IMPLICATIONS ON THE USE OF CONTINUOUS DYNAMIC MONITORING DATA FOR STRUCTURAL EVALUATION

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Abstract

This paper presents an overview of the long-term continuous monitoring system installed on the Confederation Bridge and the processing and use of the monitoring data in studies of the dynamic characteristics and behaviour of the bridge. Observations and research findings obtained from system identification of dynamic monitoring data collected under different dynamic load excitations are discussed. The variability of the extracted dynamic properties from different monitoring datasets is investigated. The implications of using these results for structural condition assessment and health monitoring are examined. The paper also presents ongoing research on development of data processing and graphical user interface tools and applications to facilitate not only the processing and evaluation of the monitoring data for research purposes, but also for timely practical applications and use of the information in bridge operations and maintenance. The application modules developed include real-time data processing, visualization and analysis of field monitoring data. These application modules form a platform for real-time health-monitoring of the bridge. The structural health monitoring and condition assessment platform based on continuous field ambient vibration monitoring can be applied to provide fast and accurate post-earthquake evaluation and assessment of structural integrity of the facilities.

INTRODUCTION

Structural condition assessment or structural health monitoring is a relatively new field of research in Civil Engineering which has seen many rapid developments in recent years. Monitoring systems have been developed and installed in the field to collect information on the material properties and structural behaviour of civil engineering structures and systems, such as buildings and bridges. In structural evaluation, the challenges and research needs of using vibration monitoring data for structural condition assessment are recognized and much research has been carried out by many researchers to address the problems, such as the development of numerical system identification techniques for accurate determination of dynamic properties from ambient vibration measurement data of which the sources of excitation are not known or measured, and the establishment of consistent baseline databases for long-term structural condition and performance evaluation purposes (Peeters and De Roeck, 1999; Peeters, 2003; Zhang, 2000; Londoño, 2003). More recently, because of the continuous streaming and availability of monitoring data from continuous monitoring systems, there is the motivation and incentive to utilize the collected data to achieve more efficient operations and maintenance of the monitored systems and facilities. The development of a continuous monitoring system to provide rapid and accurate condition assessment of the monitored structure either on a continuous basis or after the occurrence of an extreme event, such as an earthquake, is the objective of the current research. The research presents numerous challenges on the development of intelligent automatic data processing and analysis, reliable condition assessment algorithms that take into account the stochastic variations in data behavior, and the development of graphical user interface (GUI) and visualization tools to facilitate engineering interpretation the monitoring information.

The Confederation Bridge Monitoring Project in Canada presents a unique opportunity to address and explore these challenges. The structural monitoring system of the Confederation Bridge, in operation since 1997, consists of a sophisticated network of sensor instrumentation and multiple continuous data acquisition systems to capture the dynamic responses of the bridge under wind, traffic, ice impact and earthquake loads. The monitoring system is designed with advanced automatic data collection algorithms to record bridge responses under both normal ambient vibration conditions on a continuous basis and triggered extreme loading scenarios. Monitoring the ambient structures responses on a continuous basis, as opposed to capturing triggered data of events, provides a unique perspective which allows detailed studies of long-term changes of structural properties, behaviour and performance over time. An understanding of the signature characteristics and variations of the observed structural properties determined from the ambient dynamic monitoring data by system identification, and factors affecting these variations under different loading scenarios and environmental conditions, is essential for the establishment and use of a baseline behaviour and performance dataset needed for structural condition assessments that must distinguish between changes in structural properties and behaviour due to damage/deterioration of the structure and changes due to normally occurring variations.

CONFEDERATION BRIDGE MONITORING SYSTEM

Bridge Structure

The Confederation Bridge is 12.9 km long. It crosses the Northumberland Strait in Eastern Canada, linking the provinces of New-Brunswick and Prince Edward Island. It is the longest bridge constructed over ice covered water and one of the longest continuous multi-span bridges in the world. The Confederation Bridge superstructure is a prestressed haunched concrete box-girder bridge. It has 21 approach spans of 93 m each, 2 transitions spans of 165 m and 43 main spans of 250 m each at a typical height of 40 m above the mean sea level. The main span portion of the bridge is constructed of rigid frames linked by simply supported drop-in spans. Each rigid frame is composed of two piers and two 192 m double cantilever box girders linked by a continuous drop-in span. The depth of the box girders varies from 14.5 m at the pier supports to 4.5 m at mid-span.

Continuous Monitoring System

A comprehensive long-term monitoring system of the Confederation Bridge has been in operation since the bridge opening in 1997 to collect information about its behaviour and performance. The monitoring system measures and records both environmental and bridge response data related to: ice forces, short and long-term deflections, thermal effects, traffic loading, corrosion and dynamic responses. The dynamic part of the monitoring system is designed and configured to measuring the vibration responses of the bridge caused by significant sources of dynamic excitations, including wind, heavy traffic, ice loads and earthquakes. The vibration instrumentation comprises 76 accelerometers distributed mainly along a typical structural unit of one rigid frame unit and a simply supported drop-in expansion span. The response behaviour observed in this instrumented segment of the bridge is considered representative of the behaviour of the main span portion of the structure. Vibrations of the girders are measured in the vertical and transverse directions, as shown in Figure 1.

