

Department of Civil, Architectural, & Environmental Engineering

Drexel University College of Engineering

The following item is made available as a courtesy to scholars by the author(s) and Drexel University Library and may contain materials and content, including computer code and tags, artwork, text, graphics, images, and illustrations (Material) which may be protected by copyright law. Unless otherwise noted, the Material is made available for non profit and educational purposes, such as research, teaching and private study. For these limited purposes, you may reproduce (print, download or make copies) the Material without prior permission. All copies must include any copyright notice originally included with the Material. **You must seek permission from the authors or copyright owners for all uses that are not allowed by fair use and other provisions of the U.S. Copyright Law.** The responsibility for making an independent legal assessment and securing any necessary permission rests with persons desiring to reproduce or use the Material.

Please direct questions to archives@drexel.edu

Drexel University Libraries
www.library.drexel.edu

University Archives and Special Collections:
<http://www.library.drexel.edu/archives/>



<http://www.drexel.edu/>

Opportunities and challenges in health monitoring of constructed systems by modal analysis

A.E. Aktan, S.K. Ciloglu, K.A. Grimmelsman, Q. Pan

Affiliation Drexel University, Intelligent Infrastructure Institute, Philadelphia, PA, USA

F.N. Catbas

University of Central Florida, Orlando, FL, USA

ABSTRACT: Dynamic testing of constructed systems was initiated in the 1960's by civil engineers interested in earthquake hazards mitigation research. During the 1970's, mechanical engineers interested in experimental structural dynamics developed the art of modal analysis. More recently in the 1990's, engineers from different disciplines have embarked on an exploration of health monitoring as a research area. The senior writer started research on dynamic testing of buildings and bridges during the 1970's, and in the 1980's collaborated with colleagues in mechanical engineering who were leading modal analysis research to transform and adapt modal analysis tools for structural identification of constructed systems. In the 1990's the writer and his associates participated in the applications of the health monitoring concept to constructed systems. In this paper, the writers are interested in sharing their experiences in dynamic testing of large constructed systems, namely, MIMO impact testing as well as output-only modal analysis, in conjunction with associated laboratory studies. The writers will try to contribute to answering some questions that have been discussed in the modal analysis and health monitoring community for more than a decade: (a) What is the reliability of results from dynamic testing of constructed systems, (b) Can these tests serve for health monitoring of constructed systems? (c) Are there any additional benefits that may be expected from dynamic testing of constructed systems? (d) Best practices, constraints and future developments needed for a reliable implementation of MIMO testing and output-only modal analysis of constructed systems for health monitoring and other reasons.

1 INTRODUCTION

1.1 *Background*

Controlled dynamic testing of full-scale structures was initiated in California in the early 1960's. The first rotating-weight vibration generators were developed for the purpose of testing structures to validate the analytical techniques used for predicting the dynamic characteristics of building and other constructed systems (Hudson 1964). Several full-scale constructed systems were tested in California in the 1970's by rotating-weight vibration generators (e.g. Shepard & Charleson 1971, Iwasaki et al 1972, Shepard & Sidwell 1973, Kuribayashi & Iwasaki 1973, Ibanez 1973, and Stephen et al 1974). Dynamic testing of full-scale buildings and bridges in addition to analyses of their seismic responses recorded during earthquakes, and shaking table studies of scaled models continued in the US, Japan and elsewhere by earthquake engineering researchers (Gulkan & Sozen 1977, Clough & Bertero 1977, Galambos & Mayes 1978, and Gundy et al 1981). Large-capacity rotating-weight as well as linear inertia-mass excitation generators, seismic accelerometers and the associated data acquisition hardware needed for dynamic testing of constructed systems are currently being manufactured by various industries that have subsequently emerged for supporting earthquake hazards mitigation research and applications.

Meanwhile, in 1982, modal analysis specialists within the experimental mechanics/dynamics community initiated the annual International Modal Analysis Conferences (IMAC). In the two

decades following IMAC I, the modal analysis community propelled this specialty into a significant research and application area. Today, mechanical and aerospace engineers take advantage of modal analysis for supporting mechanical systems design, quality control during manufacturing, control of operational vibration, acoustics, and, damage diagnosis applications. These applications have fostered the development of an industry for producing excitation devices, sensors, data acquisition hardware and data processing software.

Although the fundamental structural dynamics theory for constructed and mechanical systems is the same (introduced to civil engineers by aerospace engineers in the 1950's), it is the writers' opinion that there has not been sufficient cross-fertilization of the seismic monitoring and dynamic testing applications in earthquake engineering by transforming the recent advances made by the modal analysis community related to sensing, data acquisition and data post-processing. Also, the importance of taking advantage of pattern recognition and other signal processing advances made in the telecommunications field for advancing modal analysis applications on constructed systems are becoming quite clear.

A third and more recent research area termed "health monitoring" has been initiated in the 1990's. Since 1997, the International Workshop on Structural Health Monitoring (IWSHM) that has been organized at Stanford University, has brought together biannually a large community of researchers from aerospace, space, automotive, earthquake and infrastructures fields. In addition to IWSHM, there have been many additional international workshops and conferences held since the 1990's related to post-earthquake damage evaluation, structural control during earthquakes, condition assessment of constructed systems by nondestructive testing, etc. that included discussions of health monitoring. Today, the health monitoring community has significantly broadened, such that, in addition to aerospace, space and automotive fields, the terms health monitoring and health assessment are widely used by many academic and practicing civil engineers specializing in the design, condition assessment, evaluation, maintenance and retrofit of all types of constructed systems. There is consensus amongst the civil engineering research community that health monitoring promises to be a critical enabler for performance-based civil engineering applications, lifecycle cost-based maintenance management of constructed systems, and asset-management applications to entire infrastructures.

The senior writer has participated in each of the earthquake engineering, modal analysis and health monitoring research and application fields since he received his PhD in 1973. During 1990-1997, writers had the opportunity of testing a mid-rise building (Hosahalli & Aktan 1994, Aktan et al 1995, Miller et al. 1993, Aktan et al. 1997, and Catbas et al. 1998), and three different types of highway bridges to controlled damage and failure. After the test bridges were loaded to various levels of damage, they were unloaded and their modal analysis was conducted. By transforming the modal vectors resulting from multi-input, multi-output (MIMO) testing by impact to modal flexibility, and by virtually loading the modal flexibility by various load patterns, the writer and his associates showed that the virtual deflection patterns of a bridge may be used as a conceptual and sensitive structural condition and damage indicator (Toksoy & Aktan 1994, Aksel et al 1994, Catbas et al 2005). The virtual deflection patterns were validated by loading the test bridges with trucks, and measuring and correlating the deflection patterns with the virtual deflections obtained from modal flexibility. Since 1992, the writers have been investigating continuous monitoring applications on constructed systems and how these may be used for long-term monitoring of highway bridges. After 1997, they started exploring the challenges in structural identification and lifecycle health monitoring of large-scale, long-span bridges, representing a special class of constructed system in terms of very large (kilometers) scale and complexity. These systems proved to be excellent field laboratories not just as constructed systems but in fact by representing infrastructure systems that cannot be fully observed and conceptualized without recognizing and incorporating every one of the interacting engineered, human and natural sub-systems and elements necessary for understanding and defining their performance (Aktan & Faust 2003).

1.2 *Objective and scope*

The writers' objective in writing this paper is to take advantage of their experiences in dynamic testing of a number of actual building and bridge structures in the field and formulate an overview of the state-of-art in dynamic testing of constructed systems, especially for health monitor-

ing applications. They are motivated to discuss the most critical prerequisites for reliable applications of MIMO and output-only dynamic testing that may lead to a meaningful understanding of the global mechanical characteristics of large constructed systems and their subassemblies.

The writers are motivated to contribute to answering some questions that have been discussed in the modal analysis and health monitoring community for more than a decade: (a) What is the range of reliability of results from dynamic testing of constructed systems; (b) Can dynamic tests serve for health monitoring of constructed systems? (c) Are there any additional benefits that may be expected from dynamic testing of constructed systems? (d) What are the best practices, constraints and future developments needed for a reliable implementation of MIMO testing and output-only modal analysis of constructed systems for health monitoring and other reasons?

Measuring the global mechanical characteristics of large constructed systems by dynamic testing requires the assumptions of their observability, time-stationarity (at least during the observation period), and linearity (of the structure and damping mechanisms). None of these three principal assumptions can be strictly valid for structures which are very large and complex, or subject to daily temperature fluctuations of 10 degrees Celsius or higher. Given that there have been very few examples of dynamic testing of constructed systems or their subassemblies in the field, with adequate instrumentation designed in a scientific context, any new application becomes an exploration into the unknown and is governed by significant epistemic uncertainty. This greatly impacts the reliability of the data and the results that are extracted from the data, and points to the importance of experience and taking advantage of any heuristics as well as the necessity of concerted efforts for mitigating many common human/application errors that impact the reliability of the test results.

Hence, to make field testing of a constructed system in the field produce reliable and sufficiently complete results, *it is necessary to approach this as a scientific exploration and not as a routine, process-oriented engineering application. The system-identification concept becomes a necessary and fundamental approach to designing such an exploration.* The writers would like to defend this viewpoint by providing examples from the laboratory and from the field. To illustrate the relationship between MIMO and output-only testing, the results from a laboratory specimen are presented. To illustrate the best recommended practices for MIMO and output-only testing of systems in the field, applications to actual bridge structures will be discussed.

1.3 Brief review of recent reported applications of dynamic testing of constructed systems

Since 1980, dynamic testing and modal analysis have been explored in integrated analytical and experimental research on: condition assessment of offshore platforms (Rubin & Coppolino 1986), large space structures (Stubbs et al 1990, Kim & Bartkowicz 1993), seismic vulnerability evaluation of buildings (Hosahalli & Aktan 1994) and condition assessment of highway bridges (Brownjohn et al 1986, Mazurek & DeWolf 1990, Salane & Baldwin 1990, Nigbor et al 1992, Raghavendracher & Aktan 1992, Samman & Biswas 1994, Aktan et al 1997, 1998, Farrar & Jauregui 1996, 1998, Lenett et al 1997, Catbas et al 1998, Wahab & De Roeck 1998, Kaito et al 2001, Chang et al 2001, Wenzel & Pincher 2005). Various additional experimental studies have been carried out in the field as well as in the laboratory to study soil-foundation-structure interaction such as Luco et al 1986, De Barros & Luco 1995, Halling et al 2001. Finally, Saiidi & Douglas (1984), Buckle et al (1985), Gilani et al 1995, Eberhart et al (1993, 1997) and Bollo et al (1990) tested full-scale bridges in the field to study their earthquake vulnerability. An extensive literature review on damage identification based on changes in modal characteristics has been prepared by Doebling et al (1996).

In the area of health monitoring, damage detection and identification techniques for constructed systems may be classified into two distinct groups. The first group aims at tracking changes in structural responses that directly or in the case of using vibration signals, indirectly, relate to the mechanical characteristics (e.g. natural frequencies, modal flexibility, strains, etc.) of a structure before and after damage. Most of the researchers referenced above subscribed to such an approach based on the system identification of a physics-based model. The second group aims at damage identification methods that utilize post-processing measurement data to detect anomalies from measurements. These include ANN (Masri et al 1996, Nakamura et al 1998, Chang et al 2000 and Zapico et al 2003), statistical pattern recognition (Sohn et al 1997,

2000, 2001 and Vanik et al 2000), ARMAV modeling (Andersen et al 1997,1998, Bodeux & Golinval 2001), wavelet decomposition (Al-Khalidy et al 1997, Gurley & Kareem 1999, Hou et al 2000, Sun & Chang 2002), Empirical Mode Decomposition (EMD) in conjunction with the Hilbert-Huang Transform (Huang et al 1998 and Yang et al 2001) and others. The motivation behind these latter methods is to automate the detection process by taking advantage of the recent advances in information technologies. An extensive literature survey of damage diagnosis techniques has been prepared by Sohn et al (2002).

Currently, a number of major long-span bridges such as the StoreBaelte Bridge in Denmark (Brincker et al 2000), the Lantau Crossings in Hong Kong (Kwong et al 1995 and Wong et al 2000), the Akashi Kaikyo Bridge in Japan (Kashima 2001), and the Commodore Barry Bridge in the U.S. (Catbas et al 2000) have been modeled and instrumented for continuous monitoring for seismic, wind and broader operational as well as structural performance and health monitoring purposes. The global dynamic properties of these bridges have been identified by conducting ambient vibration tests to serve as reference for their lifecycle health monitoring.

