An automated wireless-based system for real-time health monitoring of civil infrastructures

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ABSTRACT

This paper presents a structural health monitoring (SHM) system based on wireless smart sensor network for real-time condition assessment of civil infrastructures. The system consists of a new wireless smart sensor network and a MATLAB-based data management and data analysis toolbox. In the first part, the development process of wireless sensor system is presented, which was especially designed to meet the requirements of low-amplitude vibration measurements and sudden event monitoring of civil infrastructures. Then, the multipurpose MATLAB-based toolbox is introduced that is able to manage and synchronise time-series data, process the monitoring data, evaluate modal parameters using time and frequency domain System Identification (SI) techniques, compare the modal parameters, and identify any abnormalities as structural damage. To validate the performance of the wireless smart sensor nodes in terms of sensitivity, event-triggered sampling mode, and time synchronisation a series of shaking table tests was conducted on a steel truss bridge model at Structures Laboratory of Auckland University of Technology. Also, the system was installed on the Newmarket Viaduct to evaluate the overall performance of the wireless sensor network in an outdoor environment. The laboratory test results showed that the wireless smart sensor network is able to provide promising performance to measure various types and amplitudes of vibrations from the bridge model with high precision. In addition, the dynamic characteristics of the full-scale bridge measured using the vibration data were consistent showing the reliability of the SHM system in terms of data sensing, data management, and data analysis for SHM applications.

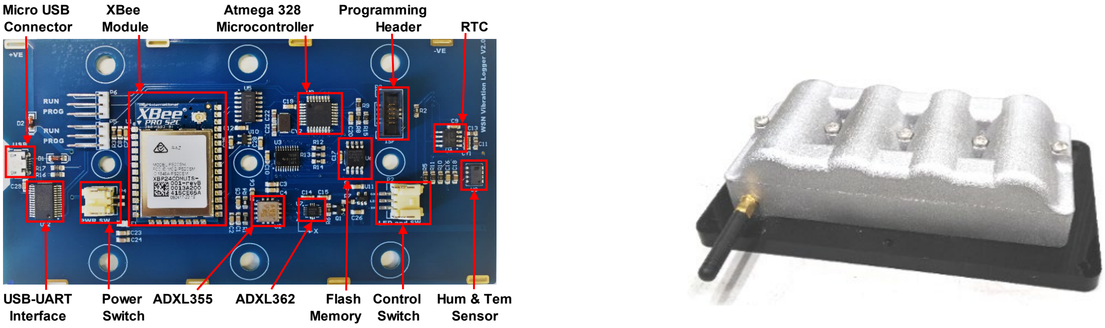
1 INTRODUCTION

Early damage identification of important large-scale civil structures and its removal within an appropriate time can increase the lifetime and safety of structures and prevent them from total failure. Therefore, structural condition monitoring using an advanced structural health monitoring system (SHMS) on a continuous basis or after unpredictable events is crucially important (Navabian & Beskhyroun, 2019). Visual inspection is one of the common approach to monitor the structural integrity. However, their time consuming nature, high cost, and lack of resolution for damage identification of large-scale structures, have limited their frequent uses (Djordjevic, 1990). On the other hand, wired-based structural health monitoring systems are the most common supplement for condition assessment of structures. According to these systems, each sensor is connected to a data logger through long cables. The use of such unscalable wired systems for large-scale structures is limited by high instrumentation and maintenance costs due to cabling (Spencer, Park, Mechitov, Jo, & Agha, 2017). The limitations associated with traditional monitoring systems can be considerably enhanced using wireless sensor network. In the past decade, improvements in Micro-Electro-Mechanical System (MEMS) and wireless sensor network provide researchers with great opportunities to develop sensor nodes with sensing capabilities, wireless communication and data processing options for SHM applications (Pakzad, Fenves, Kim, & Culler, 2008). It should be mentioned that acceleration is among most significant structural responses that has been employed in nearly most of the wireless sensor network developed for SHM applications. Several wireless accelerometer sensor nodes were developed in the literature (Sabato, Niezrecki, & Fortino, 2016). However, most of these sensor boards used analogue-output accelerometers with high noise density that cannot provide enough sensitivity to record ambient vibrations from civil structures (Zhu et al., 2018). In addition, using analogue-output accelerometers requires external analogue circuit components, such as high resolution Analogue-to-Digital Converters (ADC), which increases the design complexity, the analogue noise challenges, power consumption, and cost (Cho et al., 2008; Rice & Spencer Jr, 2008; Swartz, Lynch, Zerbst, Sweetman, & Rolfes, 2010). Few research was conducted in the literature to develop digital-output wireless accelerometer sensors for SHM applications (Bocca, Eriksson, Mahmood, Jäntti, & Kullaa, 2011; Zhu et al., 2018). It should be mentioned that a dense array of wireless sensor nodes is needed to collect sufficient structural responses from large-scale civil structures. The sensor systems usually create enormous amount of data during long-term monitoring, which cannot be managed and analysed using the traditional file-based techniques. Therefore, in addition to a high-performance sensor system network, an efficient data management and data analysis platform is required for an integrated structural health monitoring system to extract useful information from raw measurements.