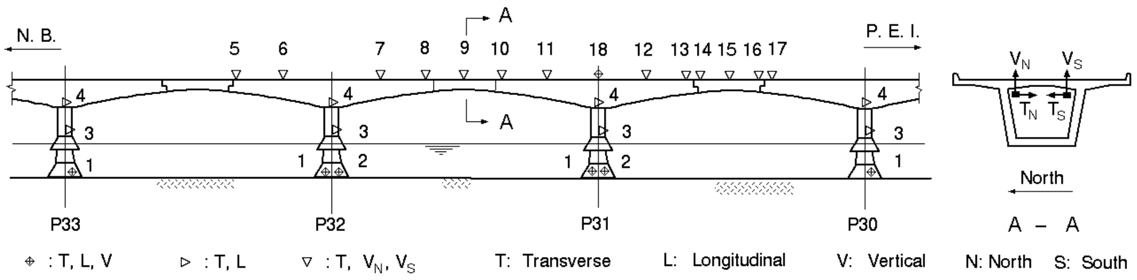

Fig. 1: Locations of accelerometers in continuous monitoring system

This setup permits the measurements of vertical bending, transverse bending and torsional vibration modes of the bridge superstructure. The vibration sensors used in the monitoring system include piezo-electric accelerometers and servo accelerometers. The measured analog accelerometer signals are conditioned and filtered for antialiasing by an 8-pole 50 Hz low-pass Bessel filter. Signals are then sampled and digitized by a network of distributed high-speed data loggers. The data-loggers may be programmed to either collect data on a continuous or triggered basis. The data acquisition can either be manually triggered or automatically triggered upon detection of specific dynamic events. Data are collected at user specified sampling rates that typically vary between 100 Hz and 167 Hz. In ‘triggered’ acquisition mode, the time interval of data recording usually varies between 90 sec and 15 min and includes a 30 sec pre-trigger buffer. Details of the monitoring system setup have been described in the reference (Montreuil *et al.,* 1998; Cheung *et al.,* 1997).

Data Transmission

Vibration responses are measured by accelerometers. The voltage signals from the accelerometer sensors are conditioned and filtered prior to analog-to-digital (A/D) conversion by the data-loggers. Sampled data are stored temporarily in logger memory until retrieval at specified scheduled intervals from a remote network computer assigned to the control and operation of each logger. The logger computer retrieves the data from the data logger and sends them to a centralized platform where they are made accessible to researchers over the internet for data processing and analysis. Figure 2 illustrates the steps and processes of high-speed dynamic monitoring data collection.

The dynamics monitoring systems of the Confederation Bridge are designed for achieving the following objectives:

i. Verifications of design assumptions;
ii. Monitoring and study of structural response under significant loading events such as earthquakes, ship impacts, wind storms, heavy traffic and extreme ice loads;
iii. Long-term condition assessment of the structure.

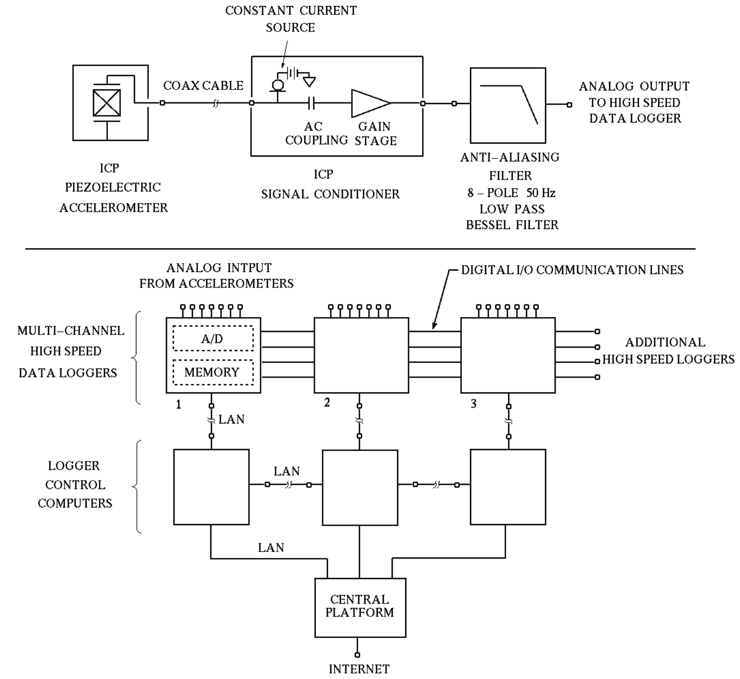

Fig. 2: Schematic of Confederation Bridge dynamic data acquisition and transmission.

