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SOFTWARE IN FIELD DATA ANALYSIS ON A BRIDGE

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Abstract

Structural Health Monitoring (SHM) has been adopted as a technique to monitor the characterization of structural performance to detect damage in infrastructure. In the last decade, vibration-based analysis has evolved as a promising method for SHM. Fast Fourier Transform (FFT) has gained popularity as an efficient means of data processing in SHM systems. This paper presents a data processing program (DPP) and a dynamic analysis program (DAG) for the in-situ monitoring of civil infrastructure. DPP is implemented in LabView with 6 functions: Average, Temperature Shift Elimination, FFT, Filters, Data Extraction, and Data File Splitter functions. The DAG program uses the harmonic method to analyze the effect of girders due to trucks moving across a bridge. The combination of two programs makes it possible to create a simple diagnostics system to assess structural health condition. The validity of this system has been successfully demonstrated in the field monitoring of the Lindquist Bridge in British Columbia, Canada. However, it should be noted that complex environmental factors make damage detection of civil infrastructure a very challenging proposition.

INTRODUCTION

A complete SHM system involves many integrated components and degrees of sophistication in data analysis and damage detection [1], mainly including: a sensor system, a data acquisition system, a data processing system, a communication system and a damage detection and modeling system. From this point of view, the SHM system is an interdisciplinary field, involving civil, mechanical, electrical and computer engineering, which provides the information necessary to achieve a reliable and durable SHM, or civionics system. [2, 3]

A Data processing system (DPS) plays an important role in a SHM system. An effective DPS approach is expected to extract essential yet concise characteristics from acquired raw signal and assist the decision-making unit in conducting a diagnosis or prognosis. The monitoring of infrastructure in the field presents several challenges that, although easily controlled in the laboratory, cannot be controlled in the field. In the field, a SHM system has to contend with non-structural components, which include adverse environmental conditions and high frequency electrical or mechanical noises that adversely affect the readings by the monitoring equipment. Therefore, the data processing of in-situ bridges is another major challenge for SHM engineers..

This paper presents a data processing program (DPP) and dynamic analysis of girder (DAG) for in-situ bridge monitoring. The objective of DPP is to provide structural engineers with basic mathematical data analysis tools for data interpretation in SHM. DAG aims at analyzing bridge girder response due to moving vehicles. Validation of the DPP and DAG programs was achieved during the monitoring of the Lindquist Bridge.

PROPOSED DPP AND DAG

Background

Vibration-based analysis has evolved as a promising method for SHM. The premise of vibration-based SHM is that damage will significantly alter the normal measured dynamic response through changes in stiffness, mass or energy dissipation because the dynamics of a structure are a function of its mechanical properties. Thus changes in these mechanical properties as a result of localized structural damage will result in observable changes in the dynamic characteristics of the structure. Research on vibration-based damage identification goes back to the late 1970s in the study of offshore oil and gas platforms as well as in the aerospace industry. The civil engineering industry became interested in vibration-based research, influenced in large part by the increased rate of infrastructure deterioration observed late in the 20th century. In the last decade, most of the previous efforts were directed towards performing modal analysis in the frequency domain using Fast Fourier Transform (FFT) [1, 4, 5].

Vibration characteristics of a structure, the frequencies, mode shapes, and damping, are directly affected by the physical characteristics of the structure including its mass and stiffness. However, in practice, there are a number of limitations associated with vibration-based damage assessment, for example, low sensitivity to damage, incomplete nature of the measured vibration characteristics, complexity of the damage identification algorithms and effect of factors other than damage. Extensive research has been carried out in the past couple of decades on the development of analytical techniques for vibration-based damage detection. A number of different analytical techniques have been developed for the identification of damage from detected changes in vibration properties. The following is a list of the various techniques proposed. The list is not exhaustive but covers most of the methods that have been explored in some detail: 1) methods based on frequency changes; 2) methods based on mode shape changes; 3) mode shape curvature method; 4) methods based on change in flexibility matrix; 5) methods based on changes in uniform flexibility shape curvature; 6) Damage index method; 7) Matrix update methods and 9) Neural network methods [6]. As modal analysis is performed in the frequency domain, most current SHM systems implement FFT. There are several detailed reviews of FFT methodology for SHM, which has resulted in a growing amount of literature in the field [4, 7, 8]. FFT has been used for many years as a reliable tool in signal analysis and has proven incredibly versatile in applications ranging from structural dynamics analysis to image processing.

