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DEVELOPMENT OF AN INTEGRATED STRUCTURAL HEALTH MONITORING SYSTEM USING WIRELESS SENSOR NETWORK

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Abstract

In this paper, the development process of an integrated Structural Health Monitoring System (SHMS) for civil structures is presented. This system includes wireless smart sensor network and MATLAB-based data management and data analysis toolbox. In the first part, the process of developing the new wireless accelerometer sensor board is presented, which was especially designed for long-term monitoring of structures. The main components of the board are a high-sensitive accelerometer, an ultra-low power motion detector accelerometer, a humidity and temperature sensor, a pico-power microcontroller, and an XBEE RadioFrequency module. The wireless accelerometer is able to record both low-amplitude ambient vibration and high-amplitude earthquake-induced vibration from structures and wirelessly transfer the measurements to the base station. The wireless smart sensor board was designed to decrease the power consumption and the costs associated with existing structural health monitoring systems and to increase the accuracy and performance of vibration-based condition assessment of large-scale structures. In the second part, a multipurpose MATLAB-based toolbox is introduced, which is able to manage and synchronize time-series data, visualize and process the monitoring data, evaluate modal parameters, such as natural frequency, mode shape and damping ratio, 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. In order to validate the performance of the developed wireless smart sensor network in terms of sensitivity and resolution, event-triggered sampling mode, and wireless communication, a series of shake table tests was conducted on a small-scale steel bridge model. The structural model was instrumented using wireless smart sensor nodes and high-performance expensive wired accelerometers as reference points. The results showed that the developed wireless smart sensors could provide promising performance for ambient and earthquake-induced vibration measurements. In addition, to assess the accuracy of time synchronization techniques and system efficiency in an outdoor environment, it was installed on one of the most important bridges in New Zealand, Newmarket Viaduct, as the first post-tensioned balanced cantilever bridge along the country. The purpose of the large-scale instrumentation was to validate the system performance for vibration-based condition assessment of large-scale structures and to evaluate performance of the superstructure after several years in operation. The developed system was installed on span 9 of the bridge under operational conditions on December 2018. In total, 20 points were selected inside the box girder on both sides of the span. The bridge dynamic characteristics obtained using the wireless smart sensor nodes were compared to the counterparts measured during previous ambient vibration tests. The results indicated that there are no obvious changes in the overall dynamic behavior of the structure. In addition, the consistency of modal parameters obtained during all ambient vibration tests evidenced on reliability of the developed wireless sensor system for vibration-based health monitoring of large-scale civil structures.

Keywords: Structural Health Monitoring; Wireless Sensor Network; Dynamic Characteristics; Bridges.

1. Introduction

Several important large-scale civil structures, such as bridges and buildings, are being utilized despite their age and the possible risk of damage accumulation. Early damage identification and removal within an appropriate time can increase the lifetime and safety of structures and prevent them from total failure. Therefore, monitoring of the structural condition using an advanced structural health monitoring system (SHMS) on a continuous basis or after strong and unpredictable events, such as earthquake, is crucially important from both life-safety and economic points of view [1].

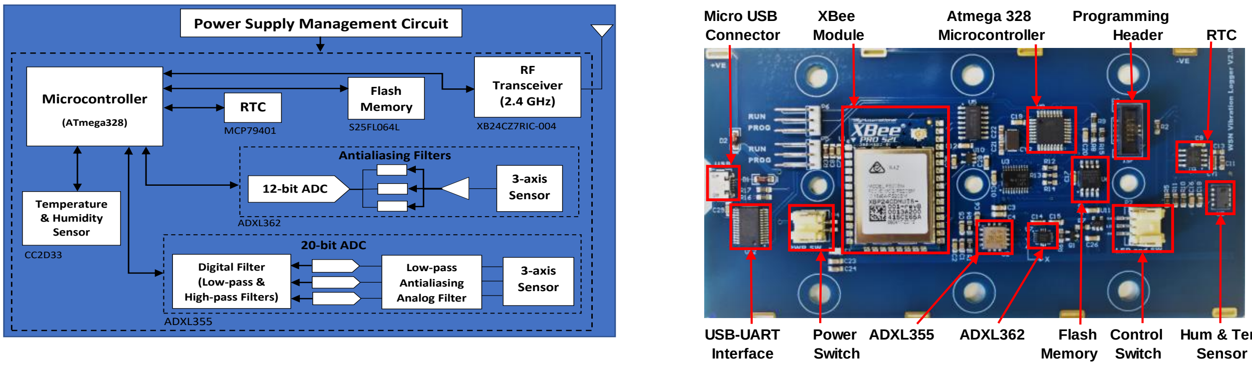
Visual inspection has become a common approach to monitor the structural integrity. However, associated disadvantages, including their time consuming nature, high cost, and lack of resolution for damage identification of large-scale structures, have limited their frequent uses [2]. Wired structural health monitoring systems have been the most common supplement for condition assessment of structures. In such 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 [3]. The limitations associated with traditional wired SHM systems can be significantly improved 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 [4]. Acceleration is one of the most important structural responses that was employed in nearly most of the developed wireless sensor nodes for SHM applications. Several wireless MEMS-based accelerometer sensor nodes were developed in the literature [5]. However, most of these sensor boards used analogue-output accelerometers with high noise density, which cannot provide adequate resolution to measure low-amplitude ambient vibrations from large-scale structures [6]. In addition, implementation of 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 [7-9] . In addition to efforts on the development of analogue-output wireless sensors, few researches was conducted in the literature to develop digital-output wireless accelerometer sensors for SHM applications [6, 10]. In addition to a high performance sensor system network, an efficient data management and data analysis toolbox is required for an accurate and reliable structural health monitoring to extract useful information on the structural condition from raw measurements. 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 measurements with high sampling rate during continuous and long-term monitoring. Based on investigations carried out, it was observed that the traditional file-based approach cannot be a promising tool for data management.