DATA PROCESSING AND ANALYSIS

Preprocessing

Preprocessing of the raw monitoring data is performed before any data analysis. The preprocessing tasks include:

i. Baseline adjustment of the accelerometer time-history signals, by mean removal or high-pass filtering;
ii. Data error corrections for small segments of data where duplication of data recording is detected;
iii. Data patches of missing sample gaps. Gaps are patched by cubic polynomial interpolation of the recorded data.
iv. Application of inverse RC filter to channels which are subjected to low-pass RC filtering at the source.
v. Resampling to bring all records to a common sampling rate and duration. This step is needed only when different data loggers operate at different sampling rates.
vi. Low-pass filtering to reduce noise in the band of interest (0-15 Hz). An eighth order Chebyshev Type I low-pass filter is applied to the monitoring data with a cut-off frequency of 16.67 Hz.
vii. Downsampling to one-third of the original sampling rate (125 Hz) is performed, resulting in a reduced sampling frequency of 41.67 Hz. The result is a substantial reduction in the number of samples without significant loss of resolution in both time-domain and frequency-domain.

System Identification

System Identification techniques are employed to analyze the data signatures and to extract structural dynamic properties of the bridge from the collected monitoring data. The extracted properties can be used to gain insight into the structural behaviour, verify design assumptions related to the dynamic responses of the bridge at the beginning, and later for condition evaluation of the structure. For large scale complex structures like the Confederation Bridge, it is impractical or cost-prohibitive to set up forced vibration measurements. Consequently, ambient loading without detailed knowledge of the sources, is relied upon as the input excitations. In the system identification analysis of ambient vibration data, output-only system identification techniques are required. Studies have shown that among the numerous system identification techniques proposed for civil engineering structural monitoring applications the stochastic subspace identification (SSI) methods are considered as more robust output-only identification techniques compared to other available methodologies (Peeters, 2000).

Stochastic Subspace Identification

The SSI algorithm identifies a stochastic state-space model of the structure. The resulting model can then be translated into a more convenient structural model form for engineering interpretation of the results. The state-space model can be related to both modal model and Finite Element (FE) model formulations. The dynamic behaviour of civil engineering structural systems is traditionally modeled through discrete Finite Element approximations, which may be represented by the following matrix equation of motion:

$$\mathbf{m}\ddot{\mathbf{u}}(t) + \mathbf{c}\dot{\mathbf{u}}(t) + \mathbf{k}\mathbf{u}(t) = \mathbf{f}(t) = \mathbf{r}\mathbf{p}(t) \tag{1}$$

For system identification from discretely sampled responses, it is more convenient to reformulate the FE model into a discrete-time state-space model form, which can be obtained after suitable manipulations:

$$\begin{aligned} \mathbf{x}_{k+1} &= \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{p}_k \\ \mathbf{y}_k &= \mathbf{C}\mathbf{x}_k + \mathbf{D}\mathbf{p}_k \end{aligned} \tag{2}$$

In this formulation, $\mathbf{x}$ is a *state vector* which describes the system displacement and velocity at the instant $k\Delta t$, where Δt is the sampling interval; $\mathbf{p}_\mathbf{k}$ and $\mathbf{y}_\mathbf{k}$ are the sampled input and output vectors respectively.

The state-space model formulation of Equation 2 is entirely deterministic. However, in civil engineering applications, especially in the context of continuous field monitoring, it is usually impractical or impossible to measure the input excitations, $\mathbf{p}_\mathbf{k}$. Thus, the identification algorithms must rely on the measured outputs $\mathbf{y}_\mathbf{k}$ only. In the SSI algorithm the input terms $\mathbf{B}\mathbf{p}_\mathbf{k}$ and $\mathbf{D}\mathbf{p}_\mathbf{k}$ are considered as random white noise terms. Thus, the discrete-time state-space model becomes:

$$\begin{aligned} \mathbf{x}_{k+1} &= \mathbf{A}\mathbf{x}_k + \mathbf{w}_k \\ \mathbf{y}_k &= \mathbf{C}\mathbf{x}_k + \mathbf{v}_k \end{aligned} \tag{3}$$

Both $\mathbf{w}_k$ and $\mathbf{v}_k$ are assumed to be white, zero-mean stochastic processes, independent of the state vector.

From the stochastic state-space model formulation of Equation 3, it can be shown that the correlations of the outputs $\mathbf{R}_i$ can be factorized into a triplet containing the state matrices (Peeters and De Roeck, 1999):

$$\mathbf{R}_i = \mathbf{C}\mathbf{A}^{i-1}\mathbf{G} \tag{4}$$

where output correlation matrices $\mathbf{R}_i$ are defined as $\mathbf{R}_i = E[\mathbf{y}_{k+i}\mathbf{y}_k^T]$, where E denotes the expectation operator; The subscript i indicates a time lag of $i\Delta t$; and $\mathbf{G} = E[\mathbf{x}_{k+1}\mathbf{y}_k^T]$ is a “next-state-output” correlation matrix.