In this paper, a structural health monitoring (SHM) system based on wireless smart sensor network is introduced. The system consists of a new wireless smart sensor network and a MATLAB-based data management and analysis toolbox. The main purposes to design the sensor network were to decrease the power consumption and costs associated with existing SHM systems and to increase the performance of vibration-based structural health monitoring. The MATLAB toolbox was also developed to manage and synchronise the SHM data measured from the wireless sensor system and extract useful information from the raw measurements using time and frequency domain System Identification (SI) techniques. In order to evluate the performance of the system, several laboratory and field experiments were conducted on a small-scale bridge model and a post-tensioned cantilever highway viaduct.

2 WIRELESS SENSOR NETWORK DEVELOPMENT

In this part, the hardware design and components of the developed wireless smart sensor node are presented. The main components of the sensor platform are: 1) a pico-power microcontroller, 2) a XBee RadioFrequency (RF) module with a built-in trace antenna (3) a fast performance flash memory, (4) a Real-Time Clock (RTC), (5) a fully calibrated humidity and temperature sensor, (6) a low-noise and low-drift 3-axis digital output MEMS accelerometer (7) an ultralow power 3-axis MEMS accelerometer with built-in event detection logic, (8) an external antenna, and (9) a USB connector. The components of the wireless smart sensor board is shown in Figure 1a. Also, final version of the sensor node enclosed with a customised weatherproof enclosure is shown in Fig. 1b. Four D-Cell batteries with 12,000 mAh capacity power up the final version of the wireless sensor nodes that could provide a supply of 6.0 V at a full charge.



(a) *(b)*

Figure 1: (a) Components, and (b) final version of the wireless smart sensor node.

ATmega328/P, picoPower Atmel AVR 8-bit microcontroller, was selected for the board design due to its low power consumption in active and sleep modes and user-selectable clock frequency ranging from 4MHz to 20MHz, which could make a great trade-off between the power consumption, performance and cost for SHM applications. For wireless communication, XBEE S2C 802.15.4 RadioFrequency (RF) module was used that can support ZigBee and DigiMesh mesh networking protocols. It should be mentioned that DigiMesh was used for the developed wireless smart sensor network. A 64Mbit (8-Mbyte) Serial Peripheral Interface (SPI) external flash memory was integrated to the design to temporarily store the measurements on the board before wireless transmission. A low power Real Time Clock (RTC) was used for the board design to provide time stamps for the sensor measurements. Another component of the sensor board is a fully calibrated humidity and temperature sensor to measure the environmental parameters. A low drift 3-axis digital-output MEMS accelerometer, ADXL355 from Analog Devices was considered for the board design to record the low-amplitude ambient vibrations from large-scale structures. This low-power and low-cost chip has an ultralow noise density of 25 µg/√Hz in three axes and an integrated analogue, low-pass, antialiasing filter with a fixed bandwidth of approximately 1.5 kHz and a further digital filtering option to maintain excellent noise performance at different bandwidth. To digitize the filtered analogue signals, this accelerometer has an integrated 20-bit ADC that is an ideal resolution for SHM applications. In addition to the mentioned components, an ultralow power trigger MEMS accelerometer, ADXL362 from Analog Device, with enough resolution and a large First In, First Out (FIFO) buffer was selected as triggering element of the wireless sensor board. It consumes only 13 µA in ultralow-noise mode and 0.27 µA in motion triggered wake-up mode at 3.3 V. Therefore, the ultra-low current accelerometer can run continuously without drastically effecting the battery life of the wireless sensor node. In addition, it has built-in logic to detect activities once the level of acceleration is above a user-defined threshold. The deep 512-sample FIFO buffer also allows the accelerometer to record and store up all data leading up to an activity detection event for more than 13 seconds, which is this case, the important part of the event-triggered signal, can be preserved. Using this accelerometer, the wireless smart sensor node is able to detect and log any sudden event. To do so, the accelerometer has been configured to continuously record accelerations on each axis. When acceleration above a predefined threshold level is detected, the ADXL362 activates an interrupt pin. The interrupt pin is tied directly to the microcontroller, so that when an event occurs the microcontroller comes out of sleep mode and powers on the high-performance ADXL355 to record the event. As soon as the ADXL365 has been configured, the acceleration data starts being logged into the flash memory; hence, the event-induced vibration signal can be captured using the sensor board. The total power consumption of a sensor node in sleep mode is between 3 to 4 µA. The AXDL355, temperature and humidity sensor, and the flash memory are completely powered off in sleep mode with no power consumption. In full operational mode, the power consumption of the sensor is 40 mA that is typically considered low power for wireless sensor network.