This paper presents a new wireless smart accelerometer sensor developed as a part of an integrated structural health monitoring system. The main goal of the sensor board design was to make a trade-off between sensitivity, power consumption, and cost for a reliable and cost-effective wireless SHM system. The wireless sensor node is able to measure very low-amplitude ambient vibrations with high accuracy from large-scale civil structures. It can also detect and record sudden events, such as low-to-high amplitude earthquakes, using a motion detector MEMS accelerometer that continuously records vibration at a very low power rate. In addition to the wireless smart sensor network, a MATLAB-based data management and analysis toolbox is introduced that is compatible with the developed wireless sensor network. The accuracy and performance of this integrated SHM system will be investigated using a series of laboratory and field experiments on a steel bridge model and an in-service highway viaduct located in Auckland, New Zealand.

2. Development of a structural health monitoring system

2.1 Wireless smart sensor network

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 schematic design and components of the wireless sensor board are shown in Fig.1.



(a) (b)

Fig. 1 - (a) schematic design, and (b) components of the wireless smart sensor board.

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 signal, 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 ultralow 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 is 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 close 40 mA that is considered low power consumption for wireless sensor network. The final version of the wireless smart sensor node enclosed with a customized weatherproof enclosure and the battery pack is shown in Fig.2. Four D-Cell batteries with 12,000 mAh capacity power up the final version of the wireless smart sensor nodes that could provide a supply of 6.0 V at a full charge.

Fig. 2 - Final version of the wireless smart sensor node.

The wireless smart sensor network workflow is presented in Fig.3, which includes four main states; Sleep state, Waiting for gateway commands state, Recording state, and Transmission state. The software considerations for the wireless sensor network in each of these states and their relationships are explained in details in the following.

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.

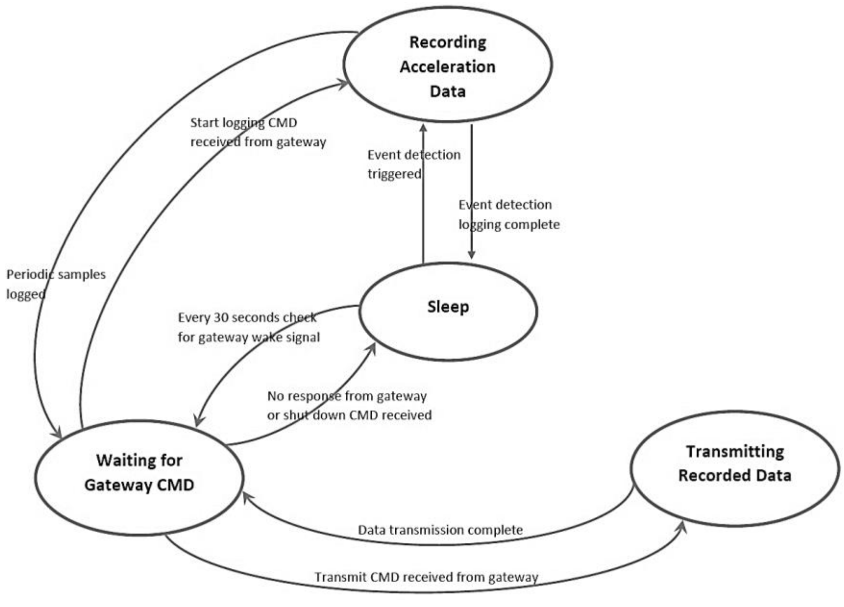


Fig. 3 - The wireless sensor network workflow.