Equation 4 represents the basis of the correlation driven output-only identification algorithm. It indicates that suitable de-composition of the correlations can yield the state-space matrices, which in turn contain the structural parameters of mass, stiffness and damping. Data correlations also offer the advantages of eliminating uncorrelated noise and compressing the data while preserving the modal information.

Correlations of data computed at a sequence of different time lags may be assembled into a block Hankel matrix as follows:

$$\mathbf{H}_{1|i} = \begin{bmatrix} \mathbf{R}_1 & \dots & \mathbf{R}_{i-1} & \mathbf{R}_i \\ \mathbf{R}_2 & \dots & \mathbf{R}_i & \mathbf{R}_{i+1} \\ \dots & \dots & \dots & \dots \\ \mathbf{R}_i & \dots & \mathbf{R}_{2i-2} & \mathbf{R}_{2i-1} \end{bmatrix} \tag{5}$$

Suitable factorization of the Block Hankel Matrix together with Singular Value Decomposition (SVD) yields the *observability* and *controllability* matrices from which the State–Space matrix **A**, which contains the mode shapes and eigenvalues, can be extracted.

The eigenvalue decomposition of the discrete-time state matrix **A** yields:

$$\mathbf{A} = \mathbf{\Psi}\left[\backslash \mu_j \backslash\right]\mathbf{\Psi}^{-1} \tag{6}$$

where Ψ is a complex eigenvector matrix and μ_j are the discrete-time eigenvalues, which are directly related to the *system poles* λ_j or eigenvalues of the original second order system of Equation 1. The system poles contain the modal frequencies ω_j and damping ratios ξ_j:

$$\lambda_j = \frac{\ln(\mu_j)}{\Delta t} = -\xi_j\omega_j + i\sqrt{1-\xi_j^2}\,\omega_j \tag{7}$$

In practice, the SSI algorithm involves some approximations due to:

i. Modeling and measurement inaccuracies;
ii. The use of finite datasets to compute estimates of the correlations;
iii. Data non-stationarity and non-linearity.

As a result, the true model order of the system is typically masked by the appearance of spurious system poles which account for all the above effects. True or stable system poles must be distinguished from the spurious poles using ***stabilization diagrams***, which allow the analyst to discriminate between them. Details of the SSI algorithm are given in the references (Peeters, 2000; Bogunović Jakobsen, 1995).

Verification of Dynamic Properties Study

The bandwidth considered for the extraction of modal properties is 0 - 5 Hz. This frequency range includes most of the dominant vibration modes of the structure. A summary of the vibration modes retrieved from the processing and analysis of 4 different field monitoring datasets is presented in Table 1.

Table 1. Summary of modal frequencies and damping ratios retrieved from the continuous monitoring data and comparison with predictions from the analytical model.

Analytical Frequency	Experimental Frequency [1]	Mode Type [2]	Damping Ratio [3]	MAC [4]	Excitation Type [5]
Hz	Hz		(%)		
0.28	0.33-0.36	T	0.15-0.79	0.94	WS, W, Tr
0.33	0.39-0.40	T	0.35-1.02	0.93	WS, W
0.46	0.47-0.48 [6]	T	0.24-0.82	0.55	W, WS
0.58	0.65	V	0.10-0.76	0.86	W
0.62	0.65-0.71	V	0.24-1.48	0.96	WS, W
0.79	0.91	V	0.07	0.94	W
0.82	0.94-1.03	V	0.03-0.60	0.72	WS, W, Tr
1.08	1.17-1.21	V-L	0.39–0.81	0.78	Tr
1.60	1.62 [6]	V-L	0.04	0.83	W
2.34	2.69–2.83 [6]	V	0.05–0.25	0.94	Tr
3.15 [7]	3.30-3.50	V-L	0.01–0.40	0.57	Tr
-----	3.38	To	0.10	-----	Tr
-----	4.63-4.81	V	0.01-0.38	-----	W
4.43	4.96-5.20	V	0.04–1.05	0.85	Tr

[1] For modes identified from different datasets, the range of identified frequencies and damping ratios are given.

[2] Mode types: T=transverse, V=vertical, To= torsional, L=longitudinal.

[3] More accurate determination of damping ratios requires further study.

[4] Modal Assurance Criterion (MAC) values presented are for analytical and experimental mode pairs. For modes identified from different datasets only the highest MAC value is given

[5] Indicates the predominant source of excitation, other types of excitation sources may also be present. Excitation types: Tr= traffic, W=wind-triggered ambient vibration, WS=windstorm

[6] Mode also retrieved in the variability study that is presented in this paper.

