	0.005	15	0.012	0.001	15	0.011	0.001	15	0.010	0.000
4	15	0.009	0.003	15	0.010	0.000	15	0.010	0.001	15	0.009	0.000
5	15	0.011	0.003	15	0.017	0.001	15	0.027	0.003	15	0.016	0.002
6	11	0.014	0.006	15	0.010	0.000	15	0.009	0.000	15	0.011	0.000
7	15	0.008	0.002	15	0.010	0.000	15	0.011	0.001	15	0.010	0.000
8	5	0.017	0.006	15	0.012	0.000	15	0.009	0.000	15	0.015	0.000
9	3	0.022	0.012	15	0.039	0.001	15	0.045	0.004	12	0.038	0.006
10	7	0.014	0.002	15	0.020	0.002	15	0.023	0.002	15	0.016	0.001
11	13	0.005	0.006	15	0.019	0.006	15	0.034	0.007	15	0.018	0.001
12	2	0.016	0.002	15	0.019	0.001	15	0.014	0.001	15	0.016	0.002

Table 4(b). Damping rations identified for Cases 5 through 8

Mode	Case 5			Case 6			Case 7			Case 8		
	n	Avg. Damp.	Std. Dev.	n	Avg. Damp.	Std. Dev.	N	Avg. Damp.	Std. Dev.	n	Avg. Damp.	Std. Dev.
1	15	0.019	0.003	0	NA	NA	15	0.016	0.002	15	0.016	0.001
2	15	0.022	0.002	0	NA	NA	15	0.018	0.001	15	0.017	0.001
3	15	0.010	0.001	15	0.020	0.002	15	0.009	0.000	15	0.008	0.000
4	15	0.009	0.000	15	0.016	0.001	15	0.008	0.000	15	0.007	0.000
5	15	0.017	0.001	15	0.019	0.001	15	0.013	0.000	15	0.013	0.001
6	15	0.009	0.000	15	0.013	0.000	15	0.009	0.000	15	0.014	0.001
7	15	0.010	0.001	15	0.014	0.001	15	0.009	0.000	15	0.009	0.001
8	15	0.015	0.000	15	0.020	0.001	15	0.014	0.000	15	0.012	0.000
9	15	0.036	0.002	15	0.040	0.001	9	0.039	0.001	15	0.031	0.001
10	15	0.019	0.002	15	0.018	0.001	15	0.014	0.001	15	0.014	0.000
11	14	0.026	0.005	11	0.024	0.001	12	0.019	0.001	15	0.020	0.001
12	15	0.021	0.002	15	0.022	0.001	15	0.017	0.001	15	0.024	0.001

Table 4(b). Damping rations identified for Cases

Mode	Case 9			Case 10		
	n	Avg. Damp.	Std. Dev.	n	Avg. Damp.	Std. Dev.
1	15	0.013	0.001	15	0.011	0.001
2	15	0.011	0.001	14	0.010	0.001
3	15	0.008	0.000	15	0.007	0.000
4	15	0.006	0.001	15	0.007	0.000
5	15	0.013	0.001	15	0.013	0.001
6	15	0.009	0.001	15	0.007	0.000
7	15	0.009	0.000	11	0.010	0.001
8	15	0.013	0.000	15	0.012	0.001
9	1	0.024	NA	5	0.019	0.002
10	15	0.012	0.000	15	0.013	0.001
11	14	0.027	0.002	15	0.020	0.001
12	0	NA	NA	14	0.019	0.002