The wireless smart sensor network workflow is presented in Figure 2, which includes four main states; Sleep state, Waiting for gateway commands state, Recording state, and Transmission state. This software architecture is explained in details in the following.

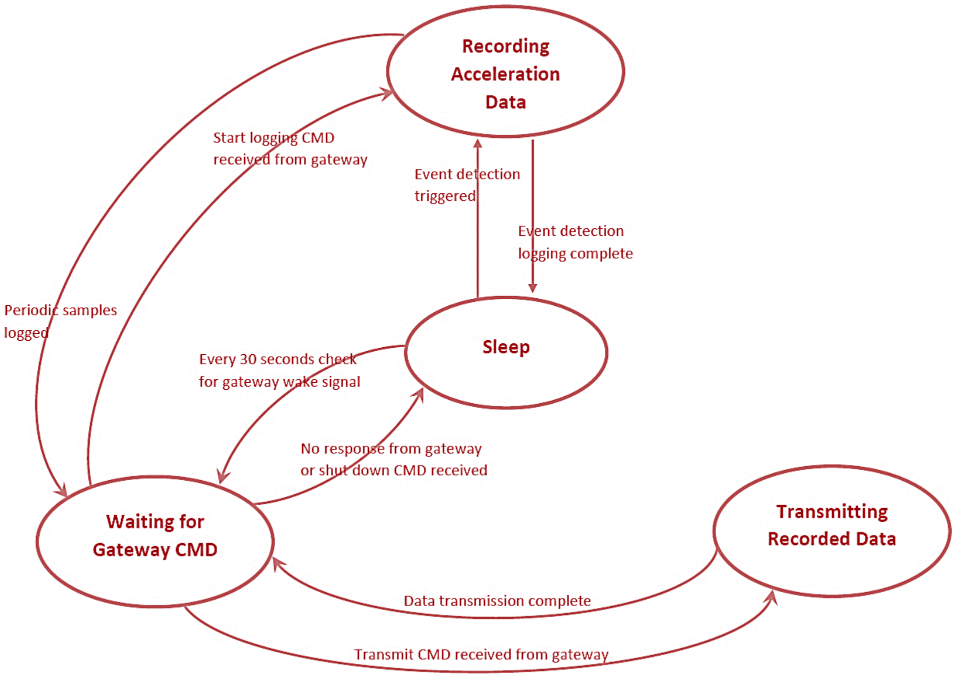


Figure 2: The wireless sensor network workflow.

1. Sleep mode: After turning on the physical switch of sensor nodes, they go to sleep or low power shutdown mode and wait to receive a command from gateway node. The nodes check for gateway wake-up signal every 30 seconds to start the sampling. If they do not receive response from gateway, they go back to sleep mode. The nodes only exit the sleep mode if either of the following conditions are met: 1) the RTC interrupt occurs, which could occur periodically every 30 seconds, and 2) event detection is enabled and an event exceeds the trigger threshold. In first case, if the RTC interrupt occurs, the state changes to the “waiting for gateway CMD” state and a time out value of 500ms will be set. In the case of occurrence of an event like an earthquake, the state will change to “Recording acceleration data” state and a time out value of 70 seconds.

2. Waiting for gateway Commands (CMD): In this state, the nodes handle the incoming commands and responses from the gateway. The nodes can receive seven different CMDs from gateway node. These commands are Wake-up CMD, Start CMD, Check for active nodes CMD, Gateway ready for transmit CMD, Transmit successful CMD, Transmit unsuccessful CMD, and Shutdown CMD.

3. Recording acceleration data: At this stage, the nodes start recording the data received from the ADXL355 accelerometer once they have been instructed by the gateway to start logging or threshold event has been detected following an event. They continue recording the data and storing the measurements in the flash memory until the number of recorded samples reaches the desired record length or the time out value is exceeded from a specific value. The time out value for recording sessions is dependent on the record time set by the user during the initial configurations of the network.