2 LESSONS FROM MIMO TESTING OF THE SEYMOUR BRIDGE

The Seymour Bridge, shown in Figure 1(a), was a three-span, 40-m long overpass with reinforced concrete deck on steel girders, constructed in 1953. The bridge was scheduled for demolition; and it served as a field test specimen for studying whether common damage scenarios could be diagnosed by modal analysis as well as additional experimental techniques such as continuous monitoring. The damage scenarios that were implemented included changes in the boundary conditions such as bearing removal, welding and locking bearings, different levels of damage to a steel girder and cross-frames, and the breaking of composite action due to the chemical bond between the reinforced concrete deck and a steel girder (Aktan et al 1997, Lenett et al 1997, Catbas et al 1998).

Extensive data was obtained before and after each type of damage was introduced by conducting modal analysis by forced-excitation, by impact, and in one case, by ambient vibration monitoring. These dynamic tests were accompanied by controlled truck-load tests. Based on the results that were obtained from the tests, the writers presented displacement coefficients as promising kernel condition and damage indices (Catbas & Aktan 2002). Displacement coefficients are very conceptual and they can be measured in a variety of manners by controlled load tests or by modal analysis.

A significant observation during the field studies on the Seymour Bridge was that dynamic properties of redundant structures, especially frequencies, may shift continuously in the course of a day due to changes in temperature and other environmental conditions such as humidity. For example, Figure 2 shows various FRF's of the bridge taken in the course of a single day and revealing frequency changes exceeding 5% due to a temperature change of 10 degrees Celsius (over a 12 hour period). More important is the change in the nature of the FRF's indicating changes in modal order due to the change in temperature. This was attributed to the contact problems caused by deteriorated bearings and triggered by the temperature changes.

The non-stationarity of the bridge dynamic properties made post-processing of modal analysis data impossible by the commonly used modal parameter estimation methods. The fact that the bridge was originally symmetric in plan, but deteriorated, caused many repeating modes to be highly coupled and damped. The writers overcame the difficulties due to time-variance by devising short-time test techniques and applying these at midnight when the bridge and ambient temperatures were stable (Lenett et al 1997). In addition, the writers had to develop a new spatial domain method to determine the modal parameters along with correct scaling by using a modal filtering approach (Catbas et al 2004). In this manner, the writers were able to post-process data and to generate reliable modal flexibility of the steel stringer bridge.

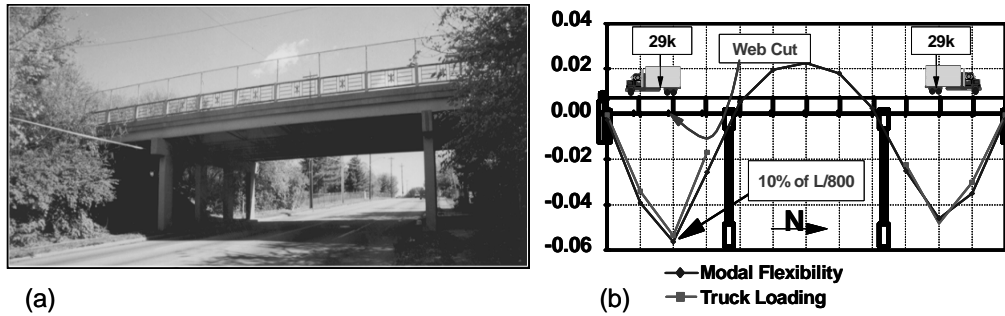


Figure 1. (a) Seymour Bridge, (b) structural deflections from modal flexibility and load testing

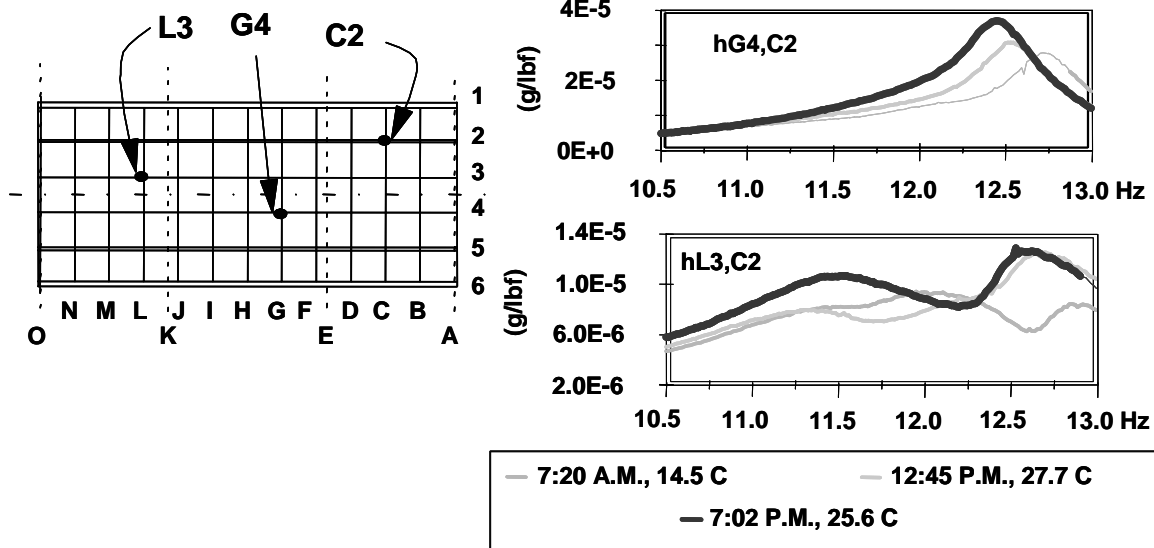


Figure 2. Temperature related variations observed in Frequency Response Functions

The Seymour Bridge tests revealed that in testing large operating structures it may not be possible to conduct a MIMO test of the entire structure with a fine grid due to operational constraints, access problems, etc. In such a case, it is possible to employ a spatially truncated test grid; however, the modal flexibility obtained from the measurements will be incomplete. The writers showed that the deflected shape of a girder under virtual uniformly distributed load, which is termed the “bridge girder condition indicator (BGCI)”, will eliminate the effects of unmeasured cross terms in the flexibility matrix due to the specific loading pattern utilized. The BGCI obtained from a full and an incomplete modal flexibility matrices showed that if the structure can be well excited within the truncated measurement grid, and the temporal modal truncation is minimized by adding an adequate number of modes, it is possible to obtain reliable girder deflection profiles (BGCI) even from an incomplete modal flexibility.

The BGCI serves as a conceptual condition index and it is possible to examine the deflection profiles or BGCI to evaluate a bridge’s condition even without baseline information. Figure 1(b) correlates the structural deflections using modal flexibility and controlled load test results following damage to one girder under a side-span. The deflection under the left side span is clearly larger, correctly indicating the damage location. However, only 10% of the maximum serviceability deflection was reached under the load of two 129 kN trucks even though one steel girder out of six was cut. The modal flexibility did not only reveal the damage, but also the remaining stiffness and performance of the bridge as a conceptual and powerful health index.

3 OUTPUT-ONLY TESTING OF THE HENRY HUDSON AND BROOKLYN BRIDGES

Output-only vibration testing is often the only practical means to experimentally determine the dynamic properties of major bridges. The author's recently conducted output-only vibration tests on two major bridges in New York City. In both applications, the objective of the testing was to measure the vibration responses at various locations due to ambient excitation sources (primarily wind and traffic) and identify the frequencies, modes shapes, and damping of the structure. The identified dynamic properties were subsequently used to improve the reliability of seismic assessments and retrofit investigations of the two bridges.

The first bridge tested was the Henry Hudson Bridge (Fig.3), which crosses the Harlem River and connects the boroughs of Manhattan and the Bronx. The bridge crossing consists of a double level steel arch span which is flanked at its north and south ends by steel towers, viaduct spans, and approach spans. The portions of the bridge that were tested included the arch span, the towers, and the viaduct spans. The vibration testing was conducted in two stages.

In the first test stage, a fixed array of 36 uniaxial accelerometers was installed on the north viaduct, north tower, and northern-half of the symmetric arch span to measure the vertical, longitudinal, and transverse vibrations. In the second test stage, a fixed array of 40 uniaxial accelerometers was installed on the south viaduct, south tower, and southern-half of the arch span to measure vertical, transverse, torsional and longitudinal vibrations. A subset of 10 accelerometers was installed at the same location for both test stages to serve as common reference sensors. The layout of the vertical and transverse accelerometers used for each test stage is shown in Figure 4.

The sensors used included Model 393C seismic accelerometers and Model 3701 capacitive accelerometers from PCB Piezoelectronics, Inc. As shown in Figure 5, the accelerometers were attached to the structure using magnets, and access to the arch and towers was obtained by using a temporary painting scaffold located below the arch span and by climbing the tower members. The accelerometer cables were routed to a central location under the bridge for data collection.