[7] Analytical Mode of 2.73 Hz yields higher MAC value (0.89) with the corresponding experimental modes. However, in the graphical displays there seems to be a better agreement with the 3.15 mode

The identification of the vibration modes is made based on one or more of the following criteria: (i) power spectra indicate that the mode is one of the dominant modes in the vibration response; (ii) extracted mode shape shows reasonable correlation with the analytical model mode, with a Modal Assurance Criterion value of 0.70 or greater; (iii) there is reasonable alignment of the corresponding pole in the stabilization diagram plot with peaks of relevant cross-power spectra estimates; (iv) the same mode is retrieved from different datasets and/or using different reference channels. Figure 3 shows some of the experimentally retrieved mode shapes compared to those predicted by the analytical model.

It is observed that wind excitation tends to excite mainly the lowest frequency vibration modes in the 0 - 1.0 Hz band. This fact is corroborated by observation of the windstorm response power spectra. On the other hand, power spectra for controlled truck traffic test responses indicate that heavy traffic excites most significantly the modes in the 2.5 - 3.5 Hz band. However, due to the fact that ambient excitations typically include a combination of different loadings, structural responses tend to contain some structural modes not typically associated to the principal source of excitation. As an example, the two modes in the 1.0 - 5.0 Hz band that are retrieved from wind-triggered data are most likely traffic-excited modes since the wind-triggered dataset used in this study is also expected to include traffic loading responses.

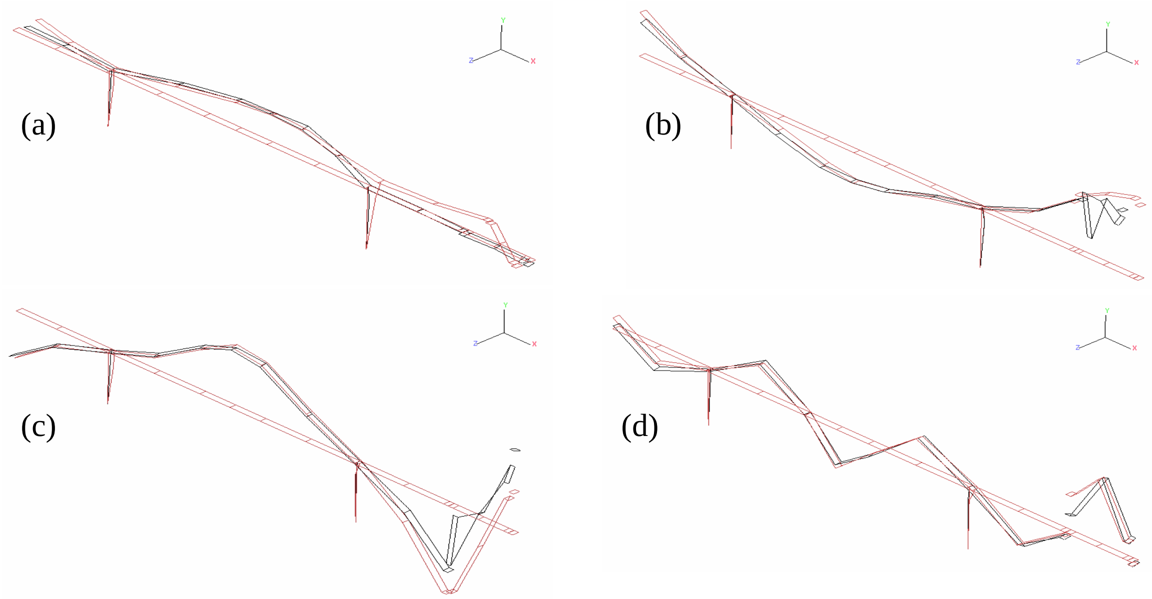

Fig. 3: Extracted and analytical mode shapes; (a) 3rd transverse mode: experimental 0.47 Hz, analytical 0.46 Hz (b) 1st vertical bending mode: experimental 0.65 Hz, analytical 0.58 Hz (c) 2nd vertical bending mode: experimental 0. 68 Hz, analytical 0.62 Hz (d) 7th vertical bending mode: experimental 2.74 Hz, analytical 2.34 Hz.

There are important differences between the predicted and experimentally extracted modal properties. The experimental frequencies are consistently higher than the analytical frequencies. It is noted that the higher frequencies lead to higher seismic design spectral values and therefore result in higher seismic loads. However, the significance of the resulting increase in seismic forces on the performance of the bridge is considered in another study of the project. The frequency shift suggests that the real structure is generally stiffer than estimated. The stiffness difference may be due to various factors, most likely including an underestimation of the elastic modulus of concrete.