Proposed system

From a practical point of view, the validation of the SHM system relies on the efficient detection of an abnormal event and the delivery of an event message concurrently to the supervisors. Besides using an intelligent algorithm to extract the event-related data, the following shows a very simple method, which is based on the comparison between the in-situ readings from a set of pre-determined sensors located at key points in the monitored structure and the corresponding theoretical value. Whenever the measured data exceeds a pre-defined threshold based on the theoretical values, damage happens and an event message will be sent out in real-time.

According to the functional and operational requirements, a simplified SHM diagnostics system is applied for simply-supported bridges (Figure 1). The system can be divided into four steps: 1) Data Processing, using DPP to deal with the acquired raw data; 2) Modal Parameters, calculating appropriate parameters from the processed data (for example, vehicle speed, vehicle load and distribution factor); 3) Modal analysis, running DAG to theoretically calculate strains and frequencies of the bridge under the same condition; 4) Matching Criteria, comparing the theoretical results and the field data to checking the health condition.

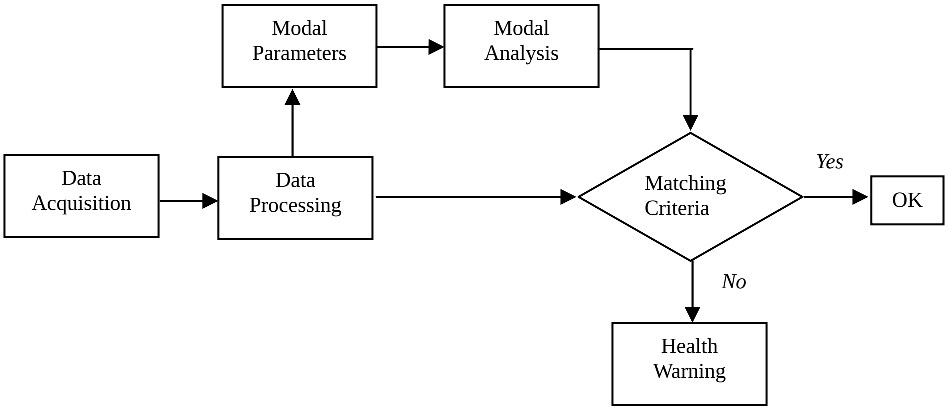

Figure 1. The flowchart for the simplified SHM diagnostics system.

DPP program

The Data Processing Program is implemented in LabView and includes 6 functions: Average, Temperature Shift Elimination, FFT, Filters, Data Extraction, and Data File Splitter. The user interface is shown in Figure 2.

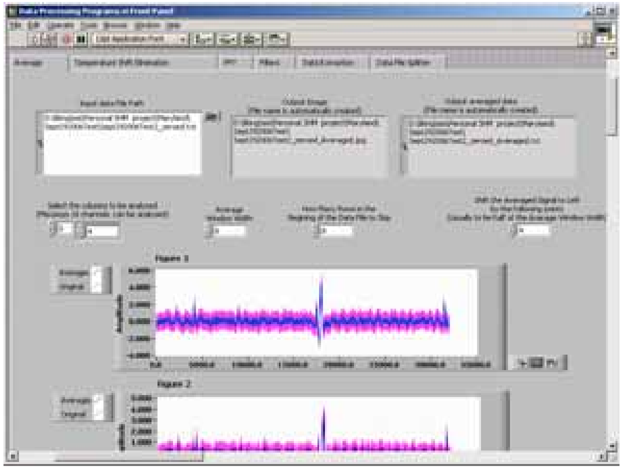

Figure 2. User interface of Data Processing Program.