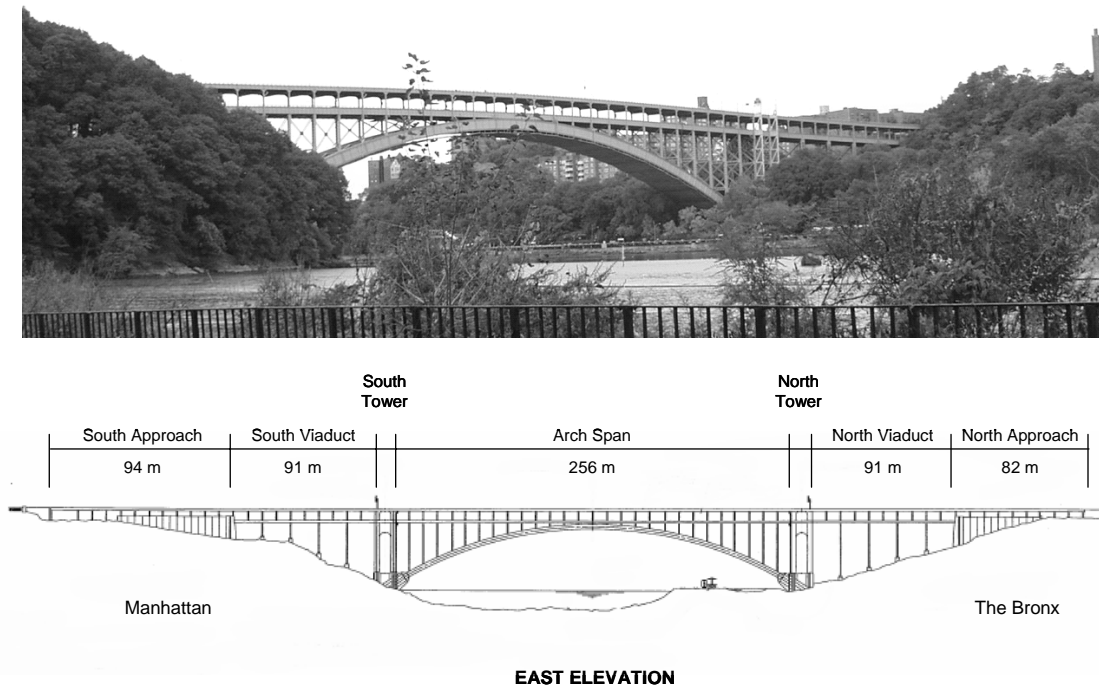


Figure 3. The Henry Hudson Bridge

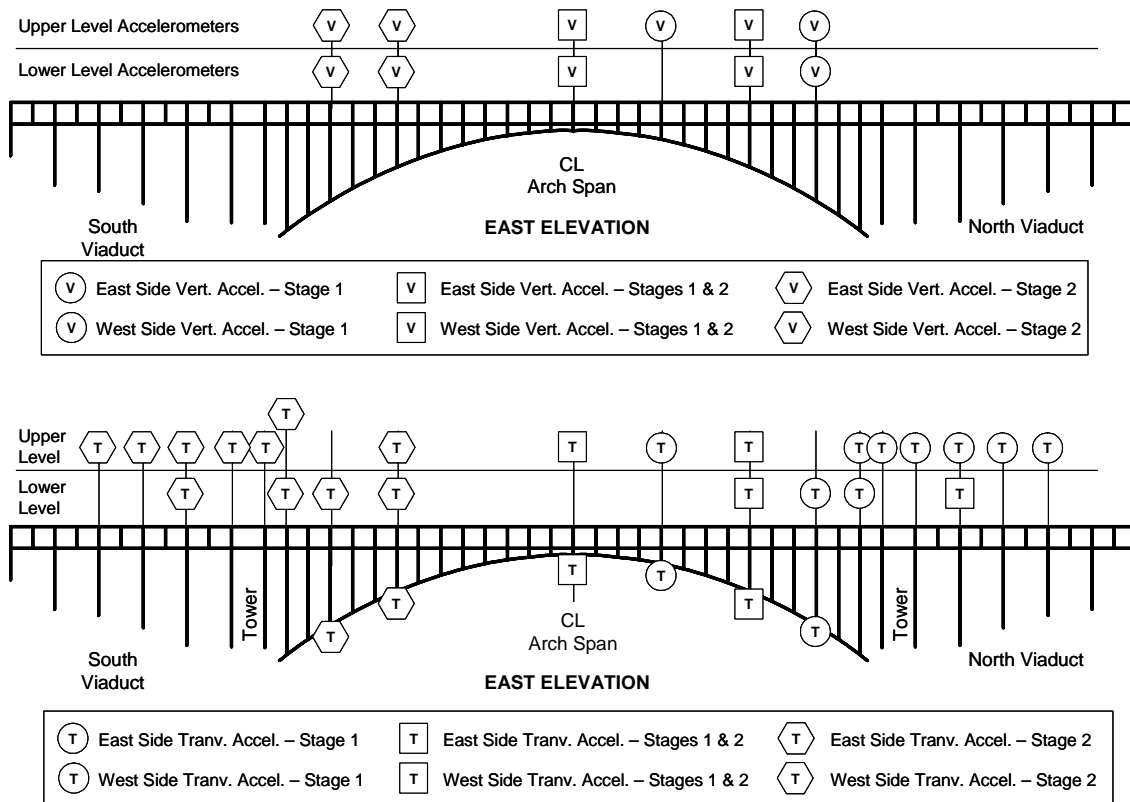


Figure 4. Instrumentation scheme for the Henry Hudson Bridge

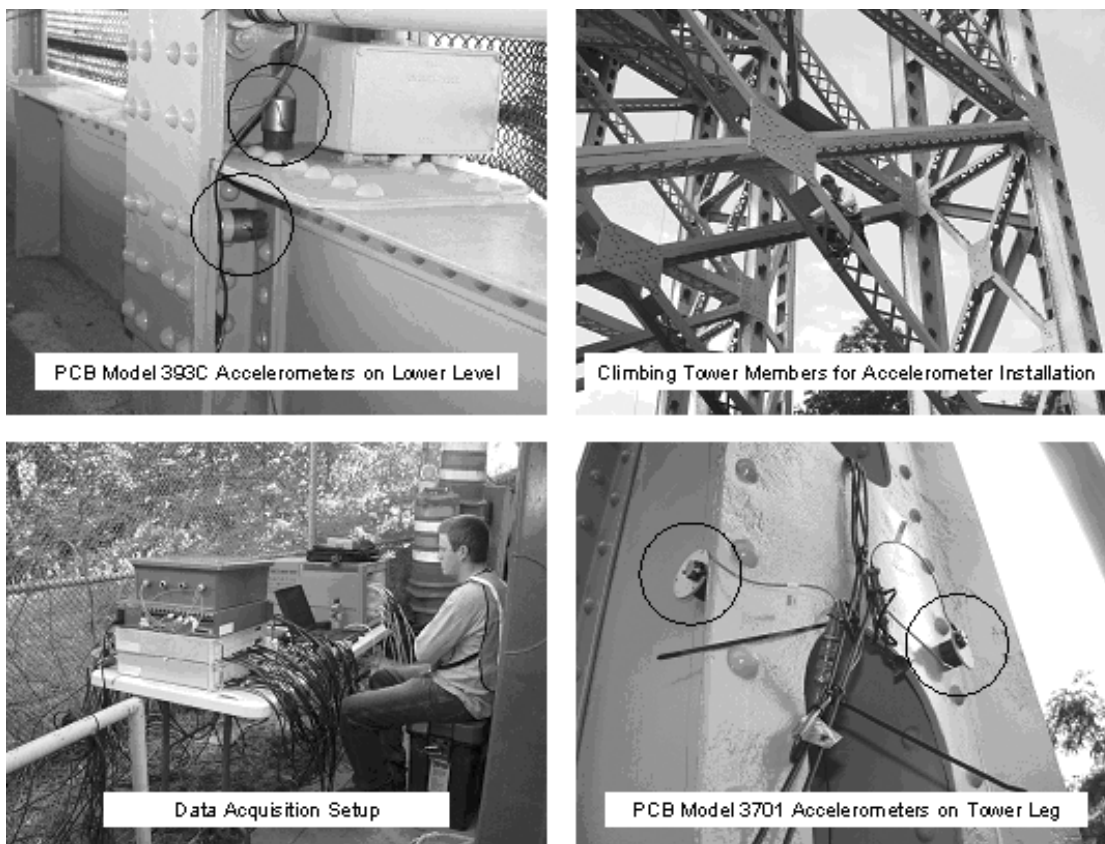


Figure 5. Instrumentation and data acquisition setup

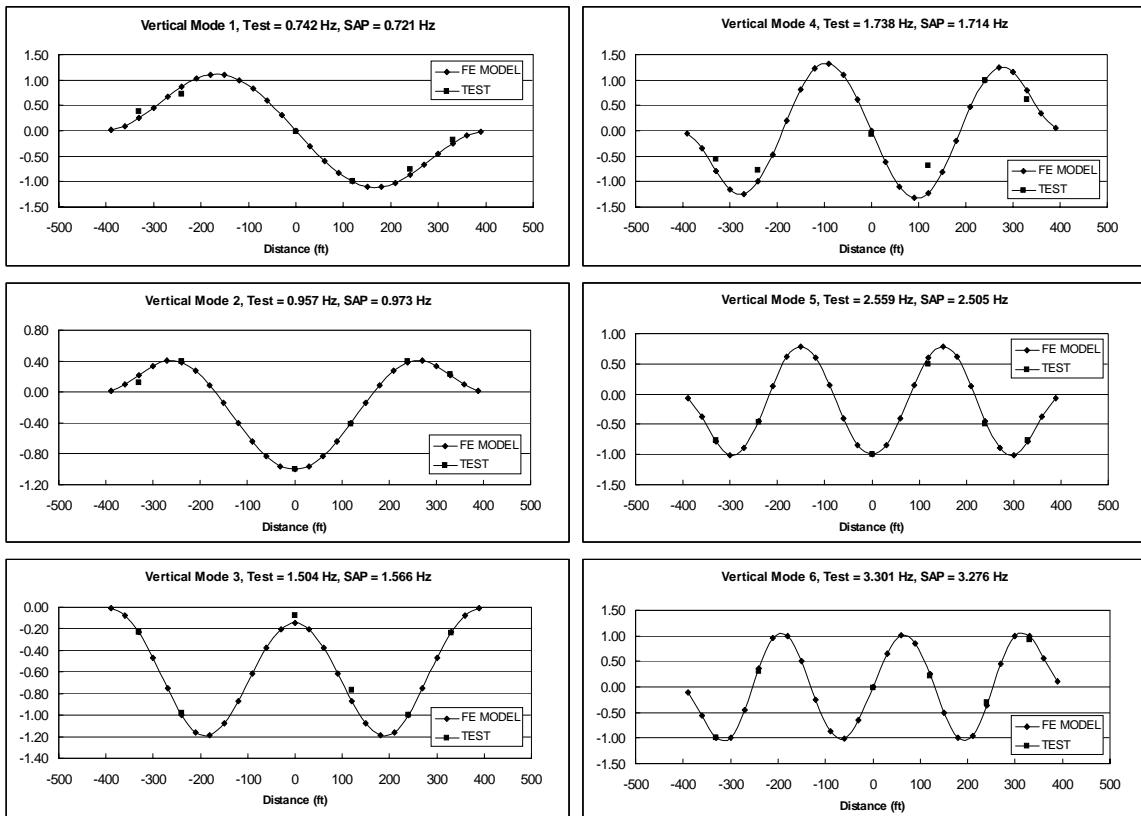


Figure 6. Vertical mode shapes for Henry Hudson Bridge

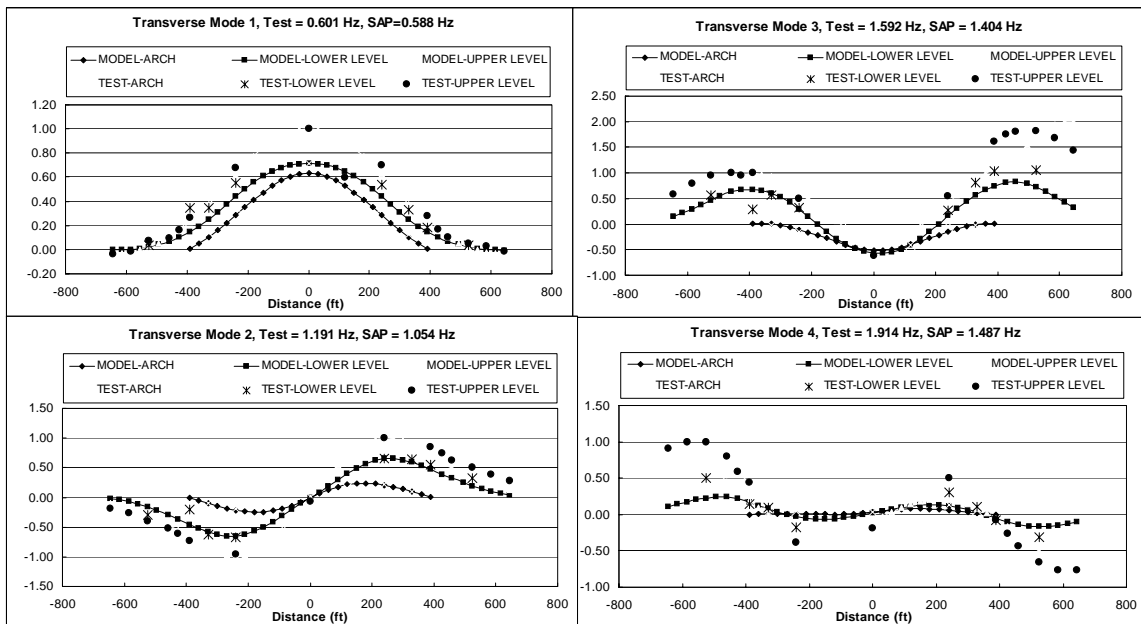


Figure 7. Transverse mode shapes for Henry Hudson Bridge

The measurement data were collected using a VXI mainframe over a several week period, primarily using a 200 Hz sampling rate for records that were 15 minutes in duration. The measurement data were subsequently processed using the peak-picking method to identify the natural frequencies and mode shapes. The damping for each mode was estimated by first applying the random decrement technique to the time domain signals, and subsequently taking the logarithm-

mic decrement of the resulting impulse response spectra. All data processing was performed using the software program Matlab. The time domain data sets were pre-processed to remove the recurrent bias, drift, and noise spikes, and decimated by a factor of 10 as the frequency band of interest was in the range of 0 – 5 Hz. The power spectral density spectra were generated using a Hanning window on each data segment and 50% overlap averaging. The identified frequencies and damping are summarized in Table 1. Examples of the corresponding mode shapes for the vertical and some of the transverse mode shapes are shown in Figures 6-7, respectively.

The second bridge tested was the Brooklyn Bridge, a landmark suspension bridge connecting the boroughs of Manhattan and Brooklyn (Fig. 8). In this application, the primary focus was to identify the dynamic properties of the towers due to ambient excitation from wind and traffic. The dynamic properties of the spans were identified in an earlier test conducted by another group. The towers are constructed from large masonry stones and are approximately 83 m tall.

In this application, a fixed array of 43 uniaxial accelerometers was installed on the Brooklyn tower and at several locations on the stiffening trusses in the adjacent main and side spans. The accelerometers were arranged to measure longitudinal, transverse, and torsional vibrations of the tower, and the vertical, transverse, and torsional vibrations of the spans. The spans were instrumented to aid in interpreting the results obtained for the tower. A wind sensor was also installed on top of the tower to measure wind speed and direction during the vibration monitoring.