Table 5 (a). MAC values for Cases 1 through 4

	Case 1			Case 2			Case 3			Case 4		
Mode	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.
1	15	0.992	0.012	13	0.993	0.007	14	0.999	0.001	15	0.981	0.006
2	15	0.991	0.002	15	0.994	0.003	15	0.996	0.009	15	0.997	0.001
3	15	0.991	0.004	15	0.994	0.002	15	0.992	0.003	15	0.992	0.000
4	15	0.991	0.011	15	0.992	0.001	15	0.993	0.002	15	0.994	0.000
5	15	0.988	0.007	15	0.992	0.002	15	0.987	0.006	15	0.983	0.011
6	3	0.974	0.005	15	0.991	0.002	15	0.992	0.001	15	0.993	0.002
7	15	0.992	0.003	15	0.994	0.001	15	0.994	0.000	15	0.994	0.000
8	3	0.950	0.039	15	0.991	0.003	15	0.991	0.002	15	0.985	0.006
9	3	0.921	0.022	15	0.970	0.016	15	0.958	0.015	8	0.978	0.002
10	4	0.941	0.011	15	0.951	0.014	13	0.957	0.027	15	0.975	0.003
11	11	0.873	0.076	15	0.968	0.015	15	0.980	0.013	15	0.964	0.004
12	2	0.960	0.002	13	0.988	0.008	15	0.989	0.008	15	0.976	0.005

Table 5(b).MAC values for Cases 5 through 8

	Case 5			Case 6			Case 7			Case 8		
Mode	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.
1	15	0.986	0.018	0	NA	NA	13	0.954	0.043	8	0.915	0.027
2	15	0.994	0.001	0	NA	NA	15	0.985	0.014	15	0.969	0.020
3	15	0.993	0.001	15	0.980	0.005	15	0.994	0.001	15	0.997	0.002
4	15	0.993	0.001	15	0.984	0.001	15	0.994	0.000	15	0.996	0.001
5	15	0.992	0.001	15	0.993	0.001	15	0.988	0.005	15	0.965	0.014
6	15	0.994	0.001	15	0.990	0.005	15	0.996	0.002	15	0.970	0.006
7	15	0.993	0.001	15	0.994	0.001	15	0.991	0.002	15	0.984	0.002
8	15	0.992	0.002	15	0.982	0.006	14	0.953	0.029	15	0.988	0.001
9	15	0.931	0.016	15	0.972	0.008	9	0.971	0.011	11	0.915	0.011
10	10	0.965	0.007	15	0.972	0.006	15	0.979	0.009	15	0.980	0.003
11	14	0.802	0.066	11	0.833	0.052	12	0.924	0.003	15	0.927	0.007
12	14	0.952	0.032	15	0.967	0.005	15	0.978	0.006	15	0.958	0.025

Table 5 (c). MAC values for Cases 9 and 10

	Case 9			Case 10		
Mode	n	Avg. MAC	Std. Dev.	n	Avg. MAC	Std. Dev.
1	15	0.990	0.004	10	0.956	0.025
2	15	0.993	0.009	12	0.985	0.014
3	15	0.991	0.002	15	0.994	0.001
4	15	0.973	0.010	15	0.994	0.000
5	6	0.918	0.016	15	0.959	0.022
6	15	0.996	0.001	15	0.997	0.000
7	15	0.988	0.002	3	0.987	0.001
8	15	0.982	0.008	15	0.977	0.010
9	1	0.973	NA	4	0.952	0.016
10	15	0.981	0.002	15	0.967	0.022
11	14	0.896	0.017	15	0.915	0.008
12	0	NA	NA	14	0.964	0.009

Discussion

The RMS acceleration amplitudes summarized in Table 2 show a larger vibration response produced by the pseudo ambient vibration testing, as compared to the uncontrolled ambient excitation. By normalizing all the RMS values with respect to Case 1, it can be observed how many times larger the response is than the pure ambient excitation case from the different pseudo ambient vibration cases. For example, Case 2 (15 shakers, full band, low force) had a vibration response 1115 times larger than the conventional ambient excitation. Furthermore, Case 3 (15 shaker, full band, high force level) produced the highest vibration response, which was 2293 times larger than the baseline characterization. Similar to Case 2, Case 4 (full band, low force, regenerated signal) had a vibration response 1078 times larger than the conventional approach. Case 4 repeated stochastic excitation signal 15 times over a 60 minute period, and the values are slightly lower than Case 2, which did not regenerate its signal. Case 5 (15 shaker, low band, low force) and Case 6 (15 shaker, high band, low force) had vibration responses 755 and 621 times larger than the conventional ambient vibration testing, respectively. Case 7 (9 shakers, full band, low force) and Case 8 (9 shakers, full band, low force) produced a vibration response 893 and 813 times larger than the baseline characterization. Case 9 (4 shakers, full band, low force) and Case 10 (3 shakers, full band, low force), produced a response of 605 and 580, respectively. Across all cases, it is evident that the pseudo ambient approach generates larger vibration responses than those generated by the conventional uncontrolled ambient vibration testing.