Average function is designed for noise reduction. External electric and/or magnetic fields often interfere with the signals from different kinds of electrical sensors. When long reaches of multiple conductors (wires) are run adjacent to each other, problems with crosstalk between conductors can be encountered, which can superimpose noise on the measurement signals. Virtually every electrical device which generates, consumes, or transmits power is a potential source for causing noise. A moving average is introduced generally for low frequency noise. The average window length should be properly selected to avoid losing dynamic information.

Filters are designed to eliminate the interfering signal including the noise with a specific center frequency and bandwidth. Four types of filters are available (shown in Figure 3). They are Low-pass, High-pass, Band-pass, and Band-stop. A Low-pass filter is a filter that passes low frequencies well, but attenuates frequencies higher than the cutoff frequency. It is sometimes called a high-cut filter. A High-pass filter is the opposite, and a Band-pass and Band-stop filter is a combination of High-pass and Low-pass. Band-pass passes frequencies between the low cutoff frequency (f_l) and the high cutoff frequency (f_h) well, but attenuates frequencies lower than the f_l and higher than f_h. A Band-stop filter is the opposite. To run the Low-pass and High-pass filters, a user inputs the cutoff frequency f_c and sampling rate f_s. To run the Band-pass and Band-stop filters, a user inputs the low cutoff frequency f_l, high cutoff frequency f_h and sampling rate f_s.

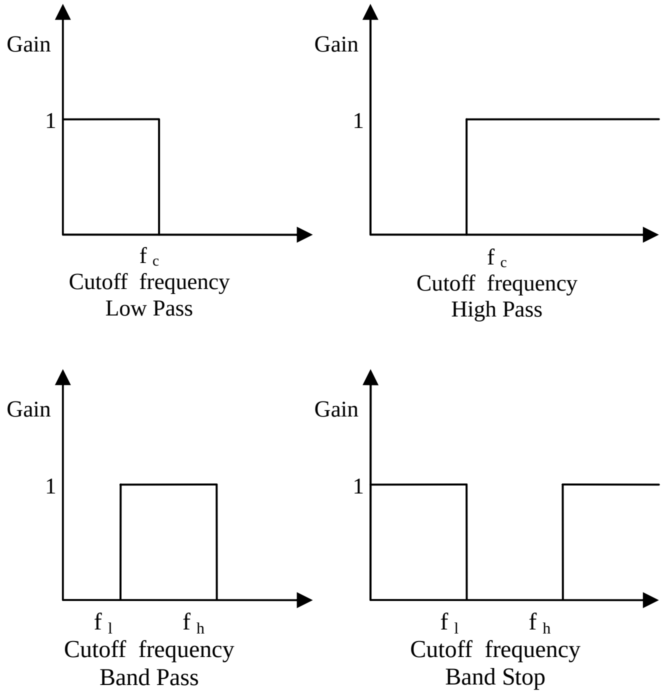

Figure 3. Four types of filters: Low-pass, High-pass, Band-pass and Band-stop.

Temperature Shift Elimination is designed to remove the temperature induced strain in a short time period (hours, days). It takes two steps: first, extract the trend of temperature induced strain by averaging the original signal upon a fairly large number of points, which covers at least a 1-minute period. The averaged signal contains only the static strain trend due to the temperature. Secondly, subtract the temperature induced strain from the original signal. This function can also be applied to subtract the strain shifting due to the DAQ system warm up in the very beginning of the testing.