Table 1. Identified dynamic properties of the Henry Hudson Bridge

Mode	Frequency (Hz)	Damping (%)
Vertical 1	0.742	3.58
Vertical 2	0.957	1.18
Vertical 3	1.504	2.45
Vertical 4	1.738	1.18
Vertical 5	2.559	1.18
Vertical 6	3.301	0.81
Transverse 1	0.615	2.60
Transverse 2	1.191	0.86
Transverse 3	1.592	1.14
Transverse 4	1.914	1.74
Transverse 5	2.363	1.25
Transverse 6	2.481	1.07
Torsional 1	1.709	1.53
Torsional 2	2.900	1.06



Figure 8. The Brooklyn Bridge

The Brooklyn tower was divided into several different levels, according to changes in cross section, and longitudinal and transverse accelerometers were installed at each level (Fig. 9). On the portion of the tower above the deck, all three legs of the tower were instrumented with accelerometers. Access to the various tower levels for installing the accelerometers was accomplished by rappelling down from the top of the tower and from the underside of the deck. The accelerometer cables were run to a data acquisition cabinet located under the roadway.

Two types of accelerometers were used in this application, the Model 393C seismic accelerometer and the Model 3701 capacitive accelerometer both from PCB Piezoelectronics, Inc. The time domain measurements were recorded using a VXI mainframe and the measurement data were sampled over a period of 1 month primarily using sampling rates of 40 Hz and 20 Hz. The duration of the collected data sets varied from 30 minutes to several days.

The raw time domain measurement data were subsequently processed in Matlab. The raw time domain signals were pre-processed to remove commonly recurring bias, drift or isolated noise spike errors. The typical character of an isolated noise spike present in the time domain data and its impacts on power spectral density are shown in Figure 10. After the time domain data was pre-processed, the frequencies and mode shapes were identified using the peak-picking approach. A Hanning window was applied to each data segment and 50% overlap averaging was applied to the data segments in transforming the time domain data to the frequency domain. The damping was estimated by first applying the random decrement technique to the time domain signals and then calculating the logarithmic decrement of the resulting signals. A summary of the six modes extracted from the results which correspond to those obtained from an isolated analytical model of the tower are given in Table 2. The corresponding mode shapes are shown in Figure 11.

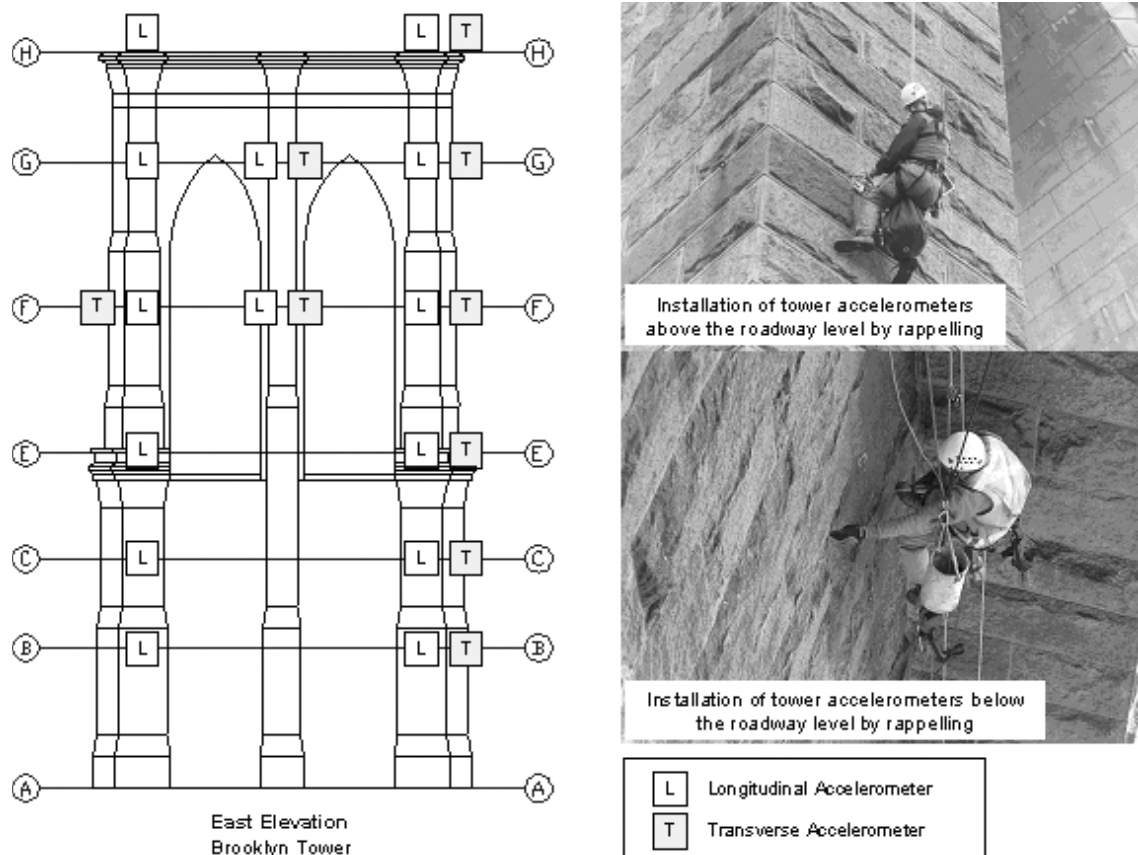


Figure 9. Instrumentation scheme for the Brooklyn tower

The Henry Hudson and Brooklyn Bridge test data analysis is continuing. The recurrent obvious and many possible hidden errors in the data, and the challenges regarding finding the most reliable manners of identifying, cleaning and mitigating the impact of these errors, require considerable research. In addition to the uncertainty caused by the errors in data, the uncertainty related to the inputs make finding the most effective manner of post-processing the data a challenge. Writers were motivated to look more closely into the causes and possible mitigation of the many sources and mechanisms of epistemic uncertainty that affect field testing, and designed a laboratory study that permitted to control some of these mechanisms for study. The dynamic interactions between various subassemblies of large bridges and their impact on the measured characteristics of each subassembly are other mechanisms that deserve further study. Meanwhile, the authors anticipate participation by their distinguished colleagues from North America, Europe and the Far East for a collaborative study of how we may improve the reliability of field testing.

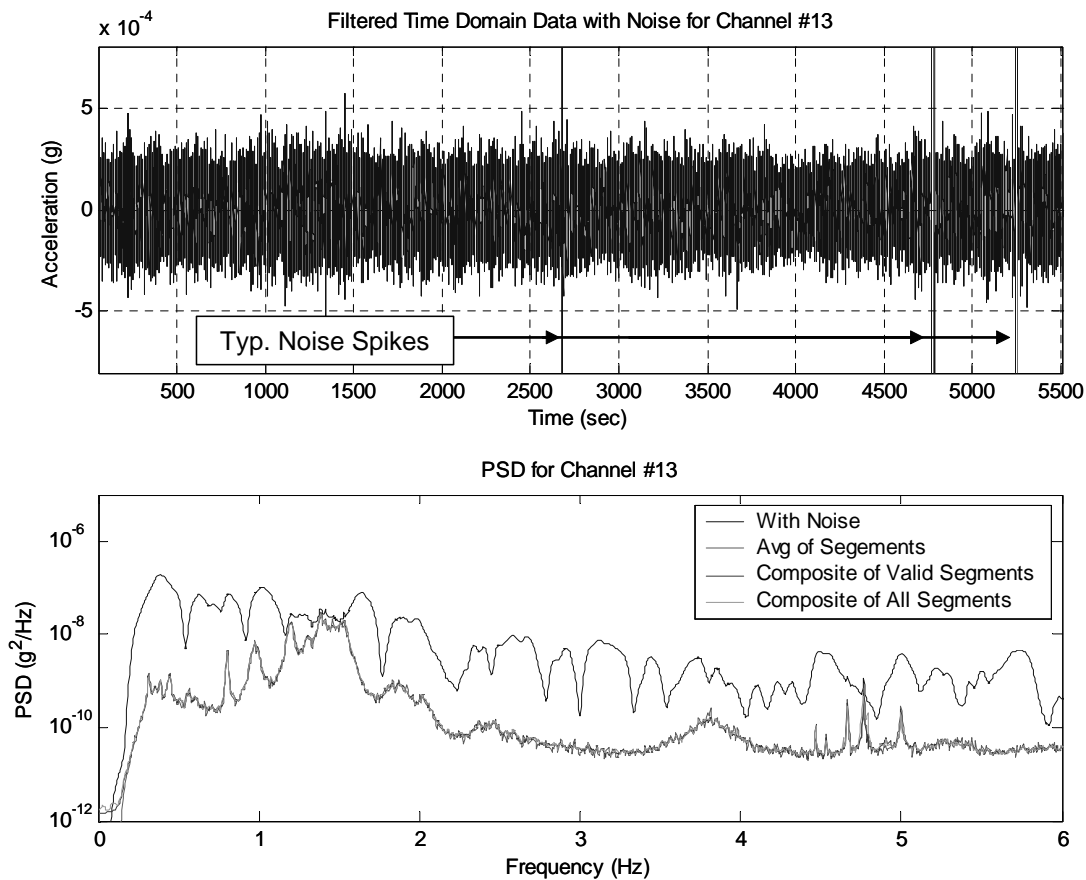


Figure 10. Time domain and power spectral density plots for middle leg of Brooklyn tower at Level F

Table 2. Identified dynamic properties corresponding to isolated analytical model of the Brooklyn tower

Mode Number	Description	Frequency (Hz)	Damping (%)
1	Longitudinal	1.201	2.66
2	Transverse	1.587	3.42
3	Torsional	2.720	3.84
4	Longitudinal	3.418	1.86
5	Transverse	4.668	1.72
6	Torsional	4.761	1.19

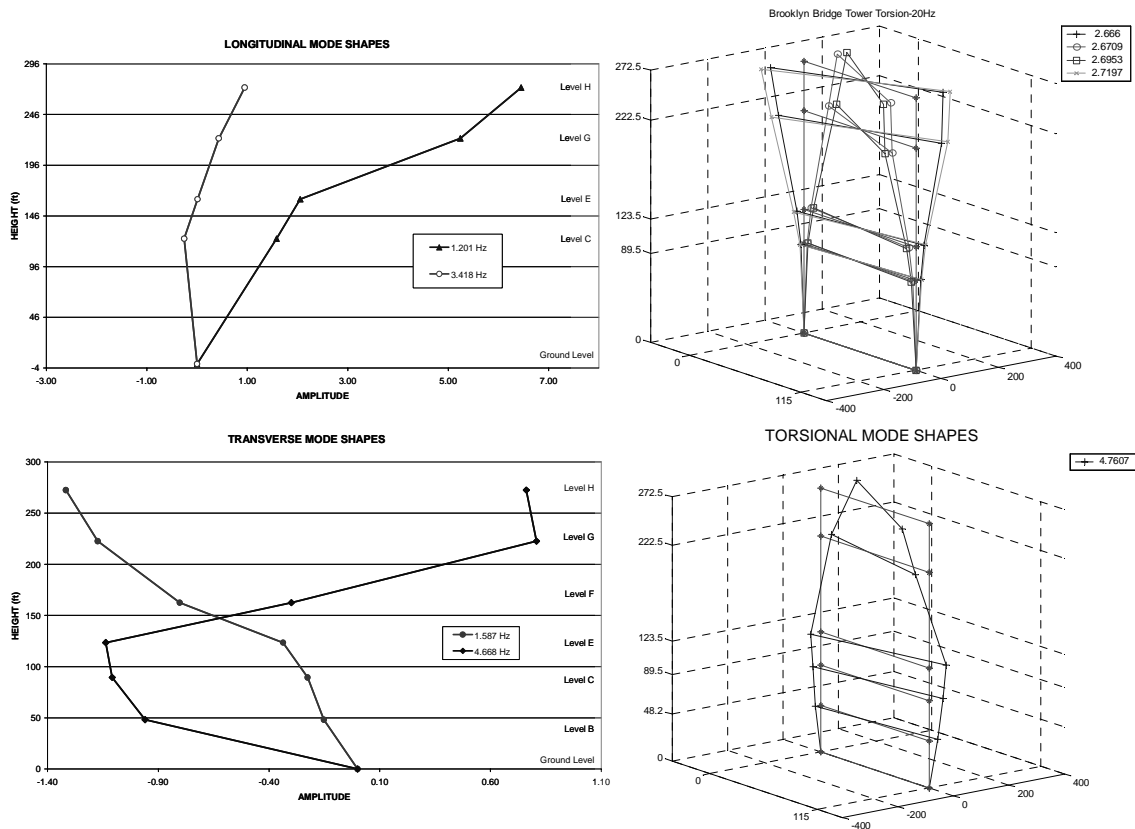


Figure 11. Longitudinal, lateral and torsional mode shape estimates for the isolated tower subassembly

4 MIMO AND OUTPUT-ONLY TESTING OF A PHYSICAL LABORATORY MODEL FOR INVESTIGATING UNCERTAINTIES

4.1 The physical laboratory model fabricated for study of uncertainty

Observations regarding the multitude of mechanisms of uncertainty affecting the reliability of dynamic test results on constructed systems in the field motivated the writers to design and fabricate a physical model for simulating the more critical of these mechanisms and for conducting additional studies related to uncertainty (Fig. 12). Some of the studies on this model related to the effects of uncertainties on modal parameter identification in output-only or operational modal analysis, are summarized in the following. The studies reported here relate to uncertainty associated with the nature of excitation, and uncertainty associated with signal post-processing.