4. Transmitting recorded data: In “Transmitting recorded data” state, the wireless sensor nodes begin transmitting all the data from flash memory to the gateway node. Once the transmission is complete and all the data is transmitted, the nodes return to the “Waiting for the gateway CMDs” state, which was mentioned above. If the transmission time out value is exceeded, then the sensor nodes return to the “Sleep” mode.

3 DATA MANAGEMENT AND ANALYSIS TOOLBOX

In this part of the paper, a brief description of the data management and data analysis toolbox, that is connected to the developed wireless smart sensor network is presented.

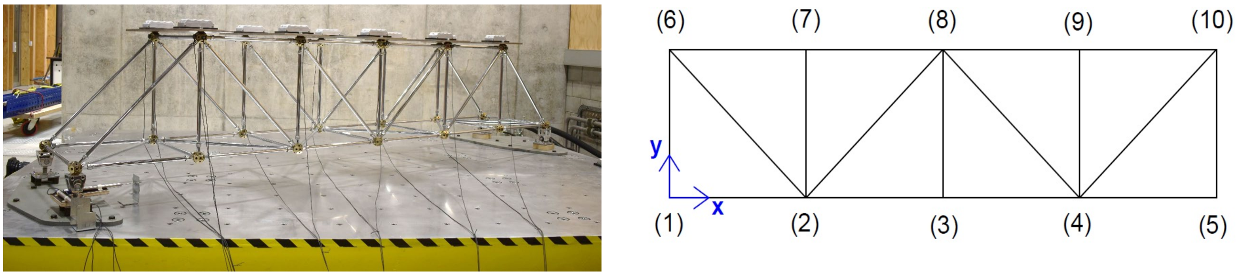
Data management: The acceleration time histories recorded using the wireless smart sensor nodes are downloaded using the 'Data Management' tab. The data from different wireless sensor nodes are synchronised using the post-processing technique introduced in the previous section. Then, new data files are automatically created and saved in a user-defined folder, which are compatible with the data analysis platform. In addition, a detailed information about the wireless sensor system is provided. This information includes the number of active sensor nodes in the network, sensor identification name (sensor ID), sampling time and date, environmental temperature and humidity recorded by smart sensor nodes, and the time offset of each sensor node. The synchronised and managed data files are then analysed using various time and frequency domain methods implemented in other tabs of the toolbox.

Data Analysis: The new data files can be uploaded to the 'Test Parameter' tab, in which preliminary data manipulation process can be performed on the acceleration time histories. It includes removing trend from data, data down-sampling and decimation, data filtering (low-pass, high-pass, and bandpass filtering options), trimming data, saving the processed data in new files, preforming preliminary time and frequency domain analysis on data (like Power Spectral Density (PSD) and Fast Fourier Transform (FFT) analysis), plotting and saving the analysis results. The vibration data sets can be also analysed using output-only Peak Picking (PP), Frequency Domain Decomposition (FDD), and Enhanced Frequency Domain Decomposition (EFDD) techniques and input-output Autoregressive eXogenous (ARX), Autoregressive Moving Average eXogenous (ARMAX), and Stochastic Subspace Identification (SSI) techniques to extract modal parameters of the structure. The analysis results, such as natural frequencies, mode shapes, and modal damping, obtained from different techniques are shown in the 'Compare Techniques' tab. The users are able to plot and visualise the analysis results and compare the results of different analysis techniques.

