Data acquisition, processing and management systems for a Canadian bridge monitoring project

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1 Summary

This paper will present a number of technical aspects for one of the most elaborate instrumentation and data acquisition projects ever undertaken in Canada. Confederation Bridge, the longest bridge built over ice covered seawater has been equipped with the state of the art data acquistition devices and systems as well as data transfer networks. The Bridge has been providing a fixed surface connection between Prince Edward Island and Province of New Brunswick in Canada since its opening in 1997. The Bridge has a rather long design service life of 100 years. Because of its large size and long span length, its design is not covered by any existing codes or standards worldwide.

The focus of the paper is to introduce the data acquisition, transfer, processing and management systems. The instrumentation and communications infrastructure and devices will be presented in some details along with the data processing and management systems and techniques. Teams of engineers and researchers use the collected data to verify the analysis and design assumptions and parameters as well as investigate the short-term and long-term behaviour and health of the Bridge. The collected data are also used in furthering research activities in the field of bridge engineering and in elevating our knowledge about behaviour, reliability and durability of such complex structures, their components and materials.

2 Introduction

This paper will cover a number of specific technical aspects of the health monitoring system in the Confederation Bridge. The interested readers can find comprehensive information about the Bridge and its monitoring system in (Tadros 1997) and (Cheung et al 1997).

The main portion of the Bridge consists of 45 spans of 250 m length frames, a combination of alternative rigid frame spans and drop-in spans (Figure 1). The top portion of the frames is a concrete box girder composed of two 95 m overhangs at the height of 40 m to 60 m above mean sea level. The drop-in members are 58 m long. The girders of the portal frame and drop-in members have a single-cell box cross-section with a total width of 12.0 m, a web spacing of 7.0 m and a depth varying from 4.5 m at mid-span to 14 m at piers. The span length, the web spacing and the girder depth are beyond the typical values for concrete box girder bridges built so far.

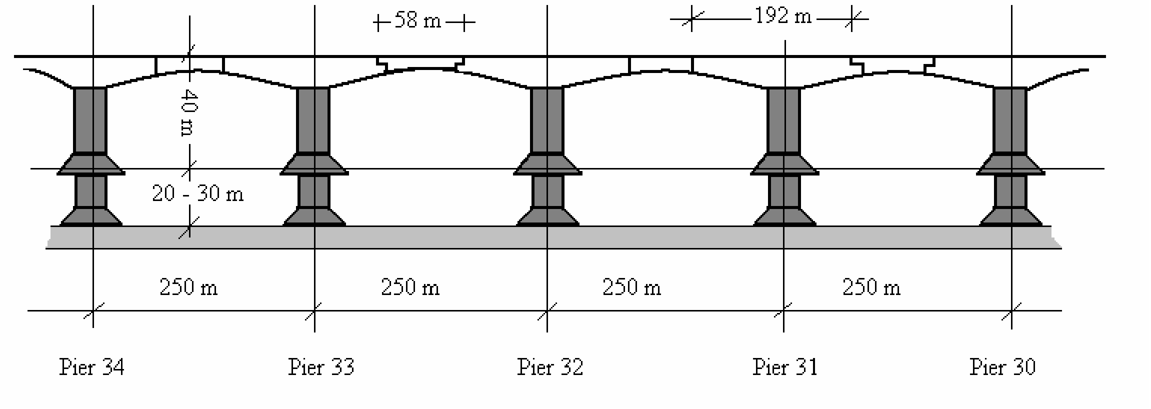

Figure 1 - The Confederation Bridge frames

In addition to its challenging analysis, design and construction, a 1-km section of the Bridge has gone under an extensive, innovative and state of the art instrumentation project ever conducted in Canada, in order to monitor its static and dynamic behavior under all types of loading.

The Bridge has been instrumented for monitoring its short- and long-term response to static and dynamic loads as well as environmental effects. The transducers, 389 in total, include a collection of thermocouples, strain gauges, displacement recorders, ice force panels (IFPs), tiltmeters and accelerometers, etc. The collected data is transferred to a number of data loggers through 674 communication channels.