FFT (Fast Fourier Transform) is applied to a time-series signal to evaluate the power density distribution against the frequency domain. FFT is very often used to analyze the natural frequency of a structure. This method is used to convert accelerometer readings to the frequency domain to provide a meaningful view of frequency response. The natural frequency of a structure is the frequency at which a structure having a specific stiffness vibrates when a specific mass (including self-mass) is applied to it. The natural frequency information is of interest to engineers for a variety of reasons; but in the context of SHM, it is of interest because changes in the vibration characteristics of a structure can in some cases provide an indication of structural damage or deterioration.

Data Extraction function is used to extract a set of data that is contained with the strain readings over a defined threshold. The strain readings are only removed if they are below the threshold and occur for a length of time specified by the user. This data extraction function is simple and fairly efficient to reduce the non-significant sensing data.

Data File Splitter, as the name implies, is to divide a fairly large data file into a set of smaller files, which can be viewed and analyzed by Excel. Excel is a basic tool for civil engineers to quickly view the data and conduct simple calculations. However, the maximum rows which can be loaded to the Excel are limited. Using data file splitter, a user defines the number of rows in each split file, which is then saved into the same directory as the original file.

DAG program

Vibration data for SHM has been processed according to a system identification requirement, the aim being to obtain the modal characteristics and track changes. Here, DAG utilizes the harmonic method to analyze the dynamical response of the bridge under investigation based on the linear behavior. Some input parameters are required to choose from the processed data. Typically, these include vehicle speed, vehicle load, and distribution factor. A dynamic analysis is then performed to produce details of the strains on the counterpart sections with a mounted sensor system and the corresponding natural frequencies of the structure.

Criteria that can be used as a measure of how well the predicted response matches its observed counterparts would include how closely predicted modal frequencies correspond to observed frequencies and corresponding associated strains. However, because of the indeterminate nature of civil engineering structures' and variable support conditions, analysis modals need to be updated continuously to suit specific functions and requirements.

IMPLEMENTATION

In order to verify the DPP and DAG, field data from the Lindquist Bridge was analyzed.

Bridge Description: The Lindquist Bridge, located on the Darlington Main logging road west of Darfield, BC, is a single 23.1 m span intended to carry logging traffic. It consists of a steel free concrete deck supported on two steel girders. (Figure 4a and Figure 4b)

Figure 4a. Overview of the Lindquist Bridge.

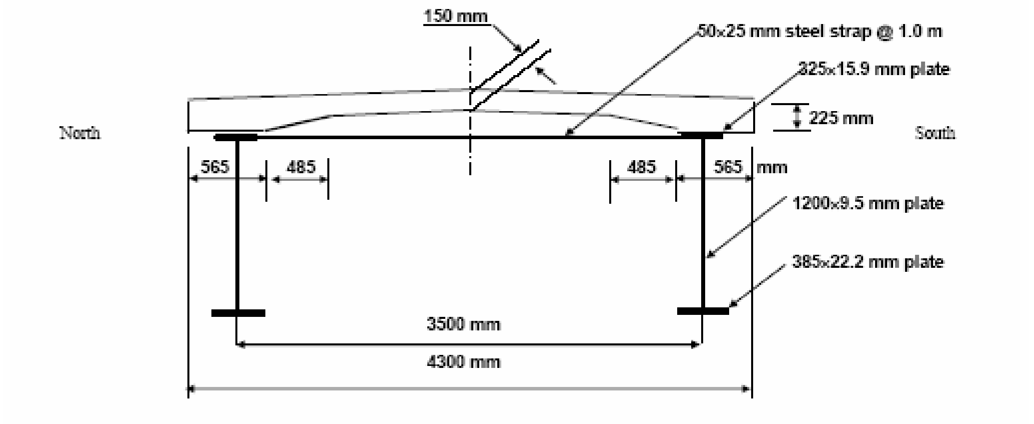

Figure 4b. Cross-section of the Lindquist Bridge.

Sensor system: The orientation of the Lindquist Bridge is roughly east-west. Both girders were instrumented at four sections identified in Figure 5 as A-A, B-B, C-C and D-D. A total of seven electrical resistance strain gauges were installed on the girders and two on the transverse straps. One of the strain gauges on the girders was used for compensating the effects of temperature drift.