Variability Study

The results of the above verification study, summarized in Table 1, indicate that there is some significant variability in the modal parameter estimates extracted from different monitoring datasets. There are differences in the modal parameters extracted from datasets collected under different loading scenarios, and also between datasets collected at different times of similar loading scenarios. The variability in the identified structural parameters has significant implications in the use of the monitoring data for structural condition assessments. The reason is that most vibration-based condition assessment algorithms rely on detecting changes in the dynamic or static properties of the structure. Therefore, the variability in the identified modal parameters of the healthy structure must be understood first, before attempts can be made in practice to determine whether observed changes in the structural properties are in fact due to structural damage or deterioration, or simply a reflection of the inherent variability in the identification results. Observed changes in the structural properties may be due to one or a combination of the following effects:

i. Environmental effects such as temperature variation;
ii. Differences in the loading scenarios;
iii. Computational inaccuracies and modeling assumptions;
iv. Stiffness degradation due to deterioration or damage.

In order to perform accurate and reliable post-disaster condition assessments a thorough understanding of these effects is needed. The continuous long-term Confederation Bridge Monitoring project provides the ideal setting for research on the variability of structural dynamic properties determined from ambient vibration data by system identification techniques.

In this section, ten independent datasets corresponding to ambient vibration responses of the Confederation Bridge under normal operational conditions are analyzed in order to quantify the level of variability in the modal parameter estimates obtained through system identification of the monitoring data. Analysis is conducted through the SSI method described earlier. The variability study considers 900 second datasets of similar loading scenario and similar environmental conditions. The objective is to determine the baseline level of variability, which is attributable to the numerical accuracy of the data and the identification processes. The determination of this baseline is essential before the variability attributable to changes in the loading scenarios or environmental conditions can be determined. The results of this study can be considered as a 'lower-bound' baseline estimate of the variability in the modal parameters extracted from the monitoring data.

The environmental conditions associated with the different datasets used in the present variability study are kept as similar as possible to avoid including significant variations in the structural properties caused by changes in the environmental conditions. Acquisition times and dates for the 10 datasets and some relevant environmental parameters at the times of acquisition are presented in Table 2. It is assumed here that the influences of the small but inevitable variations in the environmental conditions on the structural properties can be neglected.

The results of the variability study are summarized in Table 3. The four modes listed were identified from all ten independent datasets. It can be observed that the frequency estimates are much more consistent than the damping estimates. The standard deviations of the frequency estimates are all below 0.6% of the mean, while the standard deviations of the damping estimates are between 34% and 55% of the mean values.

The large uncertainty in the damping estimates indicates that the damping mechanism of the structure is more complex than that of the stiffness behavior.

Table 2. Acquisition times and environmental conditions for the variability study datasets.

Dataset Number	Starting Time of Acquisition	1-hour Average Temperature [1]	Approx 10-min average Wind Speed
		ºC	m/s
1	2003/03/10 11:17	-6.0	~10 [2]
2	2003/03/10 11:38	-6.0	~10 [2]
3	2003/03/13 12:32	-2.1	9.3
4	2003/03/13 12:47	-2.1	8.4
5	2003/03/13 13:02	-2.0	8.5
6	2003/03/13 13:17	-2.0	6.5
7	2003/03/14 11:57	-3.8	14.8
8	2003/03/14 12:12	-3.7	14.7
9	2003/03/14 12:27	-3.6	13.8
10	2003/03/14 12:42	-3.5	14.1

[1] Temperatures are from thermocouple measurements at the midspan section of the rigid drop-in (~accelerometer station 9), at deck level of the bridge girder, below asphalt.

[2] Wind speeds for March 10 datasets are extrapolations from average speeds measured from time 14:00 onwards. Wind speeds at the time of the vibration data acquisitions were not recorded due to technical circumstances. However, based on typical rates of change of wind speed averages, the given extrapolated wind speeds can be considered to be representative of those at the times of data acquisitions.

Table 3. Summary of variability analysis results.

Mode Type	Frequency	σ_f	ξ	σ_ξ	MAC
	Hz	Hz	%	%	%
Transverse	0.474	0.003	1.53	0.61	98.7
Vertical	1.641	0.009	1.34	0.56	98.4
Vertical	1.828	0.008	1.56	0.53	99.0
Vertical	2.774	0.017	0.91	0.50	97.4

The correlation between the mode shape amplitudes of the identified modes is evaluated through the Modal Assurance Criterion (MAC). The MAC provides a measure of the least squares deviation of the modal displacements of any two given modes from an ideal straight-line correlation. An MAC value of unity indicates perfect correlation while a zero value indicates no correlation. To assess the overall consistency in the identified mode shapes obtained from the different datasets, an average value of MAC is given in Table 3.