The physical laboratory structure was configured as single span, multiple pin-supported with a 6 m. clear span and an overall width of 3 m. The primary structural system consisted of rectangular steel tube sections, bolted together in a grid arrangement and a composite laminate deck. The structure may be supported in a variety of configurations, introducing different levels of uncertainty related to boundary conditions. It is instrumented with a measurement grid including accelerometers on, adjacent to, and under the supports.

The physical model was first subjected to MIMO testing with an instrumented impact hammer and 30 stationary accelerometers to obtain its modal properties (natural frequencies, damping ratio and mode shapes). This was followed by ambient vibration tests conducted by using different excitation methods: (1) uncontrolled manual impacts in various directions simultaneously on the superstructure, (2) uncontrolled lateral manual impacts on the supporting pedestals, and (3) broad-band random excitation with an electromagnetic shaker located at the base of a support pedestal (Fig. 12).

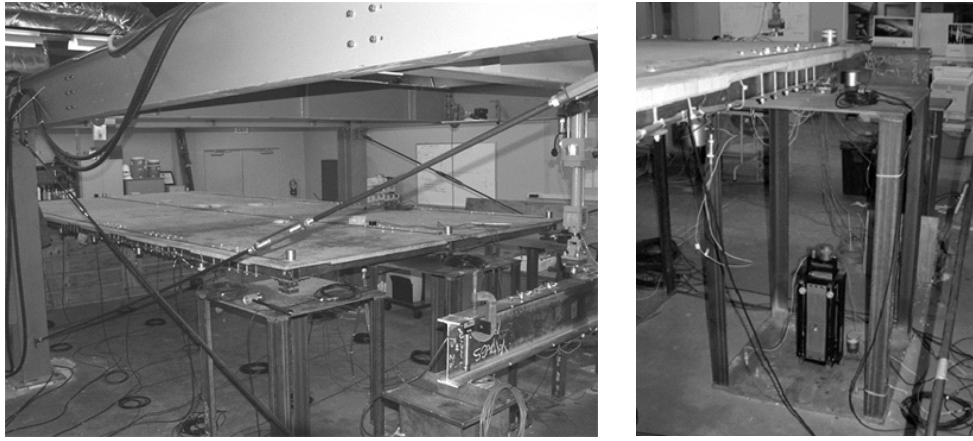


Figure 12. Physical laboratory model and shaker providing excitation at base of one support

Table 3. Dynamic properties of the physical laboratory model from MIMO testing

CMIF Mode.	CMIF Frequency (Hz)	CMIF Damping (%)	PTD Mode.	PTD Frequency (Hz)	PTD Damping (%)	MAC
1	5.050	1.359	1	5.060	1.348	1.000
2	7.802	0.949	2	7.805	0.908	1.000
3	17.835	0.766	3	17.832	0.731	1.000
4	22.284	0.992	4	22.284	0.970	0.999
5	28.089	0.690	5	28.080	0.714	0.996
6	33.129	2.016				
7	36.361	0.712	6	36.361	0.698	0.991
8	39.210	0.895				
9	40.845	1.171				
10	42.988	1.746				
11	46.506	0.897	7	46.522	0.844	0.992
12	49.261	0.876	8	49.291	0.894	0.983
13	51.841	1.100	9	51.713	1.021	0.941
14	53.492	1.029	10	53.459	0.952	0.940
15	58.240	1.300				
16	59.494	1.228				
17	63.366	0.676	11	63.371	0.685	0.966
18	65.797	0.963	12	65.628	0.823	0.879
19	66.329	1.109				
20	68.894	0.808	13	68.95	0.837	0.981

The MIMO impact test data was post-processed by a Complex Mode Indicator Function (CMIF) algorithm (Catbas et al 2004) as well as the Polyreference Time Domain (PTD) algorithm (Leuridan et al 1986). The results listed in Table 3 show that CMIF correctly identified 20 modes between 5-70 Hz bandwidth (and this was confirmed by system identification studies based on a FE model), and the PTD algorithm missed 7 of these modes. The acceleration responses under various simulated ambient vibration inputs were also analyzed with the same parameter identification algorithm (CMIF), but different signal processing methods (e.g. windowing vs. data modeling) to investigate the effect of uncertainty associated with the signal processing approach on the final results.

4.2 The effect of ambient excitation on identified modal properties

Since the impacts of the nature of excitation on output-only modal analysis was the main parameter under investigation, ambient vibrations were simulated by applying random impacts to the structure in two different manners, as well as exciting the base of a support pedestal with an

electromagnetic shaker. In the first case, the deck and grid was hit by random manual impacts whereas in the second case, the support pedestals carrying the superstructure were hit laterally. An electromagnetic shaker was used to excite the structure at the base of a support pedestal as a third excitation method. During the ten minute data collection process, streaming data was visually checked for detecting whether any malfunctioning channels were present. Modal parameters were identified with the CMIF algorithm following the application of the random decrement method (RD) to the data, as recommended by Fujino et al (2000) and Ibrahim et al (1998), to obtain pseudo-impulse response functions (P-IRF) from the ambient vibration signals. In this manner, it is possible to transform the ambient vibrations to pseudo-impact data and process data by following a similar procedure to MIMO test data. This approach may be referred to as pseudo-MIMO post processing of an output-only test data.

Figure 13 shows raw signals from an accelerometer located at the center point of the structure along with the P-IRF at the same point following the random decrement process applied to the data. The resulting CMIF plots are shown in Figure 14. Differences in the shape of the CMIF plots indicate that identified mode shapes significantly vary depending on the nature of the input excitation.

Table 4 correlates the frequencies and lists the modal assurance criterion (MAC) values of compared mode shapes from different tests conducted on the structure. When the structure was randomly impacted on the superstructure, five of the first six modes were identified, but when the supports were hit laterally, only three of the first eight modes could be identified. When the structure was excited with a shaker at the base of a support pedestal, a significantly weaker random excitation was transmitted and only one mode could be reliably extracted from the ambient vibration data.

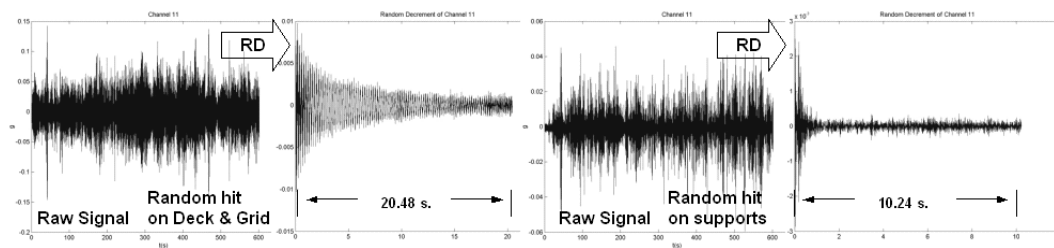


Figure 13. Ambient test data and RD results for different input conditions

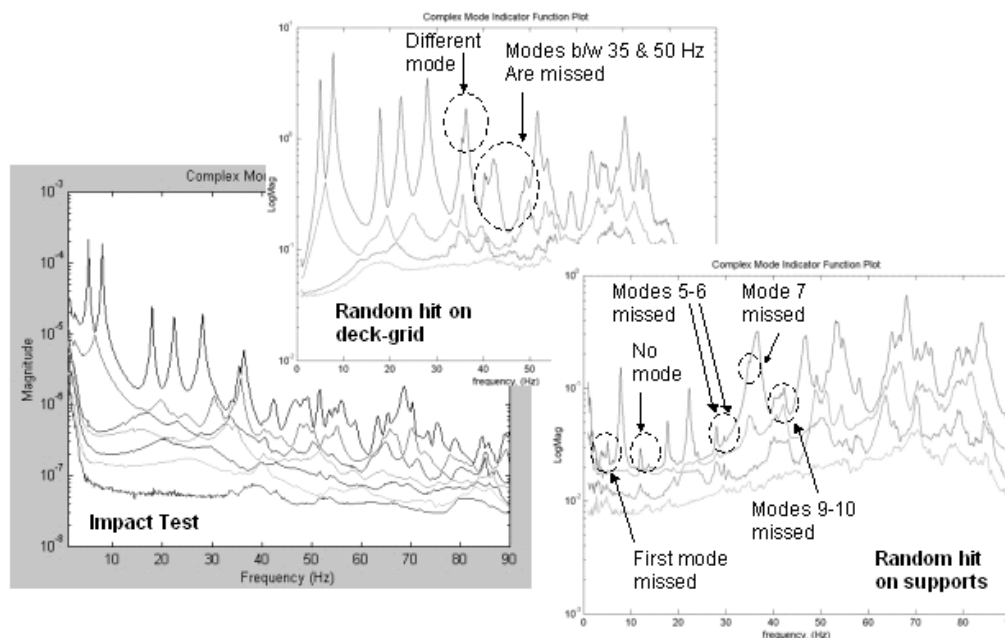


Figure 14. CMIF plots of the impact test and the two ambient vibration tests

Table 4. Comparison of impact and ambient vibration test results by non-parametric post processing

Impact test results (CMIF)	Ambient test results						
	Random vertical impacts on structure			Random lateral impacts on supports		Shaker input at base of structure	
Mode	Frequency (Hz)	Frequency (Hz)	Impact vs. ambient MAC	Frequency (Hz)	Impact vs. ambient MAC	Frequency (Hz)	Impact vs. ambient MAC
1	5.04	5.05	0.998				
2	7.81	7.80	0.994	7.86	0.984	7.475	
3	17.87	17.85	0.882	17.74	0.650	17.859	0.897
4	22.31	22.30	0.694	22.19	0.873	21.975	
5	28.04	27.99	0.819				
6	35.48						

4.3 The impact of data processing method on the reliability of output-only tests

The low amplitude ambient vibration signals that were obtained with a shaker, and that succeeded to identify only one mode with the CMIF algorithm following RD, were processed again to further investigate the uncertainty associated with signal processing. Two different signal-processing approaches were investigated prior to employing the CMIF algorithm for modal parameter identification. CMIF method utilizes frequency response functions (FRFs) and FRFs may be obtained in two different ways following the random decrement process: (1) by exponential windowing and taking a Fourier transform of the time-domain signal, or (2) by modeling the signal using a signal modeling method (e.g. Prony’s method and estimate the FRFs from model parameters).

These two different approaches are referred to as parametric and nonparametric approaches (Fig. 15) for brevity. In the nonparametric method, the RD functions are windowed and FFT of RD datasets are taken to find FRFs. In the parametric approach, RD functions are modeled using Prony’s method and FRFs are derived from model coefficients.

The results shown in Table 4 were obtained by the nonparametric approach. The results given in Table 5 for the data collected under shaker excitation are from post-processing with the parametric approach. The results given in the last two Columns of Table 5 show that when signals are processed with the parametric method, the correlation between the impact and ambient vibration test results significantly improved and the first four modes could be identified.