The paper covers four subjects. The data acquisition system will be introduced in general, with emphasize on some unique features of the system. Technical issues and corresponding solutions related to data transfer from the transducers to loggers and on-site computers as well as to remote locations where processing, management and storage of such data is performed will be addressed next. The enormous amount of data from the rather large collection of transducers need elaborate cataloguing and management before such data can be archived for future studies. The paper will address some of the most decisive solutions and techniques that were employed in this regard. Finally, the paper will address some of the important issues in data mining and data processing of the collected data and present some of the challenges. The conclusion will cover a summary of achievements and suggestions for future.

3 Data acquisition system

(Cheung et al 1997) provides a comprehensive report on the data acquisition system of the Confederation Bridge. The system has been providing information for short- and long-term monitoring of the behavior of the Bridge.

With the objective of collecting the necessary and sufficient amount of data from the enormous structure of the Bridge, which provides the required information to monitor the health of the structure by correlating the related effects, as well as delineating the undesirable ones, the designers were faced with the challenge of establishing an economical and comprehensive system.

Considering the fact that available technologies made it impractical to cover the entire Bridge, and the uniqueness of the structure, that consists mainly of 45 similar repeating frames, the transducers were positioned in a rather small portion of the Bridge. In the final design, four consecutive spans (i.e. two rigid-spans and two drop-in spans) from pier 30 to pier 34 were instrumented. The total length of instrumented portion is 1 km and the collected data is representative of the response of the whole Bridge. The installed instrumentation includes:

- 28 ice force panels (IFPs) for measuring the ice pressure on piers
- 6 biaxial dynamic tiltmeters for measuring the tilt of piers under ice force
- 4 time-lapse video cameras and 2 underwater sonar systems for observing the ice conditions, including ice thickness
- 8 displacement transducers and 20 vibrating wire strain gauges (VWSGs) for monitoring the long- and short term deformation of Bridge structure
- 243 thermocouples and 3 pyranometers for thermal measurements
- 76 accelerometers for monitoring Bridge vibrations due to seismic, wind, traffic and ice breakage events
- 1 ultrasonic wind speed/direction sonar between for measuring wind speed and direction

As mentioned earlier, the collected data from variety of transducers are used to study specific effects by correlating related effects and delineating unrelated ones. A few examples will follow.

1- The collected data from tiltmeters at the pier shafts of the Bridge, as well as from the sensitive accelerometers in charge of measuring accelerations; provide necessary information to calculate global ice forces and their corresponding dynamic effects on the Bridge. The tiltmeter readings have been calibrated by pull tests. Signals from tiltmeters are sampled with 30 Hz frequency by high-speed data loggers.

2- Advanced sonar units (e.g. Ice Profiling Sonars (IPS)) that are installed under seawater, measure ice thickness. Two underwater resistance temperature detectors (RTDs) measure the water temperature and transfer the data. Data about ice thickness, drift velocity, ocean current data and pier tilt are collected and analyzed to measure ice forces on the Bridge pier. Helicopter borne data about ice thickness complement the foresaid information. The effect of temperature, conductivity and depth on sound velocity is taken into account for calibration of the measurements.

3- In order to correlate shrinkage and creep with temperature, vibrating wire strain gauges (VWSGs) are enhanced with built in RTDs for temperature corrections. The temperatures recorded from the RTDs are also used to supplement the thermocouple readings.

4- The ultrasonic wind speed/direction anemometer that is installed on top of a light pole at the midspan of the Bridge measures the wind speed and direction. Depending on a predefined threshold wind speed of 15 m/s, the frequency of collection of data varies from every 10 minutes to one second, when a digital bit is set and sent to high-speed data loggers as a trigger signal. An additional independent weather station is installed at the highest point of the navigation span to supplement the environmental information from the main acquisition system. Its data is sent to the on-shore computer via a radio frequency (RF) modem.

5- Position transducers at the expansion joints monitor the relative movements at the joints. This data is collected by the loggers every one hour. The pyranometers measure the solar radiation intensity and gather the necessary information that will be used to correlate temperature with other effects and responses, including movements.