Despite the good overall agreement of the mode shapes identified from different datasets as reflected in the average values of MAC, it is observed that there are some localized discrepancies between the measured mode shapes and theoretical predictions. The magnitude of these localized discrepancies could potentially be comparable to the magnitude of changes in the mode shapes caused by changes in the structural properties associated with damage or deterioration of the structure. Hence, the observed variability in the identified mode shapes represents a problem for structural assessment algorithms that rely on detecting changes in the mode shapes.

Research is currently in progress to study the effects of the daily and seasonal environmental variations and the effects of differences in loading scenarios on the identification results.

Real-Time Data Processing and Analysis

The verification and variability studies described above relied on several separate processing and analysis applications that required a significant amount of time and effort to process the large datasets associated with continuous monitoring. In order to accelerate the processing of the data and to provide analysis results on a more timely basis, there is the obvious need to develop more efficient real-time data processing and analysis capabilities to allow faster engineering interpretation and utilization of the monitoring information through data display, visualization, processing and analysis.

An application platform consisting of data visualization and animation, and data processing and analysis engines has been developed with the objective to facilitate more efficient and timely utilization of the monitoring information to assist bridge engineers in the operation of the bridge. The efficiency of the data is improved by reducing the amount of time required to process large amounts of raw data by automating and centralizing all parts of the process, which significantly reduces cumbersome data porting.

This application platform consists of processing, visualization and analysis modules, which are all accessible through a single graphical user interface (GUI), as shown in Figure 4(a). The processing module receives as input the accelerometer measurements and performs all pre-processing tasks discussed earlier. A copy of the data after each stage of processing is kept for further processing by the visualization and analysis modules. Once the processing of the acceleration time histories is complete they are numerically double integrated to obtain the corresponding displacement time histories.

The visualization modules include extensive plotting capabilities which provide a user friendly and convenient platform to study large datasets in a reasonable time frame, as shown in Figure 4(b). Displacement and acceleration time histories and spectral plots can be easily manipulated to obtain the desired information on the behaviour of the structural system. Data may be viewed at any stage of processing to qualitatively evaluate the processing results. This module also includes a 3D bridge model for animation of bridge displacement responses. The animation module permits flexible user interaction. Parameters of the animations include scaling factor, view angle and playback speed. The animation and plotting capabilities are seamlessly integrated. There is also an option to record animation sequences for playback on common media players.

The analysis module consists of a power spectral density analysis tool for preliminary evaluation and identification of bridge responses in the frequency domain. Spectral analysis can be conducted on data at any stage of the processing to allow a better understanding of the processing methods. A tool to incorporate the stochastic subspace identification algorithm presented earlier in this paper is currently under development. The objective of the integrated real-time data processing and analysis platform is to facilitate timely condition assessment of the monitored facility based on evaluation of continuous dynamic monitoring data.

The processing and animation modules are designed and adapted to run in a real-time mode. A tool has been developed to automatically handle and redirect incoming data to the processing module and to animate the resulting bridge displacements in real-time. Modules for automatic detection and repair of common data error problems, gaps in sampling, duplication of records and lack of synchronization in the incoming data files, have also been developed and implemented in the integrated platform. The ability to visualize the bridge response in real-time adds a significant amount of engineering value to the monitoring data. Responses of the bridge under normal and severe conditions may be viewed and assessed by operators of the bridge in near real-time with minimal time delay as limited by the network speed.

(a)

(b)