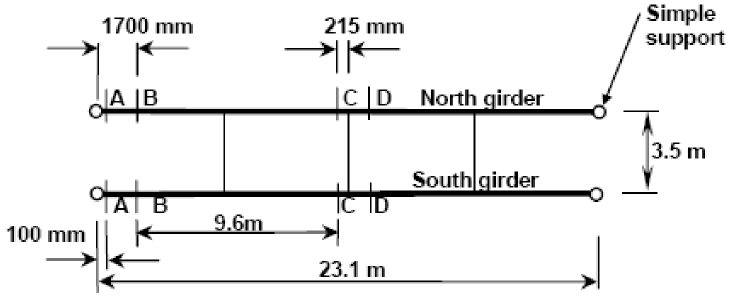

Figure 5. Instrumented girder sections.

Test load: The Lindquist Bridge was tested under two 5-axle vehicles, Truck 1 and Truck 2, illustrated in Figure 6 and Figure 7, respectively. Truck 1 had a gross weight of 437.91 kN, with a wheelbase of 14.17 m, and was traveling at fast speed; Truck 2 had a gross weight of 438.50 kN and wheelbase of 14.17 m, and was traveling at a very slow to medium speed.

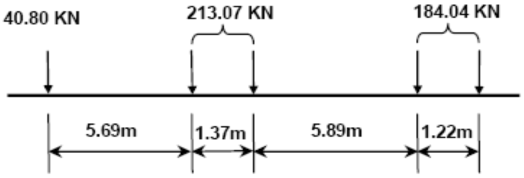

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Figure 6. Inter-axle spacing and weights of Truck 1.

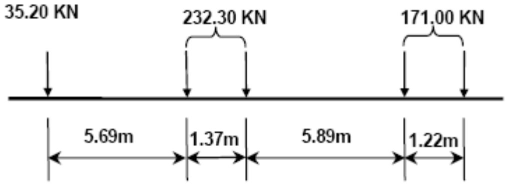

Figure 7. Inter-axle spacing and weights of Truck 2.

Data acquisition: Data from all the sensors were collected at a sampling rate of 128 readings per second, except the data in the crawl speed test which were recorded at 32 readings per second.

Data processing: In order to obtain cleansed data for further interpretation, the raw data was processed by DPP. A sample Filters and FFT analysis is displayed in Figure 8 and Figure 9, respectively. It shows that the bridge has a natural vibration frequency of 5.6 Hz. Any significant change in this frequency response, which may indicate damage, can be observed immediately.

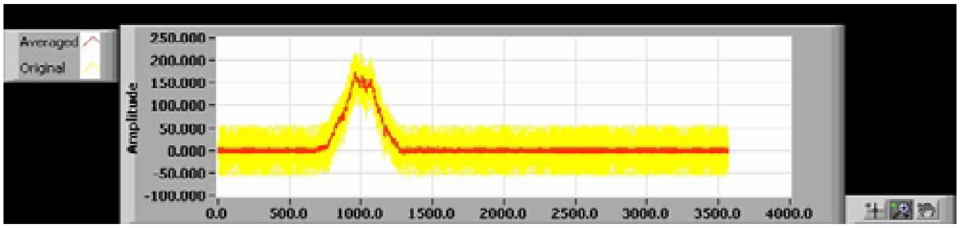

Figure 8. Data after running ‘Filter’ function on raw data.