The transducers provide a continuous stream of data to the data loggers at pre-define frequencies. Among them, the accelerometers gather the highest density of data. Their maximum sampling rate is 167 Hz. The 167 Hz sampling will ensure the error due to aliasing to be less than one percent. In the time-averaged mode of data gathering, data is collected only for time-averaged statistical values (i.e. mean, standard deviation, minima and maxima). Additionally, in case of extreme events (i.e. the event-driven burst mode) when, pre-defined threshold responses are exceeded, a number of transducers are triggered to collect data of higher density from which, time histories of recorded data will be established for further detailed studies. Such extreme events happen in storms, heavy truck pass-over, the impact of large ice floes and earthquakes.

The design team selected data loggers that can operate in the spectrum of air temperature (-25° to 50°) that the Bridge may be exposed to. Due to huge differences in sampling rates for various transducers and due to the large number of channels being involved and distance between the distributed transducers, two sets of loggers have been utilized in the Bridge. The six high-speed data loggers collect vibration data related to ice forces, traffic loads as well as wind and earthquake effects; whereas the nine low-speed data loggers collect static data related to thermal stresses, deformations, strains and wind speed. The low-speed loggers can measure signals from variety of sensors at sampling rates of up to 64 Hz and without any extra signal conditioning. They have 6-channel differential measurement capacity, which can be increased up to 64 channels, using external multiplexers. Analog to digital converters with accuracy of ± 2% of reading, integrate the signal over the period of 60 Hz wave in order to eliminate the possible noises from the power line.

The digital signals from video cameras are directly transmitted to the loggers. The analog signals however, are filtered, amplified and scaled to engineering units using signal conditioners and then converted to digital signals by data loggers.

Special communication architecture between the high-speed data loggers has been set up such that in times of special events, synchronized data collection is ensured among these loggers. In this architecture, each data logger is connected to the other members of the group and sends a digital word of “0” in normal situations. When an extraordinary event occurs, the logger that has sensed the event sends a digital word of “1” to the other loggers, triggering them for the capture of the event as well. The time stamps recorded by the loggers however, are not coincident. Overcoming this mismatch will reduce the overhead in data processing and data management efforts. The loggers are connected with co-axial cables.

It is very important to consider redundant components in the system in case one or multiple components of the system fail to operate. The system should also be designed in such a way that extension to the system or repair and maintenance activities will not interrupt the smooth operation of the system.

Three levels of redundancy have been provided in the Bridge instrumentation system. Redundancy in data logging system is provided with multiple data loggers. The redundancy in transducers level is provided with extra number of sensors, and multiple computers provide the redundancy for data collection, management and processing.

One improvement in data acquisition system for huge structures such as the one at the Bridge is to overcome the limitation in the number of transducers. For example, with even the most advanced multiplexing systems, it is still not practical to install large number of measurement points using available strain sensing devices. The advents of new techniques such as distributed strain sensing technology (DeMerchant et al 2000) are promising solutions.

4 Data transfer

Originally, fiber optic cables were used to connect the data loggers to personal computers (PCs) that were installed in an instrumentation chamber inside the Bridge girder. 4 PCs are dedicated to 4 high speed data loggers, where a 5th one is used by the other 2 which collect ice force measurements as well as video camera outputs for monitoring ice status. The low speed loggers are also connected to the latter PC. Fiber optic cables are superior to copper cables since, (1) the signals will not be affected by outside noises and (2) the cables have a much higher capacity than the copper ones and so can transfer an extended amount of data if expansion is necessary. In 2003, however, the computers were transferred to on-shore location and the loggers are connected to them through an intranet (Figure 2).