4 EXPERIMENTAL TESTS

4.1 Shake table testing

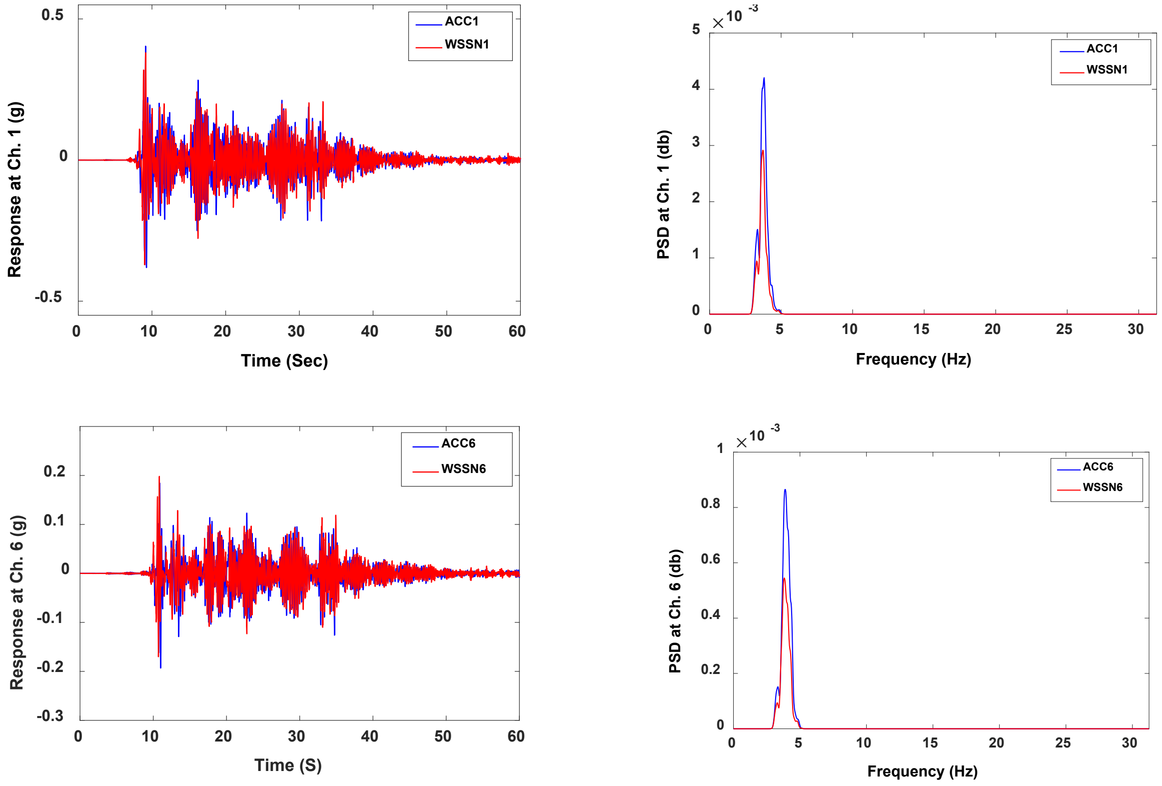
A series of dynamic testing was performed on a shake table at Structures Lab of Auckland University of Technology to investigate the performance of the developed SHM system. The uniaxial shake table, one of the largest in New Zealand, has a dimension of 4 m ×3 m with a maximum displacement of ±200 mm. The tests were conducted on a steel truss bridge model made of MERO joining system. Each span of the bridge includes steel tubes with length of 60.5 cm and 85.5 cm. The model was placed on two pinned and two roller supports. Five steel plates with weight of 10 kg were added to top chord of the bridge to provide high inertia mass during the dynamic tests. Figure 3a shows the structure on the shake table instrumented using wireless and wired sensor systems. The sensor locations are also shown in Figure 3b. Ten wireless smart sensor node (WSSN1-WSSN10) and ten wired accelerometers (ACC1-ACC10), Model 4610A by TE Connectivity, were installed on top chord of the model to record structural responses. The uniaxial wired accelerometer is an ultra-noise accelerometer with a sensitivity of 1011 mV/g. The wireless smart sensor nodes recorded the structural vibrations in X, Y, and Z directions of the bridge, i.e., longitudinal, transverse, and vertical directions, while the wired sensors measured the vibrations only in transverse direction of the structure.



(a) *(b)*

Figure 3: (a) The bridge model on the shake table, and (b) sensor locations on top chord of the bridge.