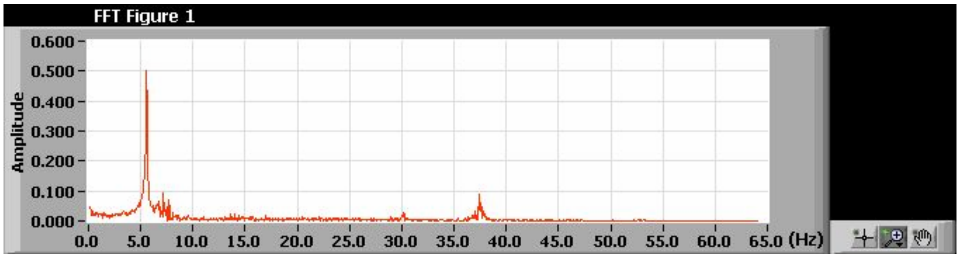

Figure 9. Data after running ‘FFT’ function on filtered data.

Modaling: DAG uses the harmonic method to analyze the effect on a simply-supported girder due to a truck moving across the bridge. At the present state of DAG, the analysis is limited in the linear stage and will include nonlinear consideration. Based on the input of the bridge design characteristics such as stiffness, mass, and span, the program outputs the strains on the referred points where sensors are mounted, as well as the first frequency of the bridge.

Based on the vibration approach, structural damage will significantly alter the measured dynamic response due to changes in stiffness and frequencies, both of which are damage-sensitive parameters. Frequencies are derived from the values of the stiffness and so, stiffness becomes the most important feature during modal analysis. In order to investigate the influence of parameter stiffness (EI) on response, several values of this parameter, ranging from 5.54E09 N.mm^2 to 7.92E09 N.mm^2, were considered in the analysis (Figure 10).

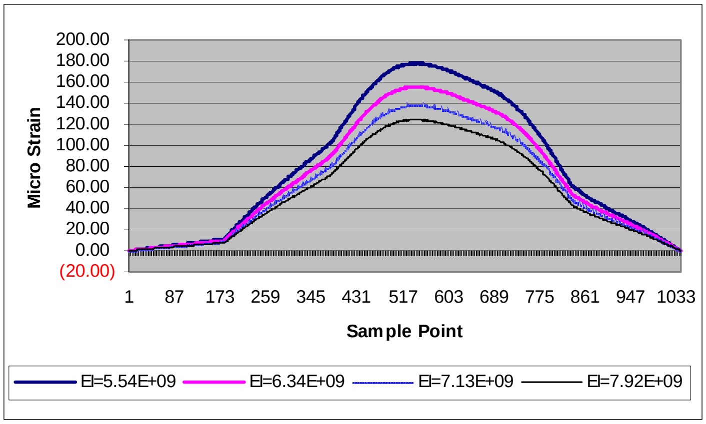

Figure 10. Comparison of the strain with different stiffness EI (unit: N.mm^2).

Result: The outputs of DAG are strains and the frequencies. Strain results obtained from the DAG program for Lindquist Bridge have been compared with field data in Figure 11. As for frequency, the first frequency calculated by DAG is 5.70 Hz, which was close to the FFT result, 5.60 Hz.

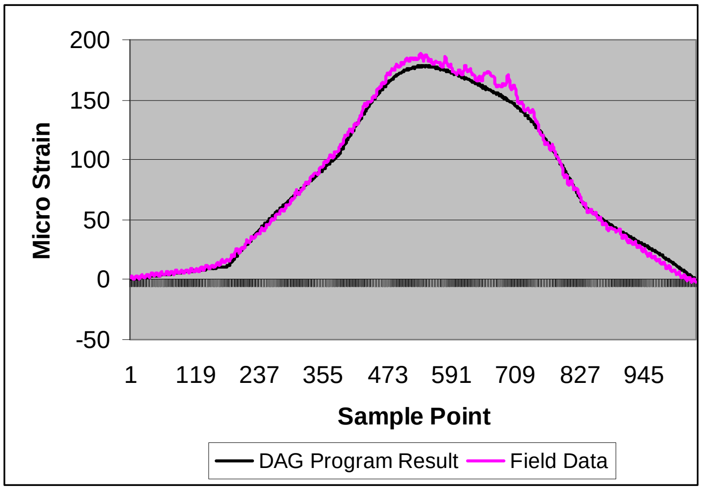

Figure 11. Strain compared between the DAG result and monitoring data.