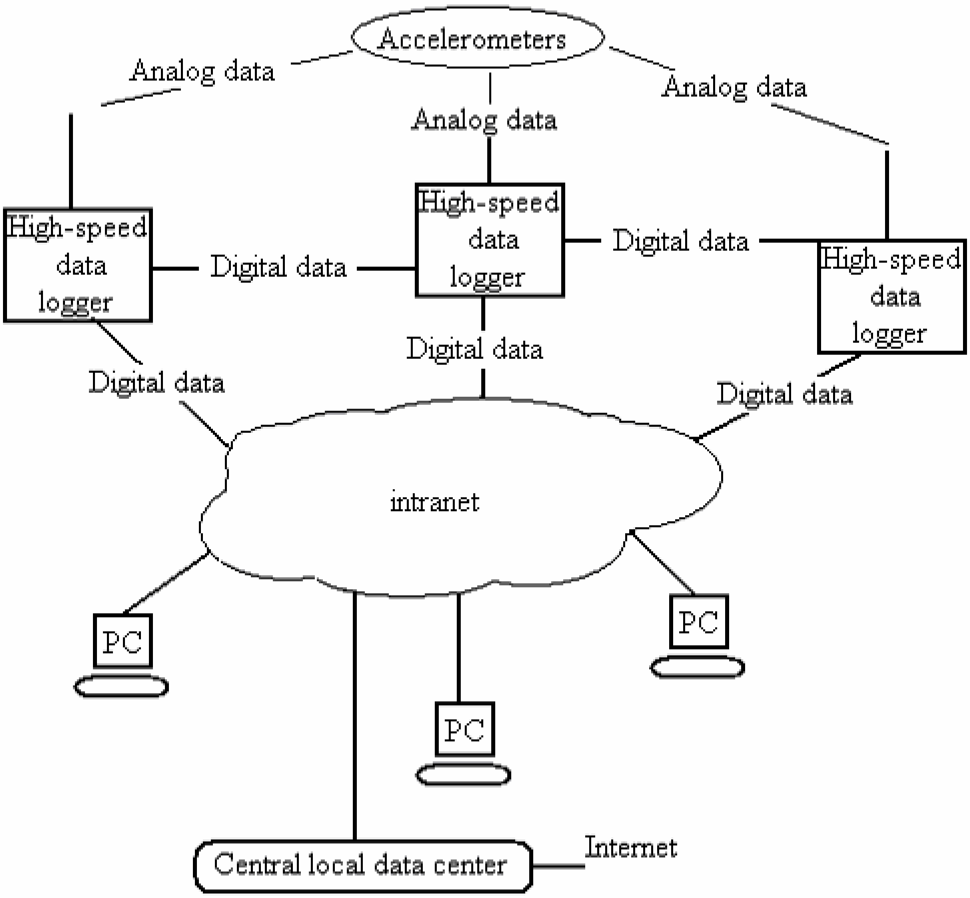

Figure 2 Communication architecture for high-speed data loggers

It is of utmost importance to protect the data from noise. For the case of the Bridge, such protection has been delicately practiced. For example in case of data transfer from thermocouples to data loggers, shielded thermocouple extension wires are used together with covering the cables with conduits or cable trays for extra protection.

The on-shore computers are connected to the Internet and can be remotely controlled. The remote computers at Public Works and Government Services Canada (PWGSC) have access to the data of the on-site computers as well as the data loggers through the Internet. The communication architecture between these computers is a client-server one. The client computers, i.e. the on-site computers, send new data to the servers at user specified intervals. The remote computers can perform remote switching of the on-shore PCs.

Signal conditioning for 8 Wheatstone bridges of the 28 IFPs required special design. Although constant voltage excitation (rather than constant current excitation) is preferred, this solution was uneconomical for a 224-channel system. The design team decided to use one power supply for 8 bridges in every IFP providing a constant 10 Vdc. In this design, in case one power supply is out, the power supply to other panels is not disrupted. In case a panel is destroyed, an output fuse will protect the power supply against a short circuit.

Technology for wireless sensors has advanced in the recent years. The issue of data transfer and data integrity and security as well as power supply for such sensors is under development. Adoption of wireless sensors makes the task of extension and maintenance of the system possible and less disruptive. The use of wireless or satellite technologies for transfer of data from remote locations and in similar projects should be investigated and studied considering the large amount of digital data that are to be transferred and the limitations that are currently inherent in data transfer rate of cellular systems.

In case of the Bridge, an RF modem has been utilized to transfer data from weather station to the on-site computer, an experience in using a wireless system for data transfer.

5 Data management

The volume of collected data by the transducers is extremely large. It is in the order of 7 to 9 gigabytes of data per day in stormy weather. This volume of data is collected by the loggers and transferred through the on-site computers to remote computers where they are gathered, catalogued and stored for further processing, examination, analysis and usage.

Due to the large amount of collected data, it is impossible and inefficient to keep the whole collection of datasets on-line. The challenging task of segregating the most important portions of data, and keeping them on-line, while the whole collection is saved on roles of disks is accomplished by a semi-automatic system.