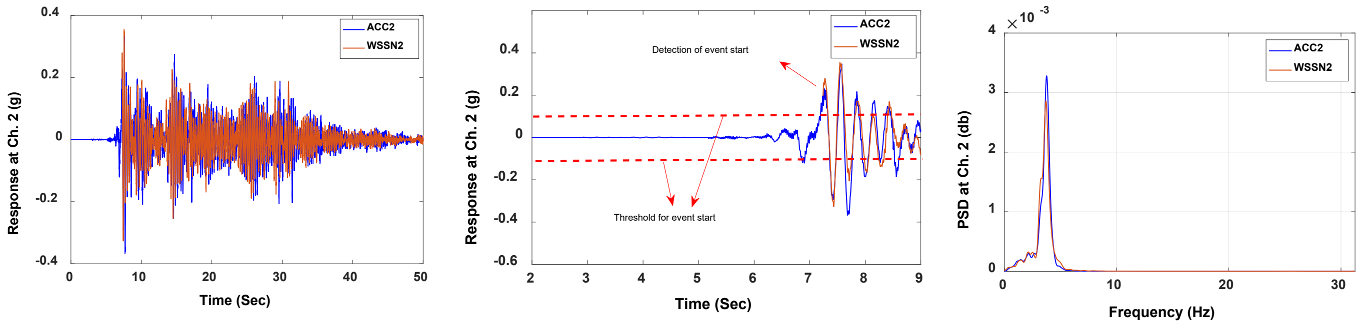
During the first test, the bridge model was subjected to a real ground motion, El Centro Earthquake, with various amplitudes of excitation, including a moderate amplitude of 43 mm and a high amplitude of 85 mm. Figure 4 presents the acceleration time histories and the corresponding Power Spectral Density (PSD) measured using channels 1 and 6 of the wired and wireless accelerometer sensors in transverse direction of the bridge model, respectively. As can be seen from the results, the amplitudes of acceleration time histories measured using the two channels of wired and wireless sensors match well. In addition, the natural frequencies measured using the acceleration time histories are similar. Both the time and frequency domains results show the high resolution of the developed wireless smart sensor nodes in measuring different amplitudes of vibration. It should be mentioned that the small differences between the measurements is because the wireless and wired accelerometer sensors were not perfectly synchronised as they were sampled using different acquisition systems.



(a) *(b)*

Figure 4: (a) Acceleration time histories, and (b) PSD values recorded in Transverse direction.

In the next part of experiments, the wireless sensor nodes were set to event-triggered sampling mode to assess the event-triggered sampling mode of the wireless smart sensor nodes. According to this sampling mode, the wireless sensors are able to detect and sample the event-triggered data sets at 125 Hz. The wired accelerometer sensors were also set to log the vibrations at same sampling frequency. El Centro Earthquake with a peak amplitude of 85 mm was subjected to the bridge model as the sudden event. The triggered threshold of 100 mg was considered for this vibration test. It means that the ADXL362 accelerometer wakes up the sensor board in case of any event greater than 100 mg. Then, the high-performance ADXL355 starts to log the data. Figure 5 shows the acceleration time histories of the earthquake-induced vibration and the PSD values measured by channel 2 of the wired and wireless sensors. As is clear, after the first peak greater than 100 mg, WSSN2 was awakened to log the structural response. The acceleration time histories and the PSD values measured using the wireless node and the reference wired sensor match well, showing ability of the wireless smart sensor nodes to detect and record sudden events with a high precision.



(a) *(b)* *(c)*

Figure 5: (a) Acceleration time histories, (b) acceleration time histories for the event start, and (c) PSD values.

A common concern in developing a wireless sensor network is time synchronisation between various wireless sensor nodes. In such network, each sensor node operates with its internal clock that owns a unique offset specification. The developed network uses a synch pulse that is broadcast to all nodes in the network for a synchronized sampling. This command is transferred using an electromagnetic wave, so the wireless sensor nodes will have a nanosecond difference to receive this starting command. In addition, a post-processing time synchronization technique was also performed on the vibration measurements using the time offset of each wireless sensor nodes. Figure 6 presents the acceleration time histories recorded by all the wireless smart sensor nodes in both transverse and longitudinal directions. During this test, the bridge model was subjected to Chi-Chi earthquake with an amplitude of 190 mm. As can be seen from the results, the wireless nodes maintained phase among themselves with a maximum synchronisation error of 1 to 2 milliseconds, indicating an accurate time synchronisation between various sensor nodes. Therefore, the acceleration data sets can be reliably used for accurate estimations of the bridge dynamic characteristics.