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 as follows:

- Wake-up CMD: this command is periodically sent based on the user's configuration of the gateway setting. When the Wake-up CMD is received, the wireless sensor nodes read the on-board data, such as time, temperature, humidity and battery percentage and then store this information in the first section of the on-board flash memory. The nodes then wait for the start command from gateway.
- Start CMD: Start CMD is sent from gateway to all the nodes to synchronize the network in every time of recording. After receiving this command, the nodes start the data recording process. The synch pulse from gateway to the sensor nodes could provide minimum synchronization error (close to zero) between the nodes and keep the network synchronized for long-term SHM applications.

- Check for active nodes CMD: This command is sent from gateway to the network of sensor nodes when the gateway is ready to receive the logged data from one of the nodes. If this CMD is received with one of the nodes, then the node responds with another CMD that tells the gateway how many samples the gateway should expect (used for error checking).
- Gateway ready for transmit CMD: This CMD is received from the gateway to signal the active node to start transmitting the recorded samples. Only one node can transmit at a time and the first node to respond to the "Check for active nodes" CMD is the node that is selected.
- Transmit successful CMD: This CMD from the gateway to the active node indicates that the number of received samples is the same as the expected samples, which was indicated in the response to the "Check for active nodes" CMD for error checking. This command helps to avoid any loss of data and information recorded by the sensor nodes.
- Transmit unsuccessful: This command shows that the number of received samples by the gateway node was not the same as the expected samples as indicated in the response to the "Check for active modes" CMD. After receiving this command, the node retries 10 times to transmit the logged data when instructed by the gateway.
- Shutdown CMD: this command is sent by the gateway when transmission process is complete for all the nodes in network. This is determined to be when the network goes quite for at least 5 seconds.

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.

For an accurate vibration-based damage identification, an accurate time synchronization between different wireless sensor node is required. In this study, two techniques were implemented to provide an accurate time synchronization. The first technique is the use of a synch pulse from gateway node to wake up and start logging at exactly a same time. A post-processing technique was also considered for time synchronization to provide precise measurements from different nodes. Based on the ADXL355 datasheet, this accelerometer should sample 100 samples at a frequency rate of 65 Hz, which results in 1.35 s of sampling (the ideal time). However, the actual sampling time of each accelerometer varies due to the fluctuations of its internal clocks. As shown in Eq. (1), the difference between the ideal sampling time (T_{ideal}) and the actual sampling time (T_{actual}) is considered as the time offset of each accelerometer (T_{offset}).

$$T_{offset} = T_{ideal} - T_{actual} \tag{1}$$

The time offset is calculated using on board analysis and the value is shown on the header of each data files. This offset is used to calculate the compensated time for providing an accurate time synchronization between nodes. The compensated time (T_{com}) for each sensor board is different and calculated using Eq. (2):

$$T_{com} = \left(\frac{n_s}{f_s}\right) \times \left(1 + \frac{T_{offset}}{100}\right) \tag{2}$$

where n_s and f_s are the number of samples and sampling frequency, respectively. After calculating the time offset values for each sensor board, they are used to calculate a new sampling time for wireless sensor nodes. The process of synchronization using the compensated times is performed using the data management toolkit developed in MATLAB environment, which is introduced in the following section.

2.2 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 through the 'Data Management' panel. The data from different wireless sensor nodes are synchronized 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 toolkit. In addition, a detailed information about the wireless sensor network 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 synchronized and managed data files are then analyzed using various time and frequency domain methods implemented in the data analysis toolkit.

Data Analysis: The new data files can be uploaded to the 'Test Parameter' panel, 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), and plotting and saving the analysis results. Also, the vibration data sets can be analyzed using Peak Picking (PP), Frequency Domain Decomposition (FDD), and Enhanced Frequency Domain Decomposition (EFDD) techniques and 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' panel. The users are able to plot and visualize the analysis results and compare the results of different analysis techniques as shown in Fig.4.