It follows from the laboratory study presented above that the properties of input excitation should be regarded as the major parameter affecting the reliability of output-only dynamic test results. It is also evident that the post-processing technique may have a major impact on the results of output-only tests, while the impact of post-processing may be considerably less in the case of MIMO testing.

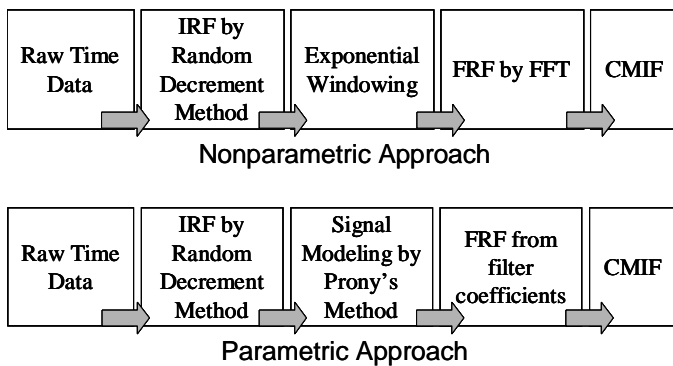


Figure 15. Nonparametric and parametric approaches for obtaining FRFs

Table 5. Comparison of impact and ambient vibration test results by parametric post-processing

Impact test results (CMIF)	Ambient test results						
	Random impacts on structure			Random lateral impacts on supports		Shaker input at base of structure	
Mode	Frequency (Hz)	Frequency (Hz)	Impact vs. ambient MAC	Frequency (Hz)	Impact vs. ambient MAC	Frequency (Hz)	Impact vs. ambient MAC
1	5.04	5.05	0.998			5.090	0.9806
2	7.81	7.80	0.994	7.86	0.984	7.849	0.9912
3	17.87	17.85	0.882	17.74	0.650	17.861	0.8839
4	22.31	22.30	0.694	22.19	0.873	22.327	0.8342
5	28.04	27.99	0.819			28.688	
6	35.48						

5 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Reliability of results from dynamic testing of constructed systems

The first objective of this paper was to evaluate the reliability of results from dynamic testing of constructed systems. Analysis of the reliability that can be expected of dynamic testing in the field is a complex systems problem. Reliability is strongly affected by the geometric and mechanical characteristics of the soil-foundation-structure system, the environmental conditions, the experiment and the data post-processing, the latter two including major contributions of human factors. The system and various sources of uncertainty affecting the system are summarized in Figure 16. The uncertainty includes both *epistemic* and *aleatory* types, as well as human *in-experience and errors* that may be regarded as a different class of uncertainty than epistemic or aleatory uncertainty.

The systems diagram shown in Figure 16 is based on defining dynamic testing of any system in the field as a system identification problem. Although some engineers may still approach dynamic testing of a constructed system in the context of only an experiment, without the analytical and heuristic experience that should accompany the experiment, it may be impossible to recover reliable information from a field test. The global relationship that should therefore govern the design of any field test to ensure success is illustrated in Figure 17. An integration of analytical and real worlds through the heuristics and experience of the observer is essential for a scientific approach to field research, known since Plato but since forgotten by many engineers. Reality can exist only for observable, repeatable and systemic phenomena, and without a complete integration of analytical conceptualization, experimental observation and measurement and the heuristics and experience of the observer we may not be able to consider the results of a dynamic testing of a complex constructed system as reality.

The dynamic test of a constructed system should therefore be executed with a careful evaluation of observability, repeatability and the system of interacting elements of the engineered structure, nature and human systems. Based on the writers' experience, there are significant limits to characterizing many constructed systems as observable, and field experiments as repeatable, unless controlled experiments and continuous long-term monitoring of a constructed system and its environment with a dense sensor array are properly integrated. If the non-stationary nature of constructed systems and their environment can be properly recognized, together with the many forms of non-linearity that affect their mechanical characteristics and behavior, *then it may be possible to smear these into meaningful analytical models.*

In general, aged constructed systems with material deterioration and with highly uncertain boundary and continuity conditions are difficult to measure and characterize in a repeatable manner by dynamic testing. The individual global frequencies, mode shapes and damping coefficients resulting from a MIMO dynamic test should not be assigned a confidence of greater than 75%-90% even under the most favorable conditions. In the case of output-only modal analysis of large systems, unless there are unusual sources of stationary wide-band excitation input, expecting a confidence that is greater than 60%-80% is not realistic. *In any case, whether*

all of the critical natural frequencies and modes within a bandwidth of interest are captured, or whether some coupled and/or highly damped modes are being missed, or whether some non-physical “numerical” modes are being mistakenly identified as fundamental modes, will be very difficult to determine without a system identification approach and without extensive experience.

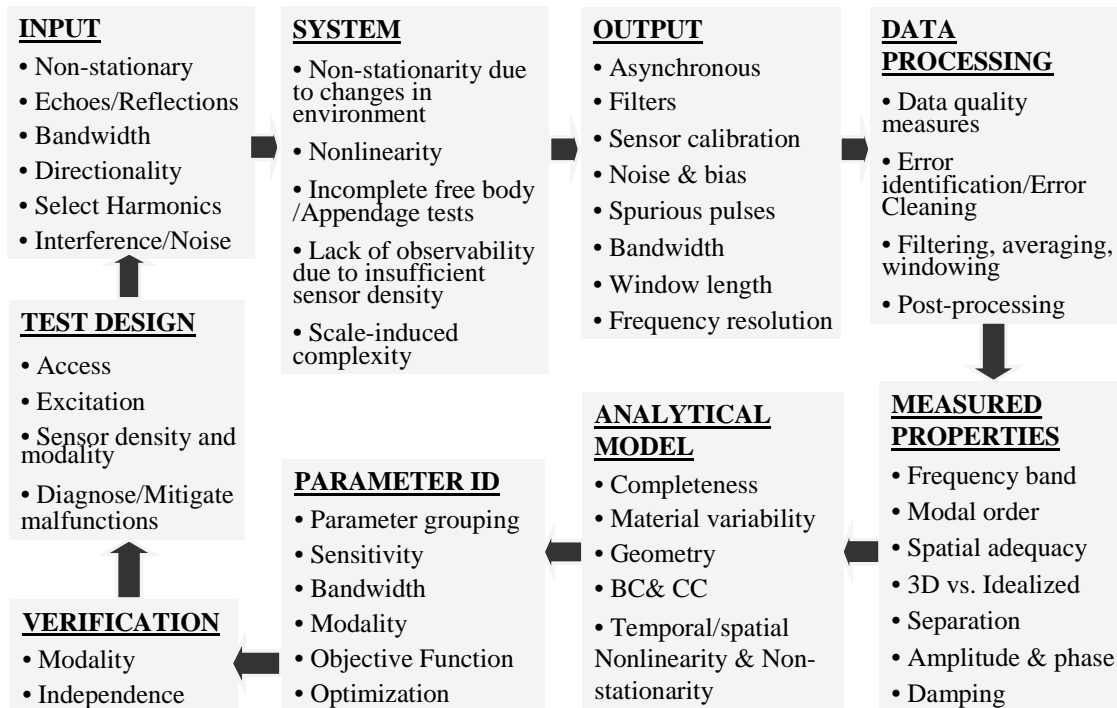


Figure 16. Errors and uncertainty impacting the reliability of dynamic tests

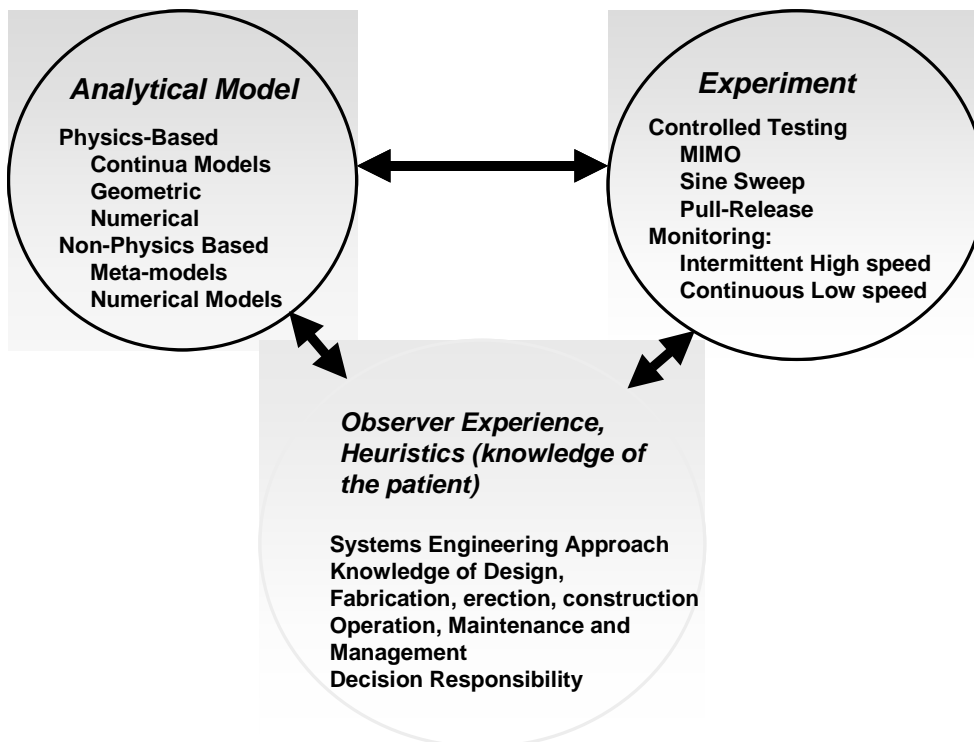


Figure 17. Global relationship showing interacting elements of successful field experiment

5.2 *Can we rely on dynamic testing for health monitoring of constructed systems?*

This is a question that has been asked by many researchers, and a large body of damage detection and diagnosis methods have been proposed based on vibration data, as briefly discussed earlier. Given the limits in the reliability of results from modal analysis, especially output-only modal analysis, it is difficult to answer this question affirmatively. At the same time, there is evidence that *modal flexibility* generated from a modal analysis with a sufficient bandwidth, offers the most stringent and best possible measure of the success and reliability of a modal analysis. It is very common to miss a critical mode due to modal coupling and/or high damping, and/or perhaps in addition to a lack of proper measurement, and it is also equally common to obtain numerical modes that do not really exist. It would be very difficult to recognize these errors unless one generates modal flexibility and uses this to simulate displacements under various virtual load patterns, and gage the reliability of modal analysis by a scrutiny of whether the simulated displacements are realistic.

Therefore, in spite of the lack of reliability under many circumstances, we should not give up on modal analysis as a health monitoring tool, especially when integrated with additional experimental tools. In certain cases, it is quite possible to execute a comprehensive MIMO test in conjunction with a controlled truck-load test, and generate a baseline modal flexibility for health monitoring. We may then envision many scenarios where the modal flexibility of a reduced number of coordinates may be obtained from a brief/practical MIMO or output-only test data processed by a pseudo-MIMO approach. These tests may serve for health monitoring as long as the limitations in reliability are understood, and the tests are executed by experts. Further, it is possible to envision MIMO dynamic tests of bridges to be carried out by FWD and similar high-impact devices, or with the presence of static loads due to stationary trucks. Such experiments may offer insight into the linearity of a structure and may serve as highly powerful tools for health monitoring.

However, given the examples in the paper and the analysis of the systems and factors affecting the reliability of dynamic testing presented earlier, *whether output-only modal analysis alone may serve for reliable health monitoring should be questioned*. The multitude of signal processing and patterning techniques proposed as health indicators from output-only vibration measurements should be evaluated based on real data as opposed to simulated data. The more perceptive researchers add noise to their simulated data to show that their algorithms work even with the presence of noise. The large bridge tests described in this paper indicate that there are too many potential error sources and many obvious as well as subtle kinds of error and uncertainty in *most* data measured in the field, and one should expect an extensive investment into data quality assurance and error mitigation before one may explore whether output-only measurements may serve for diagnosis of damage. Catbas and Aktan (2002) offered a detailed discussion of the issues governing the damage indices that have been proposed for constructed systems.