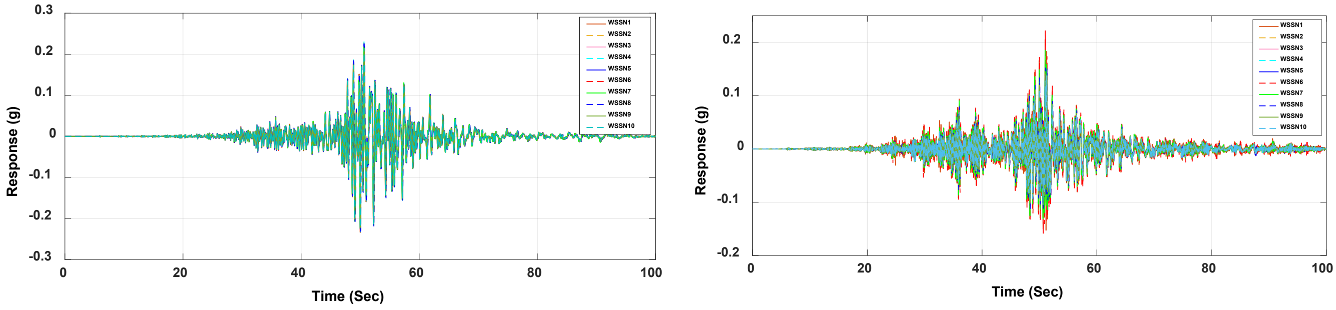
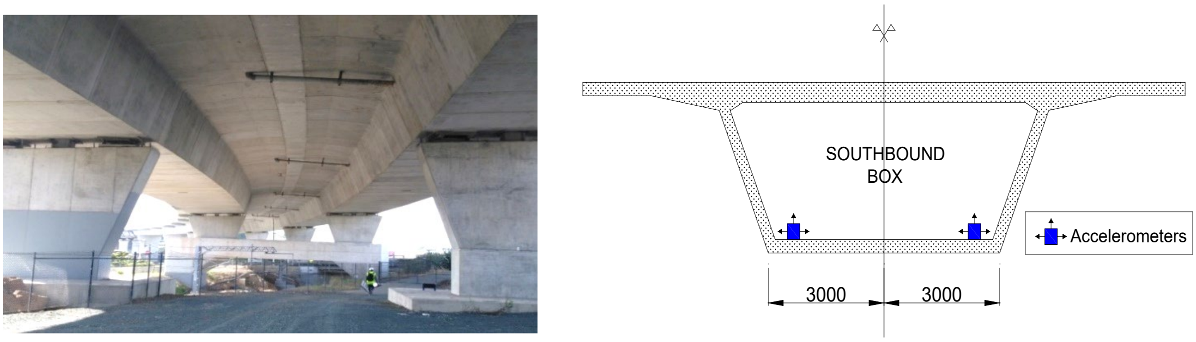


Figure 6: Acceleration time histories measured using ten wireless sensor nodes installed on the bridge model.

5 FIELD TESTING

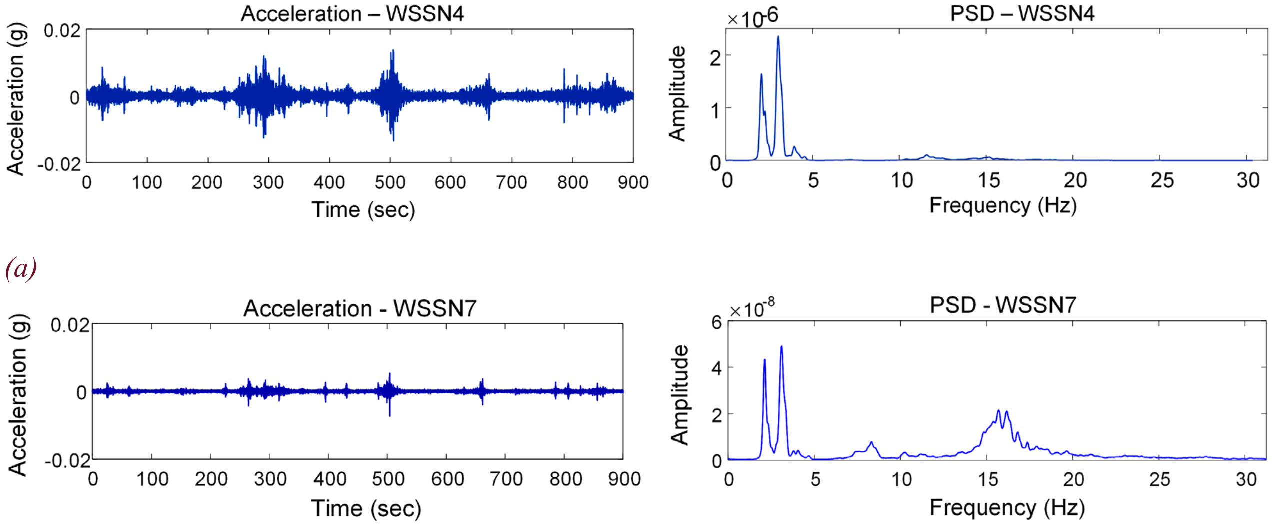
A series of ambient vibration tests was conducted on Newmarket Viaduct, located in Auckland, to test the performance of wireless sensor system for a full-scale structure. This bridge is a horozontally and vertically cureved, post-ternsioned concrete box bridge comprising two parallel twin bridges. The seven-lane state highway viaduct with the length of 690 has twelve spans with average length of 60 m. Span 9 of the bridge was instrumented using the sensor system. The experiemnets were performed under operational condition on November 2018. In total, 20 wireless smart nodes were installed inside the box girder on both sides of the span. 14 wireless sensor nodes (WSSN1-WSSN14) were installed on internal surface of the bridge deck and the remaining 6 accelerometers (WSSN15-WSSN20) were fastended to post-ternsioning cables. Figure 7a and 7b show a view of Newmarket Viaduct ans the sensor locations in girder cross section, respectively.