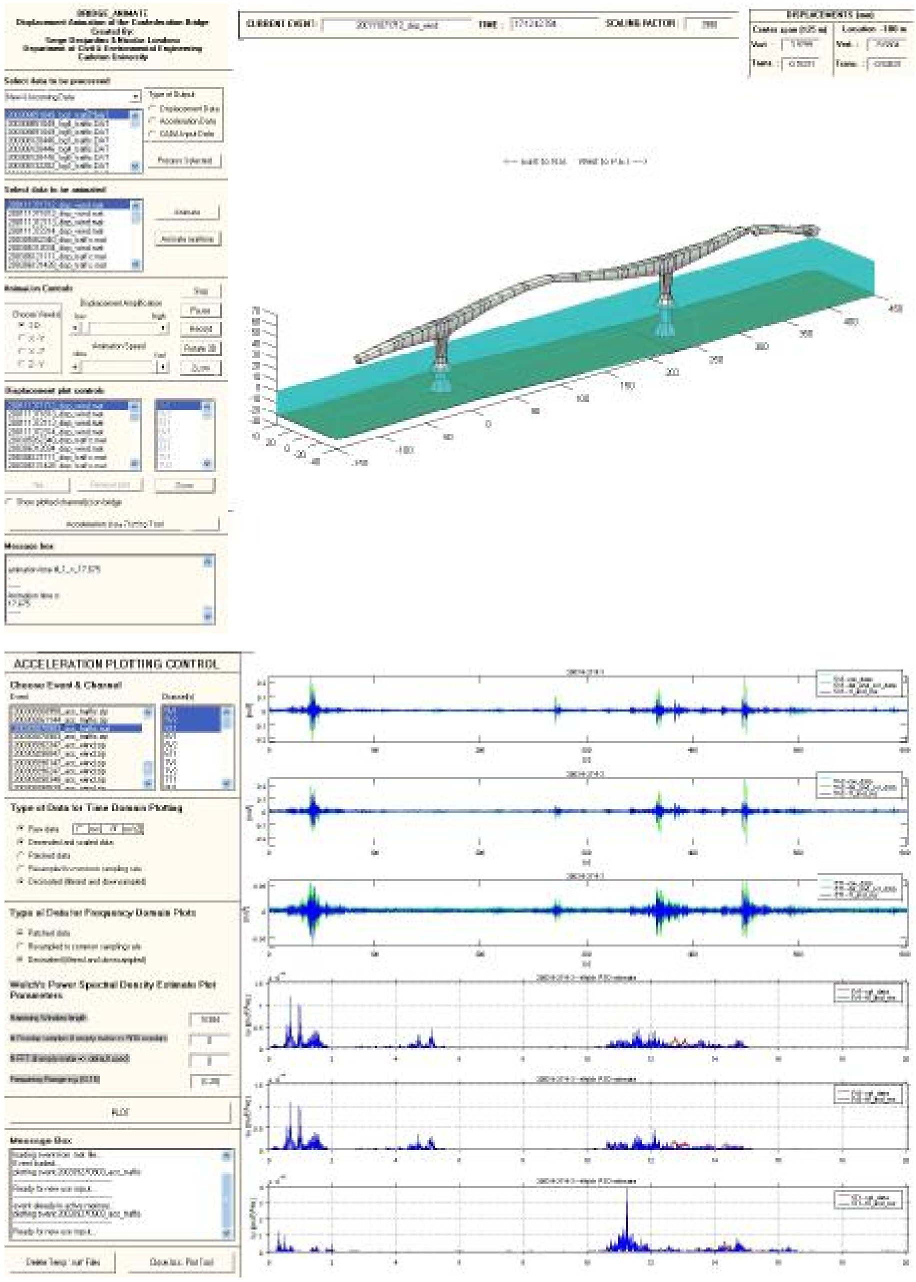

Fig. 4: (a) GUI of monitoring data processing, visualization and analysis application. (b) GUI of data plotting and analysis tool.

FUTURE DEVELOPMENTS

Collaborative research with a research group in applied physics at the University of Ottawa is currently under way to study the feasibility of using distributed Brillouin-based fiber-optic sensors for the monitoring of civil engineering structures. By measuring the frequency response of two counter propagating laser beams, it is possible to determine the strain distribution along the optical fibers (Zou *et al.*, 2003). By installing sensing fibers over the entire span of a bridge structure, it is possible to monitor localized changes at any point along the bridge span. This eliminates the need to predetermine the specific sensor locations, which is a significant advantage of the new Brillouin-based fiber-optic sensor monitoring technology compared to most other existing monitoring systems. Laboratory tests have been conducted, to assess the feasibility of using Brillouin fiber-optic sensors to detect impact loads and load locations on a simple beam specimen. The results of the tests will provide valuable information regarding the potential of practical application of the distributed fiber optic sensors as the basis of a viable monitoring system.

Another ongoing research is to develop and implement new analysis and system identification algorithms based on new advanced data analysis techniques for non-stationary and non-linear data such as the empirical mode decomposition (EMD) and Hilbert Spectrum (HS) analysis developed by Huang *et al.*, (1998). These techniques eliminate the leakage and loss of resolution caused by the spurious harmonics that are needed in traditional Fourier based analysis and spectra to reflect the non-stationary and non-linear behaviours of the data. As a result, the EMD coupled with the HS analysis allow a sharper, more accurate and more physically meaningful analysis of the data.

CONCLUSION

Recent studies on the verification and variability of the dynamic properties of the Confederation Bridge have been presented. In the verification study, design assumptions of the bridge are evaluated by comparing dynamic properties extracted from field monitoring data to those obtained from theoretical finite element models of the bridge based on design drawings. The observation of significant variability in the dynamic properties extracted from different monitoring datasets demonstrates the need of the variability study to obtain a better understanding of the behavior of the bridge and signature characteristics of the monitoring data. In the variability study, a baseline level of variability is determined by comparing extracted dynamic properties under similar environmental conditions and loading scenarios. In order to perform accurate and reliable post-disaster condition assessments a thorough understanding of the variability of the extracted dynamic properties of the healthy structure is needed.

The development of data processing and graphical user interface tools and applications has been presented. The objective is to facilitate not only the processing and evaluation of the monitoring data for research purposes, but also for timely practical applications and use of the information in bridge operations and maintenance. The application modules developed include real-time data processing, visualization and analysis of field monitoring data. These application modules form a platform for real-time health-monitoring of the bridge.

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