The natural frequencies summarized in Table 3 show that regular ambient vibration testing (Case 1) revealed the natural frequencies of 6 of the 12 modes being analyzed. The natural frequencies identified in Case 1 were only consistent with the first two modes identified in the pseudo ambient vibration test cases in the frequency band of 0 to 11 Hz. Furthermore, the pseudo ambient vibration testing was able to identify more frequencies more frequently ranging from 0 to 156 Hz. It is important to note that high force (Case 3) did not lead to the identification of more natural frequencies than the low force (Case 2). This could be caused by nonlinearities that only occur when the structure is excited with high force. The regenerated signal (Case 4) had very consistent and reliable results. This means that multiple repetitions of the same excitation input yields more consistent results than pure stochastic excitation signal. When varying the band using low band (Case 5) and high band (Case 6), while keeping a constant low force level, the results indicate that a low band can identify the natural frequencies up to mode 12 at 155 Hz, but high band is unable to identify the first two natural frequencies. When reducing the amount of shakers to 9 and varying their locations from spread out (Case 7) to close together (Case 8), there is no considerable observation. Finally, when reducing the number of shakers to 4 (Case 9) or 3 (Case 10), the higher order natural frequencies are not confidently identified, which could be due to a lack of excitation required to achieve the vibration required.

After inspecting the damping ratio and MAC results from Table 4 and Table 5, respectively, similar observations to the natural frequencies are drawn. The baseline characterization (Case 1) had damping ratios with smaller values than the ones obtained from the pseudo dynamic testing cases. The damping ratios produced by a low force level produced values that were consistent with each other. In addition, the MAC value obtained from the cases that used pseudo ambient vibration testing were more reliable than the values those produced by the pure ambient case. The variation in force level, band width, number of shakers, or location of shakers did not seem to generate highly different MAC values from one another. Again, the regenerated signal (Case 4) had more consistent data than the rest because the band of interest was repeated several times.

Conclusions and Recommendations

In this research project, a large steel grid structure was dynamically characterized and evaluated using the conventional method of ambient vibration testing, and by a new pseudo ambient vibration testing method. The pseudo vibration testing used the combination of uncontrolled and unmeasured ambient dynamic excitation, and stochastic dynamic excitation provided by a novel dynamic excitation system. This system consisted of tactile transducers that were spatially distributed throughout the structure and which provided uncorrelated Gaussian white noise excitation to the structure that is consistent with those normally assumed for conventional ambient vibration test. The results obtained from a conventional ambient vibration test were used as the baseline for comparing the results from the various pseudo ambient vibration test cases.

The grid structure's output accelerations consistently showed that the global vibration responses were considerably larger than those measured from the baseline ambient vibration test (around 1000 times larger in most cases). This presumably provided much greater signal-to-noise ratios in the vibration measurements than from conventional ambient vibration testing. The character of the measured accelerations from the pseudo ambient vibration cases was also observed to be consistent in terms of total RMS acceleration amplitudes and repeatability with the character of the unmeasured but controlled stochastic excitation signals sent to the tactile transducers in each case.

The pseudo ambient vibration testing method provided substantially more consistency and reliability when identifying the modal parameters (natural frequencies, damping ratios, and modal vectors) than the conventional ambient vibration test case. Furthermore, the baseline ambient vibration test only provided modal parameters in a narrow frequency range. Conventional ambient vibration testing only provided quality results in the frequency range from DC to 11 Hz, whereas pseudo ambient vibration testing provided reliable results for a larger frequency band of DC to 156 Hz.

The pseudo ambient vibration testing allowed for a more consistent and reliable identification of modal parameters when compared to the ambient vibration testing. The dynamic excitation system used for the research was found to be capable for providing controlled stochastic input that was consistent with the characteristics normally assumed in ambient vibration testing. Of the pseudo ambient vibration test cases evaluated, the case that employed a 4 minute long excitation signal that was replayed a total of 15 times generally produced the most consistent results. This indicates that the 4 minute long stochastic signals likely included enough excitation content at the structural frequencies and that multiple averages of this signal enhanced the consistency of the dynamic characterization results.