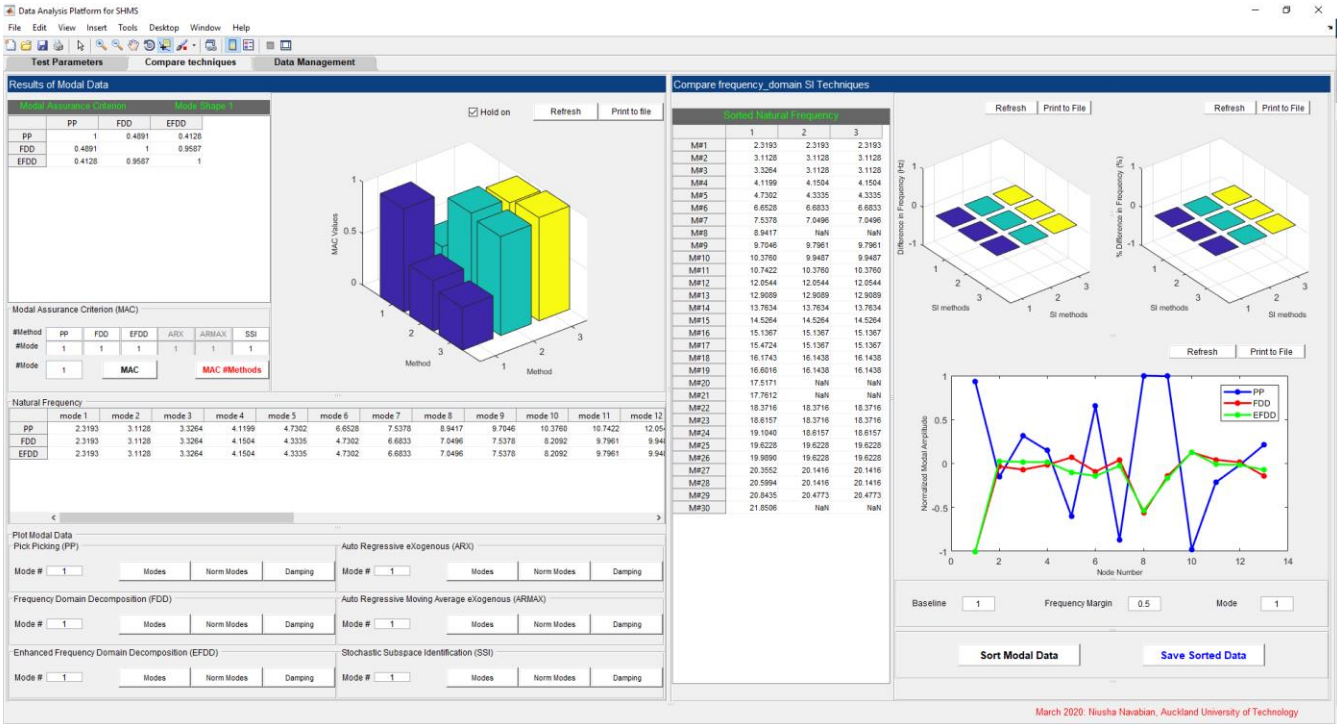
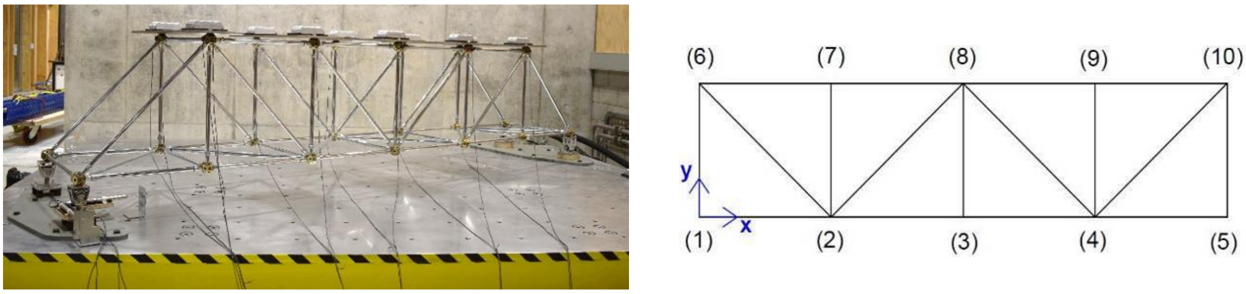


Fig. 4 - MATLAB-based data management and analysis toolbox.