Since the results from DAG show agreement with the field monitoring data, it can be surmised that the analysis modal represents the actual structural behavior under investigation. Correlation of the theoretical values with the measured results has two major purposes. One is to update or calibrate the modal and to evaluate its performance under future loading conditions. The other is to be an index to detect damage. Whenever measured data exceeds a pre-defined threshold based on theoretical values, damage happens and an event message will be generated in real-time.

CONCLUSIONS AND FUTURE WORK

This paper introduces a data processing program (DPP) and a dynamic analysis program (DAG) for the in-situ monitoring of civil infrastructure. The combination of the two programs makes it possible to create a diagnostics system that is capable of cleaning data, calculating parameters, and recognizing structural health condition based upon a comparison of the measured results with the theoretical analyzed results. Sample results on the Lindquist Bridge demonstrate that the analysis technique is accurate in identifying structural damage for a simply-supported linear bridge. Even so, the following aspects require further study.

1) Intelligent software systems should be developed and updated to process and assess the health condition of infrastructure based on collected field data. Future work will include the real-time implementation of a novel event detection algorithm, the integration of the novel event detection algorithm into the current SHM system and the verification of the generality of the novel event detection algorithm, especially for different types and designs of monitored structures.

2) Vibration-based damage detection shows promise as a method for the SHM of civil engineering structures. FFT can only provide good frequency resolution without time resolution. As well, most of the vibration-based methods fail to give reliable results when only a limited number of incomplete mode shapes are available, and measurement errors are present. Methods based on semi- analytical techniques, such as statistical pattern matching, artificial neural networks and genetic algorithm, have been successfully applied in practical health monitoring. It is possible that a combination of one of them with a vibration based analytical technique, may be more successful in detecting damage location and magnitude.

3) At present, it is possible to predict that damage might exist in a structure. In some cases, it may be possible to predict the location. Estimates of the severity of damage are difficult to provide since the present methods for estimating the severity of damage are not robust.

In addition, computer simulations provide a useful method for replacing expensive field tests when it comes to estimating structural behavior; however, they fail to reproduce environmental effects. As a result, these simulations cannot be relied upon completely by the engineering community. This is another of the areas which remains a challenge for researchers.

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REFERENCES

1. Mufti, A.A., 2001, ‘Guidelines for structural health monitoring’, Design Manual No. 2, ISIS Canada Research Network. Winnipeg, Manitoba, Canada
2. Rivera, E. and Mufti, A. A., 2003, ‘Civionic Specifications (Design Manual No. 6)’, ISIS Canada, Winnipeg, Manitoba, Canada
3. Brownjohn J. M. W., Moyo P., Omenzetter P. and Chakraborty S., 2005, ‘Lessons from monitoring the performance of highway bridges’, Structural Control and Health Monitoring,; 12:227-244
4. Doebling, S.W., Farrar, C.R. and Prime, M.B., 1998, ‘A summary review of vibration-based damage identification methods’, The Shock and Vibration Digest, 30(2): 91-105
5. Pothisiri, T. and Hjelmstad, K.D., 2003, ‘Structural damage detection and assessment from modal response’, ASCE Journal of Engineering Mechanics, 129(2):135-145
6. Humar J., Bagchi A. and Xu H., 2006, ‘Performance of vibration-based Techniques for the identification of structural damage’, Structural Health Monitoring, 5(3): 215-27
7. Ren, W.-X. and De Roeck, G., 2002, ‘Structural damage identification using modal data. I: simulation verification’, ASCE Journal of Structural Engineering, 128(1): 87-95.
8. Reda Taha. M. M., Noureldin A., Lucero J. L. and Baca T. J., 2006, ‘Wavelet Transform for Structural Health Monitoring: A compendium of Uses and Features’, Structural Health Monitoring, Vol. 5(3): 267-29