(a) *(b)*

Figure 7: (a) A view of Newmarket Viaduct, and (b) sensor locations in girder cross section.

The vertical acceleration recorded by the nodes located in the middle and end of span 9 are shown in Figure 8a and 8b, respectively. After a preliminary data manipulation, the PSD values were also plotted for each time-series signals. It can be seen from the results that the amplitude of ambient vibration recorded from the bridge deck was about ±1 mg throughout the test duration, but spikes of near to 15 mg were also observed. These spikes were likely caused by travelling of heavy vehicles on the motorway. A consistent structural peak was also measured using the sensor nodes showing the first few vertical modes of the bridge deck.



(a)

(b)

Figure 8: Acceleration time histories and PSD values measured using two channels of wireless nodes.

Figure 9 also presents the acceleration time histories and the corresponding PSD values measured from three post-tensioning cables in vertical direction using three wireless sensor nodes. As is obvious, the time domain data measured from the cables ranged from 7 mg to a peak of close to 30 mg. Two precise and distinct spectral peaks were also observed showing the first two vertical natural frequencies of post-tensioning cables. Based on these results, it can be concluded that the developed wireless smart sensor nodes are capable to record high resolution time histories of low-amplitude ambient vibrations from full-scale civil structures. It should be mentioned that the data management and analysis for both laboratory and field experiments were performed using the developed MATLAB-based toolbox introduced in this paper.

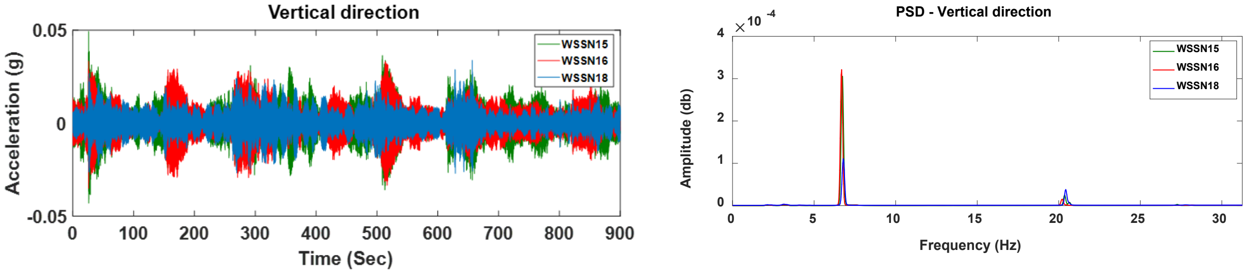


Figure 9: Vertical acceleration time histories and the corresponding PSD values of three post-tensioning cables.

6 CONCLUSION

In this paper, a structural health monitoring (SHM) system based on wireless sensor network is introduced. The system consists of a new wireless smart sensor network and a MATLAB-based data management and analysis toolbox. The main purposes to design the wireless sensor network were to decrease the power consumption and costs associated with existing SHM systems and to increase the performance of vibration-based structural health monitoring. The MATLAB toolbox was also developed to manage and synchronise the SHM data measured from wireless sensor system, visualise the monitoring data, evaluate modal parameters using time and frequency domain System Identification (SI) techniques, compare the modal parameters extracted from various SI methods, and identify any abnormalities as structural damage. To evluate the performance of the system, several laboratory and field experiments were conducted on a small-scale bridge model and a post-tensioned balanced cantilever highway bridge. The results obtained from the shake table tests showed high resolution and sensitivity of the wireless smart sensor nodes same as the expensive wired accelerometer sensors. In addition, the wireless nodes could record high fidelity structural responses induced by sudden events using the high performance accelerometer. Consistent structural peaks were obtained during the dynamic tests from the bridge deck and post-tensioning cables, which indicates reliability of the wireless smart sensor network for estimation of dynamic characteritics of large-scale structures. The wireless sensor nodes also maintained phase among themselves and were well synchronised that confirms efficiency of the time synchronisation techniques used for the wireless sensor network. The results also showed that the vibration measurements were seamlessly transferred using DigiMesh topology, confirming the efficiency of this topology in development of wireless-based SHM systems.

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