The grid structure evaluated in this study is a light and simple structure when compared to full-scale systems, but the results obtained suggest that there is merit for using this new vibration testing approach to dynamically characterize short to medium span bridges and other small to moderate sized structures. Additional studies should be done with the pseudo ambient vibration testing method on in-service structures subject to dynamic excitation from both environmental sources and service loads to validate its capabilities and performance under real-world conditions. The proposed pseudo ambient vibration testing approach has the possibility of leading towards more reliable dynamic characterizations than are currently possible with conventional ambient vibration testing.

This could lead to more effective structural health monitoring and damage detection and characterization applications for a wide range of constructed systems.

References

Allemang, R. (2002). "The Modal Assurance Criterion – Twenty Years of Use and Abuse," Proceedings of the 20th International Modal Analysis Conference (IMAC XX), Los Angeles, CA.

American Society of Civil Engineers (ASCE) (2013). "Report Card for America's Infrastructure." <http://www.infrastructurereportcard.org/a/#p/bridges/conditions-and-capacity> (May 14, 2014).

Brincker, R., Ventura, C.E., and Andersen, P. Why Output-Only Modal Testing is a Desirable Tool for a Wide Range of Practical Applications. *Proc. of the 21st IMAC, A Conference on Structural Dynamics*, Society for Experimental Mechanics, 2003.

Carreiro, J.L., Fernstrom, E. V., and Grimmelsman, K.A., (2013). "Evaluation of Low Cost Dynamic Exciters for Controlled Dynamic Testing of Bridges," Proceedings of the Structures Congress 2013, Pittsburg, PA. USA.

Dorvash, S. and S. Pakzad. Uncertainties in Identification of a Steel Bridge Dynamic Characteristic, *Proc. of the 2013 Structures Congress*, ASCE, pp. 328-339, 2013.

Fernstrom, E.V., Carreiro, J.L. and K.A. Grimmelsman. Evaluation of Economical Dynamic Exciters for Vibration Testing of Bridges. *Proc. of the 31st IMAC, A Conference on Structural Dynamics*, Society for Experimental Mechanics, pp. 423-434, 2013.

Fernstrom, E.V. and Grimmelsman, K.A. Comparative Evaluation of Excitation Schemes for Multi-Shaker Testing of Bridges. *Proceedings of the 32nd IMAC, A Conference on Structural Dynamics*, Society for Experimental Mechanics, 2014.

Grimmelsman, K.A., Lindsey, J., Norris, J.T., and Dufour, R.T. A Study on the Effects of Excitation Characteristics in Operational Modal Analysis of Bridges. *Compendium of Papers, Transportation Research Board 93rd Annual Meeting*, Washington D.C., 2014.

Guillaume, P., De Troyer, T., Devriendt, C. and De Sitter, G. OMAX – Operational Modal Analysis in presence of eXogenous Inputs, *Proc. of the 25th IMAC, A Conference on Structural Dynamic*s, Society for Experimental Mechanics, 2007.

Reynders, E., Degrauwe, D., De Roeck, G., Magalhaes, F. and Caetano, E. Combined Experimental-Operational Modal Testing of Footbridges, Journal of Engineering Mechanics, 136(6): 687-696, 2010.

Reynders, E., Degrauwe, D., De Roeck, G., Van den Broeck, P., Deckers, K. and Guillaume, P. OMAX Testing of a Steel Bowstring Footbridge, Proc. of the 29th IMAC, A Conference on Structural Dynamics, Society for Experimental Mechanics, 2011.

Van Overschee, P. and De Moor, B. (1996). “Subspace identification for linear systems: Theory, implementation, applications.” Kluwer Academic Publishers.

Yun, G., (2009) “Modal Identification and Damage Detection for Structural Health Monitoring under Ambient Vibration Environment,” Proceedings of the Structures Congress 2009, Austin, TX. USA.