In this system, pre-defined thresholds are set up to establish criteria for extracting the most critical and representative portion of the incoming data for further screening. The extracted data are then passed on, to full time staff who perform cursory review through further examining the data and extracting the most important segments for immediate analysis and processing.

The selected data segments are kept on the active core, whereas the whole dataset is stored on tapes while being catalogued and categorized based on date, time, type and so on. The tapes will be kept for an extended period of time for access, analyses and studies. The computer center of Carleton University in Ottawa, Canada, provides the facilities and services.

6 Data processing

The challenging task of designing automatic data mining and processing techniques and systems for the collected data from the Bridge is still under way. Moreover, design of visualization software with user-friendly graphical user interface (GUI) software makes the task of data processing and analysis easier (Desjardins, S. L. et al 2003). Such systems should provide the means for correlation between the collected data from various sources and delineating the unwanted effects whenever deemed necessary by the analyst or engineer, in order to come up with the necessary interacting effects in a particular response. For example, the ambient dynamic response of the Bridge is very important information for the researchers in order to understand the dynamic characteristics of the structure and estimating its behavior under predicted or expected server events of the future. The ambient response however, is a function of the input forces, i.e. wind, ground tremor, traffic or ice forces as well as on the performance of the material; in this case concrete which itself is dependent on temperature, humidity, creep and shrinkage. As a result, correlation between the collected data from strain gauges, deflection transducers, tiltmeters, etc. from one hand and the dynamic measurements from accelerometers from the other hand is a challenging task. Moreover, the system should be able to take away the effects of unwanted factors, in the response of the structure. As an example, the monitoring team has observed changes in natural frequencies of the Bridge. Research is underway to find possible factors in this phenomenon. Among such factors, relaxation of pre-tensioned cables should be considered. Design of more efficient data mining and data processing systems is still ongoing by research teams. For dynamic studies of the Bridge, the Stochastic Subspace Identification (SSI) technique was used, as one of the most robust output-only identification techniques, (Desjardins et al 2003).

The frequency of data processing for different effects changes during the course of time. For example, in case of short-term and long-term responses of the Bridge under effects of creep and shrinkage, the focus of intensive study was limited to the first few years of the age of the Bridge and due to the obvious fact that, rate of shrinkage and creep reduces substantially after a few years. On the other hand, dynamic response of the Bridge due to ice forces is limited to the months of November to April, when the water is covered with ice, and it will continue for many years, where the records from tiltmeters, ice temperature transducers, accelerometers, etc. will be thoroughly analyzed.

Detection and elimination of corrupted data due to noise effects is part of any data processing system. Implementation of efficient sampling techniques will reduce the rate of sampling and the demand on the networks as well as data storage systems.

Another issue in data processing is to fill in the time lapse in data collection, i.e. data collection gaps which occur due to malfunction of one or more of the transducers. Interpolation techniques should be devised to fill in such gaps. Research activities are on going to come up with better techniques. Recognition, extraction and elimination of duplicated data should be automated.

An important objective of data processing efforts is the definition of baseline responses and signature characteristics of the structure for comparison purposes. It is the objective of on-going research activities to define such baseline responses for the Bridge by devising and implementing more rigorous system identification methods.

7 Conclusions

The instrumentation strategy of the Confederation Bridge has been a successful achievement for Canadian engineering researchers and professionals. The condensed instrumentation scheme has been adequate to collect required dada for health monitoring of the system and provides enough data among which correlation of related ones and delineation of undesirable effects on particular responses is possible. Use of fiber-optic strain gauges and wireless sensors will revolutionize instrumentation plans and will enhance data gathering capabilities of instrumentation projects of comparable magnitude.

Research is ongoing to come up with baseline responses and signature characteristics of the Bridge and implementation of rigorous system identification methods.

In near future, wireless and satellite telecommunication systems can provide the infrastructure for transmission of collected data from very remote sites to the processing and management centers. GPS and GIS technologies will enhance the capabilities of instrumentation systems by providing accurate measurements of displacements as well as observation of natural phenomena like ice movements and water currents, etc.

8 References

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