5.3 *Additional benefits in dynamic testing of constructed systems*

Given the above discussions regarding limitations in the reliability of results from dynamic testing of constructed systems, one would need to question whether there are other benefits to this experimental technology other than for health monitoring. We note that excessive vibration is a recurrent major reason why some constructed systems do not perform desirably at the serviceability limit states. Various flexible and long-span systems such as footbridges, convention center or shopping mall floors have been easily excited by human-induced inputs to objectionable levels. Some slender mid-rise steel building structures have been excited by wind, jamming their elevators. Highway bridges have been excited by trucks. Such vibration problems are not easy to mitigate without a clear understanding of the input excitation, properties of the system, and dynamic responses. Dynamic testing is therefore often necessitated for an effective and feasible solution of such vibration problems.

A more pressing concern that may benefit from dynamic testing of constructed systems relates to earthquake hazard mitigation. Constructed systems that are critical for emergency response, others that are vital for economic recovery following an emergency recovery, and, historic monuments are retrofit as we learn more about soil-foundation-structural behavior after

each new earthquake. Retrofit of bridge piers and the welded beam-column connections in steel buildings are two common weaknesses in systems constructed with the 1960's and 1970's codes. These vulnerabilities were discovered in 1989 following the Loma Prieta and in 1994 after the Northridge earthquakes, respectively. "Control" strategies and technologies, such as base isolation and various passive or hybrid damping devices have been developed and are being installed as retrofit as well as new construction.

Many constructed systems that are being retrofit can greatly benefit from dynamic testing for their identification to increase the reliability of analytical simulations needed for design of retrofit. However, this is not yet a practice. It is a fact that dynamic tests are carried out at low stress levels and a structure may change its response mechanisms at higher stress levels. However, if a structure is properly modeled in 3D by structural identification, the reliability of simulation at higher stress levels due to accurate and complete modeling of the critical mechanisms that affect the 3D kinematics of a structural system would also be considerably improved. It is anticipated that as dynamic testing becomes more reliable due to improvements in excitation, sensing and signal post-processing, and with the dissemination of research experiences, we should also be able to improve the practice of seismic vulnerability evaluation, retrofit design and monitoring.

5.4 Recommended best practices and future developments needed for reliable implementations of modal analysis of constructed systems

Modal analysis is one of the most challenging experimental technologies in mechanics that may be at the boundary of engineering and physics. A complete mastery of the fundamental theory of structural mechanics, followed by structural dynamics, with an adequate background in mathematics and numerical methods covering complex variables to multivariate statistics and signal processing, is desired. This should be followed by a complete mastery of experimental mechanics. Moving the technology from the laboratory to the field is another major step requiring considerable additional expertise. Given such a complex and demanding technology, with so many sources of inherent uncertainty (Fig. 16), it is recommended to approach it as an art-science and in a systemic manner. The integration of theory, numerical applications, physical model testing in the laboratory and field testing can only be accomplished within a multi-disciplinary graduate education and research curriculum. As importantly and as depicted in Figure 17, it is also critical to incorporate the heuristics related to the behavior of soil-foundation-constructed systems, and how various environmental inputs affect their forces and kinematics. These requirements for success indicate that experts from civil, mechanical and electrical engineers should be working together in a problem-focused and coordinated manner. This requires a significant investment into human resources and equipment for a university or government agency. The payoff in advancing civil engineering and infrastructures research and education is over a long-term, and for the society and the public without any great financial return for a university. Clearly, the championship of civic leaders, administrators and politicians are required for making such an investment.

In the last decade there have been great advances in sensing, communication, signal conditioning and computing technologies, and further advances are forthcoming. We anticipate that reliable wireless and intelligent multi-hopping sensor networks employing both conventional sensors as well as MEMS will soon become available. Robots employing wireless communication and control, and emulating biological organisms for movement are also becoming available. These technologies will facilitate overcoming some of the experimental challenges to reliable modal analysis of constructed systems. However, the main challenge remains in the complexity and size of phenomena that we are trying to conceptualize, observe, measure and model and data quality assurance. Therefore, while we should welcome such advances in technology, these should not be at the expense of fundamental, problem focused research on large systems with intersecting and interacting natural, human and engineered elements. Agencies that fund research and education in the US, and many university administrators interested in quick returns on investment have been promoting technology-push as opposed to fundamental investigations into the science of infrastructure engineering. The lack of appreciation for the investment needed for multi-disciplinary research and education that are essential for advancing large infrastructure systems and performance problem may be a time bomb for the civilized world. Investment into long-term public interest payoff research and education is needed.

The physical model of a constructed system subassembly that has been described in this paper is a useful vehicle for a systematic investigation of the impacts of various mechanisms of error and uncertainty on the results of dynamic testing. The writers are inviting their colleagues for an international study of how to improve the reliability of results in dynamic testing of constructed systems so that this technology may serve for health monitoring. A proposal will be formulated to various funding agencies in the US and elsewhere for this purpose.

5.5 *Specific recommendations for best practices*

- Measurement grid: Select spatial distribution carefully to capture 3D behavior, including free-field, foundations and supports. If testing only a subassembly of a large structure, measure responses at the boundaries and at several other locations away from the test subassembly.
- Bandwidth: Match bandwidth of the input, the critical bandwidth of the structure and the optimal bandwidth of *the experimental system and the captured data*. In general the very low end (lower than 0.5 Hz) of the frequency band is difficult to capture accurately due to many bias errors and the low energy that are common for this part of the bandwidth. Do not collect data at less than 100 Hz so that high-frequency data errors may be better characterized.
- Input: Evaluate the input(s), stationarity, coupling of the input with time and environmental conditions and take many windows of data, including a measurement of the input. Use digital video records, and a weather station. There are various ways of augmenting input by impacts, by ground tremors, construction activity, etc. but these require their proper capturing and documentation.
- Data collection errors and malfunctions: It is preferable to collect data in time-domain without any filters. If set-ups have to change, keep sufficient number of stationary reference channels. Prepare and have ready quality-control measures. Statistical measures such as kurtosis may be useful. Bias errors such as drift, high frequency spikes, momentary data loss, etc. due to cable/connection malfunctions, power problems, electro-magnetic pulses, various types of microwave/radio/cellular interferences, etc. are *inevitable*. Therefore, data should not be taken blindly, a continuous check of data and correction of any recurrent problems with any data channels is critical during the experiment.
- Picking and eliminating data errors, and data quality assessment: A hierarchical strategy is needed related to manual cleaning, filters, windows, averages, ARMA pre-processing, etc.
- Peak picking, auto and cross-correlation functions should be fully leveraged for understanding the physics of the structure, inputs and responses, especially excitation sources and transmissibility.
- More sophisticated algorithms: Random decrement and Pseudo-MIMO are useful only after understanding the physics of excitation sources and structural responses. Be careful with damping and trying to use algorithms that assume complex mathematical characterizations of damping. In many cases, such algorithms may lead to numerical modes but may miss critical real modes. Damping mechanisms of actual constructed systems are highly complex, but uncertainty in field testing does not permit mathematically advanced characterizations of damping. Instead, many sophisticated algorithms may commonly misinterpret the non-stationarity of system mechanical properties as high damping.
- Completeness checks: Analytical simulation and testing of whether the results of modal analysis conform or violate physics is essential. Experience and taking advantage of heuristics are important for this reason. Transform modal analysis results to geometric space, for example, to flexibility and displacement fields, in order to test physics. *In general one would capture many spurious modes and some critical real modes will be missed*. If there is a separate controlled test of flexibility such as a controlled load test this would offer the most stringent quality check.

6 ACKNOWLEDGEMENTS

The authors deeply appreciate the invitation extended by the organizers and Scientific Committee of EVACES for this keynote paper. They gratefully acknowledge the championship of Dr. Steven Chase and Dr. Hamid Ghasemi of FHWA, Dr. Steven McCabe and Dr. Ken Chong of

NSF, Messer's Gary Hoffman and Scott Christie of Pennsylvania Department of Transportation, and Mr. Daniel Faust of the Delaware River Port Authority of PA and NJ for their support of multi-disciplinary fundamental research on constructed systems and infrastructures in the field. They also gratefully acknowledge the support and encouragement that has been extended to infrastructure systems research by Dr. Constantine Papadakis, civil engineer and President of Drexel University. Ambient monitoring tests of the Henry Hudson and Brooklyn Bridges were conducted under the guidance and leadership of Dr. Arzoumanides, Parsons TG of NY. The confidence extended by Parsons TG of NY, and the support extended by the NY City MTA and the NT City DOT, are gratefully acknowledged. Multi-disciplinary collaboration on complex societal problems may occur through serendipity, but universities and government agencies cannot afford not to take full advantage of policy and strategies to systematically promote and foster multi-disciplinary interactions and scientific explorations in the field. Forward-thinking champions of multi-disciplinary research and education on infrastructures are highly critical for solving our societal problems related to infrastructures that may soon become crises. Renaissance civil engineers have to lead multi-disciplinary teams for advancing effective and safe operation, preservation and protection of infrastructures and their lifecycle management by adapting systems engineering principles in conjunction with field research on actual systems.

REFERENCES

- Aksel, T., Lee, K. L. & Aktan, A. E. (1994). Condition assessment of highway bridges. *Proc. of the ASCE Structures Congress XII*, Atlanta, GA. 1124-1130.
- Aktan, A. E., Naghavi, R. & et al. (1995) Nondestructive/destructive tests and associated studies on two decommissioned steel truss bridges. *Final Report, FHWA/OH-95/013*.
- Aktan, A.E., Helmicki, A. J. & et al. (1997) Structural identification for condition assessment of civil infrastructure. *Proc. Of the American Control Conference*. Albuquerque, NM.
- Aktan, A. E., Farhey, D. N, & et al. (1997). Structural identification for condition assessment: experimental arts. *Journal of Structural Engineering, ASCE*, 123(12): 1674-1685.
- Aktan, A. E. & Faust, D. (2003). A holistic integrated systems approach to assure the mobility, efficiency, safety and integrity of highway transportation. Invited Keynote Paper, *First International Conference on Structural Health Monitoring and Intelligence Infrastructure (SHMII-1'2003)*, Tokyo, Japan.
- Al-Khalidy, A., Noori, M. & et al. (1997). Health monitoring systems of linear structures using wavelet analysis. *Proc. of the International Workshop on Structural Health Monitoring*, Stanford University, Palo Alto, CA. 164-175
- Andersen, P. (1997). Identification of civil engineering structures using vector ARMA model. *PhD thesis*, Aalborg University, Belgium.
- Andersen, P. & Kirkegaard, P. H. (1998). Statistical damage detection of civil engineering structures using ARMAV models. *Proc. Of the 16th International Modal Analysis Conference (IMAC)*, Santa Barbara, CA. 356-362
- Bodeux, J. B. & Golinval, J. C. (2001). Application of ARMAV models to identification and damage detection of mechanical and civil engineering structures. *Smart Materials and Structures*, 10: 479-489.
- Bollo, M., Mahin, S., Moehle, J. & Stephen, R. Observations and Implications of Tests on the Cypress Street Viaduct Test Structure, *Report No. UCB/EERC-90/21*, College of Engineering, University of California at Berkeley, December 1990.
- Brincker, R. Frandsen, J. B. & Andersen, P. (2000). Ambient response analysis of the Great Belt Bridge. *Proc. Of the International Modal Analysis Conference (IMAC)*, San Antonio, TX. 26-32.
- Brownjohn, J. M. W., Chandu, R. & et al. (1986). Ambient vibration testing on the Humber Suspension Bridge. *Proc of 8th European Conference on Earthquake Engineering*, Lab. Nacional de Fngenharia Civil, Vol.4: 89-96.
- Buckle, I. G., Dickson, A. R. & Phillips, M. H. (1985). Ultimate strength of three reinforced concrete highway bridges. *Canadian Journal of Civil Engineering*, 12(1): 63-72.
- Catbas, F. N., Lenett, M., Aktan, A. E., Brown, D. L., Helmicki, A. J. & Hunt, V. (1998). Damage detection and condition assessment of Seymour bridge. *Proc. Of 16th International Modal Analysis Conference (IMAC)*, Santa Barbara, CA. 1694-1702.
- Catbas, F. N., Grimmelmsan, K. A. & Aktan, A. E. (2000). Structural identification of the Commodore Barry Bridge. *Proc. Of SPIE – Nondestructive Evaluation of Highways, Utilities and Pipelines IV*, Newport Beach, CA. 84-97.

- Catbas, F. N. & Aktan, A. E. (2002). Condition and Damage Assessment: Issues and Some Promising Indices. *Journal of Structural Engineering, ASCE*, 128(8): 1026-1036.
- Catbas, F. N., Brown, D. L. & Aktan, A. E. (2004). Parameter estimation for multiple-input multiple-output modal analysis of large structures. *Journal of Engineering Mechanics, ASCE*, 130(8): 921-930.
- Catbas, F.N., Brown, D.L. & Aktan, A. E. (2005). Use of Modal Flexibility for Damage Detection and Condition Assessment. *Journal of Structural Engineering, ASCE*, in press.
- Chang, C. C., Chang, T. Y. P., Xu, Y. G. & Wang, M. L. (2000). Structural damage detection using an iterative neural network. *Journal of Intelligent Material Systems and Structures*, 11(1): 32-42.
- Chang, C. C., Chang, T. Y. P. & Zhang, Q. W. (2001). Ambient vibration of long-span cable-stayed bridge. *Journal of Bridge Engineering, ASCE*, 6(1): 46-53.
- Clough, R. W. & Bertero, V. V. (1977). Laboratory model testing for earthquake loading. *Journal of Engineering Mechanics Division, ASCE*, 103(6): 1105-1124.
- De Barros, F. C. P. & Luco, J. E. (1995). Identification of foundation impedance functions and soil properties from vibration tests of the Hualien containment model. *Soil Dynamics and Earthquake Engineering*, 14(4): 229.
- Doebbling, S. W., Farrar, C. R., Prime, M. B. & Shevitz, D. W. (1996). Damage identification literature review. *Los Alamos National Laboratory Report LA-13070-MS*, 1996
- Eberhard, M.O., Marsh, M.L., O'Donovan, T.O. & Hjartarsson, G. (1993). Lateral-Load Tests of a Reinforced Concrete Bridge. *Transportation Research Record*, No. 1371: 92-100.
- Eberhard, M.O. & Marsh, M.L. (1997). Transverse-Load Response of Two Reinforced Concrete Bents. *Journal of Structural Engineering, ASCE*, 123(4): 461-468.
- Eberhard, M.O. & Marsh, M.L. (1997). Transverse-Load Response of a Reinforced Concrete Bridge. *Journal of Structural Engineering, ASCE*, 123(4): 451-460.
- Farrar, C. R. & Jauregui, D. A. (1998). Comparative study of damage identification algorithms applied to a bridge: I. Experiment. *Smart Materials and Structures*, 7(5): 704-719.
- Fujino, Y., Abe, M. & et al. (2000). "Forced and ambient vibration tests and vibration monitoring of Hakucho suspension bridge." *Transportation Research Record*, 5th International Bridge Engineering Conference, Tampa, FL. Vol. 2: 57-63
- Galambos, T. V. & Mayes, R. L. (1978) Dynamic tests of a reinforced concrete building. *Research Report No. 51*, School of Engineering and Applied Science, Department of Civil Engineering, Washington University.
- Gilani, A. S., Mahin, S. A. & et al. (1995) Field testing of bridge design and retrofit concepts: Part 1 of 2: Field testing and dynamic analysis of a four-span seismically isolated viaduct in Walnut Creek, California. *UCB/EERC-95/14*.
- Gulkan, P. & Sozen, Mete A. (1977). Inelastic response of reinforced concrete structures to earthquake motions. *Publication SP American Concrete Institute SP -53, Symposium on Reinforced Concrete Structures in Seismic Zones*. 109-115.
- Gundy, W. E., Howard, G. E. & et al. High Level Seismic Test Using Shaker and Snapback Methods on a Hot Plant. *Transactions of the International Conference on Structural Mechanics in Reactor Technology*, 1981, 8p
- Gurley, K. & Kareem, A. (1999). Applications of wavelet transform in earthquake, wind and ocean engineering. *Engineering Structures*, 21(2): 149-167.
- Halling, M. W., Muhammad, I. & Womack, K. C. (2001). Dynamic field testing for condition assessment of bridge bents. *Journal of Structural Engineering, ASCE*, 127(2): 161-167.
- Hosahalli, Somaprasad. R. & Aktan, A. E. (1994). Seismic vulnerability of flat slab-core buildings. *Journal of Structural Engineering, ASCE*, 120(2): 339-359.
- Hou, Z.K. Noori, M., & St. Amand, R. (2000). Wavelet-Based approach for structural damage detection. *Journal of Engineering Mechanics, ASCE*, 126(7): 677-683.
- Hudson, D. E. (1964). Resonance testing of full scale structures. *Journal of the Engineering Mechanics Division, ASCE*, 90(EM3): 3923.
- Huang, N. E. & et al. (1998). The Empirical Mode Decomposition and the Hilbert Spectrum for Non-linear and Non-stationary Time Series Analysis. *Proc. Royal Society*, 454: 903-995.
- Ibanez, P., Spencer, R. B. & Smith, C. B. (1973). Forced vibration test on electrical distribution equipment. *Nuclear Engineering and Design*, 25(1): 94-111
- Ibrahim, S. R., Asmussen, J. G. & Brincker, R. (1998). Vector triggering random decrement for high identification accuracy. *Journal of Vibration and Acoustics, ASME*, 120(4):970-975.
- Iwasaki, T., Penzien, J. & Clough, R. (1972) Literature survey - Seismic effects on highway bridges. *EERC report 72-11*, University of California, Berkeley.
- Jauregui, D. V. & Farrar, C. R. (1996). Assessment of damage identification algorithms on experimental and numerical bridge data. *Proc of the 14th Structures Congress*, Chicago, IL. 892-899,

- Kaito, K., Abe, M. & Fujino, Y. (2001). An experimental modal analysis for RC bridge decks based on non-contact vibration measurement. *Proc. of the International Modal Analysis Conference (IMAC)*, Kissimmee, FL. 1561-1567
- Kashima, S., Yanaka, Y., Suzuki, S. & Mori, K. (2001). Monitoring the Akashi Kaikyo Bridge: first experiences. *Structural engineering International Journal of the International Assn. for Bridge and structural Engineering (IABSE)*, 11(2): 120-123.
- Kim, H. M. & Bartkowicz, T. J. (1993). Damage detection and health monitoring of large space structures. *Sound and vibration*, 27(6): 12-17.
- Kuribayashi, E. & Iwasaki, T. (1973) Dynamic properties of highway bridges. *Proceedings of the 5th World Conference on Earthquake Engineering*, Rome, Italy. pp938-941.
- Kwong, H. S., Lau, C. K. & Wong, K. Y. (1995). Monitoring system for Tsing Ma Bridge. *Proc. of the 13th Structures Congress*, Boston, MA. Vol.1: 264-267.
- Lenett, M., Catbas, N., & et al. (1997). Issues in multi-reference impact testing of steel-stringer bridges. *Proc. of the 15th International Modal Analysis Conference (IMAC)*, Orlando, FL. 374-380
- Leuridan, J. M., Brown, D. L. & Allemang, R. J. (1986). Time domain parameter identification methods for linear modal analysis: a unifying approach. *Journal of vibration, Acoustics, Stress, and Reliability in Design*, 108(1): 1-8
- Luco, J. E. Wong, H. L. & Trifunac, M. D. (1986). Soil-structure interaction effects on forced vibration tests. *Department of Civil Engineering, Rep. No. 86-05*, University of Southern California, Los Angeles, CA.
- Masri, S. F., Nakamura, M. & et al. (1996). Neural network approach to detection of changes in structural parameters. *Journal of Engineering Mechanics*, ASCE, 122(4): 350-360.
- Mazurek, D. F. & Dewolf, J. T. (1990). Experimental study of bridge monitoring techniques. *Journal of Structural Engineering*, ASCE, 116(9): 2532-2549.
- Miller, R., Aktan, A. E. & Shahrooz, B. M (1994) Destructive testing of a decommissioned concrete slab bridge. *Journal of Structural Engineering*, ASCE, 120(7): 2176-2198.
- Nakamura, M., Masri, S. F. & et al. (1998). A Method for nonparametric damage detection through the use of neural networks. *Earthquake Engineering and Structural Dynamics*, 27: 997-1010
- Nigbor, R., Cakmak, A. & Mark, R. (1992). Measured to the max. *Civil Engineering*, 62(11): 44-47.
- Raghavendrachar, M. & Aktan, A. E. (1992). Flexibility by multireference impact testing for bridge diagnostics. *Journal of Structural Engineering*, ASCE, 118(8): 2186-2203.
- Rubin, S. & Coppelino, R. N. (1986). Sensitivity of flexibility monitoring of offshore jacket platforms. *Journal of Energy Resources Technology, Transactions of the ASME*, 108(1): 72-76.
- Saiidi, M. & Douglas, B. M. (1984) Effect of design seismic loads on highway bridge. *Journal of Structural Engineering*, ASCE, 110(11): 2723-2737.
- Salane, H. J. & Baldwin, J. W. (1990). Identification of modal properties of bridges. *Journal of Structural Engineering*, ASCE, 16(7): 2008-2021.
- Samman, M. M. & Biswas, M. (1994). Vibration testing for nondestructive evaluation of bridges. I: Results. *Journal of Structural Engineering*, ASCE, 120(1): 290-306.
- Shepard, R. & Charleson A. W. (1971) Experimental determination of the dynamic properties of a bridge substructure. *Bulletin on the Seismological Society of America*, 61: 1529-1548.
- Shepard, R. & Sidwell, G. K. (1973) Investigations of the dynamic properties of five concrete bridges. *Fourth Australian Conference on the Mechanics of Structures and Materials*, University of Queensland, Brisbane. 261-268.
- Sohn, H., & Law, K.H. (1997). A Bayesian probabilistic approach for structure damage detection. *Earthquake Engineering and Structure Dynamics*, 26: 1259-1281
- Sohn, H., Czarnecki, J.A., & Farrar, C.R. (2000). Structural health monitoring using statistical process control. *Journal of Structural Engineering*, ASCE, 126(11): 1356-1363.
- Sohn, H., Farrar, C.R. & et al. (2001a). Structural health monitoring using statistical pattern recognition techniques. *Journal of Dynamic Systems Measurement and Control*, ASME, 23(4): 706-711.
- Sohn, H., Farrar, C.R. & et al. (2002). A Review of structural health monitoring literature: 1996-2001. *Los Alamos National Laboratory Report*.
- Stephen, R. M., Hollings, J. P. & Bouwkamp, J. G. (1974). Dynamic Behavior of a Multistory Pyramid-Shaped Building, *UC Berkeley EERC Report No. 73-17*.
- Stubbs, N., Broome, T. H. & Osegueda, R.(1990). Nondestructive construction error detection in large space structures. *AIAA Journal*, 28(1): 146-152.
- Sun Z. & Chang, C.C. (2002). Structural damage assessment based on wavelet packet transforms. *Journal of Structural Engineering*, ASCE, 128(10): 1354-1361.
- Toksoy, T. & Aktan, A.E. (1994). Bridge Condition Assessment By Modal Flexibility. *Experimental Mechanics, Journal of SEM*, 34(3): 271-278.
- Vanik, M.W., Beck, J. L. & Au, S.K. (2000). Bayesian probabilistic approach to structural health monitoring. *Journal of Engineering Mechanics*, ASCE, 126(7): 738-745.

- Wahab, M. M. A. & De Roeck, G. (1998). Dynamic testing of prestressed concrete bridges and numerical verification. *Journal of Bridge Engineering, ASCE*, 3(4): 159-169.
- Wenzel, H. & Pichler, D. (2005). *Ambient Vibration Monitoring*. New York: John Wiley & Sons, Ltd
- Wong, K. Y., Chan, W.Y.K. and et al. (2000). Structural health monitoring results on Tsing Ma, Kap Shui Mun and Ting Kau bridges. *Proc. Of SPIE – Nondestructive Evaluation of Highways, Utilities and Pipelines IV*, Newport Beach, CA. Vol. 3995: 288-299.
- Yang, J. N., Lei Y. & Huang, N. E. (2001). Damage identification of Civil Engineering Structures using Hilbert-Huang Transform. *Proc. Of the 3rd International Workshop on Structural Health Monitoring*, Stanford University, Palo Alto, CA. 544-553.
- Zapico, J. L., Gonzalez, M. P. & Worden, K. (2003). Damage assessment using neural networks. *Mechanical Systems and Signal Processing*, 17(1): 119-125.