3. Experimental validations

2.1 Shake table testing

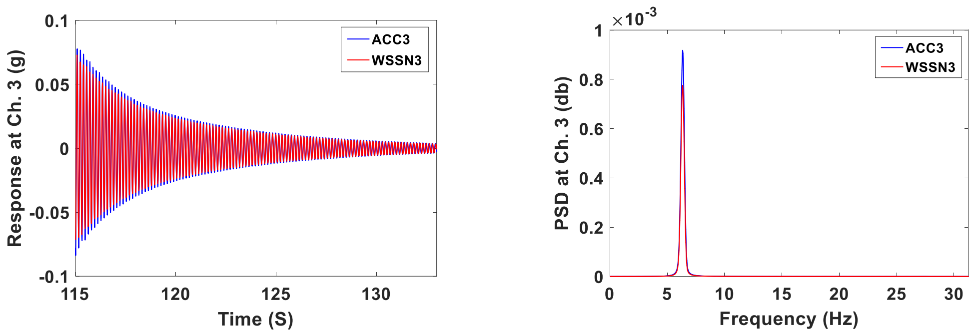
To evaluate the performance of the smart nodes, a series of dynamic tests was conducted on a uniaxial shaking table at Structures Lab of Auckland University of Technology. The shaking table has a dimension of 4 m ×3 m with a maximum displacement of ±200 mm in one axis. A six-span steel truss bridge model made of MERO joining system was used for the dynamic tests. Each span of the bridge includes steel tubes with length of 60.5 cm and 85.5 cm and it was placed on two pinned and two roller supports. To provide high inertia mass for the bridge during the dynamic testing, five steel plates with approximate weight of 10 kg were added to the top chord of the bridge in transverse direction. Figure 5(a) shows the steel truss bridge model on the shake table instrumented with wireless accelerometer sensor nodes and high-performance wired accelerometer sensors as reference system. The sensor locations are shown in Fig.5(b) in plan view.



(a) (b)

Fig. 5 - (a) The bridge model on the shaking table, and (b) sensor locations on top chord of the bridge.

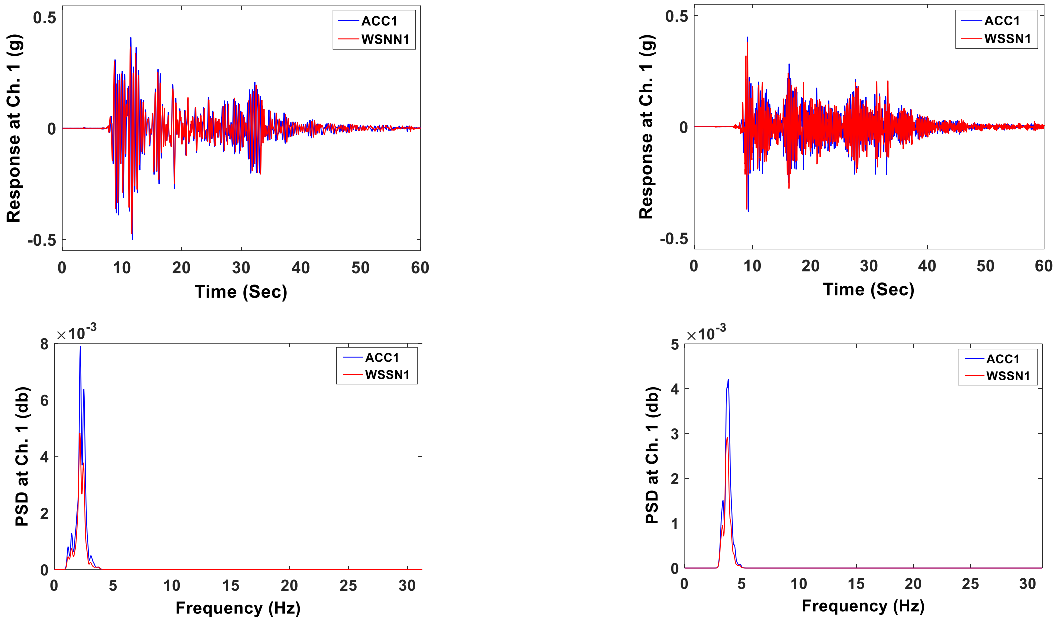
In total, eleven wireless smart sensor nodes were utilized during the test. One wireless smart sensor node (WSSN0) was placed on the shake table to measure the ground motions. Ten nodes (WSSN1-WSSN10) were installed on top chord of the bridge to measure the structural responses. Model 4610A accelerometer by TE Connectivity was used as the reference wired accelerometer. This uniaxial sensor is an ultra-low-noise accelerometer with a sensitivity of 1011 mV/g, and noise level of 2 µg/rms over 0-400 Hz. Similar to wireless accelerometer nodes, one wired accelerometer (ACC0) was located on the shake table and ten wired accelerometers (ACC1-ACC10) were attached to the joints to measure the structural responses. wireless nodes recorded the vibrations in X, Y, and Z directions of the bridge, i.e., longitudinal, transverse, and vertical directions, while the wired sensors recorded the vibrations only in transverse direction.



(a) (b)

Fig. 6 - (a) A time window of acceleration time histories, and (b) PSD values.

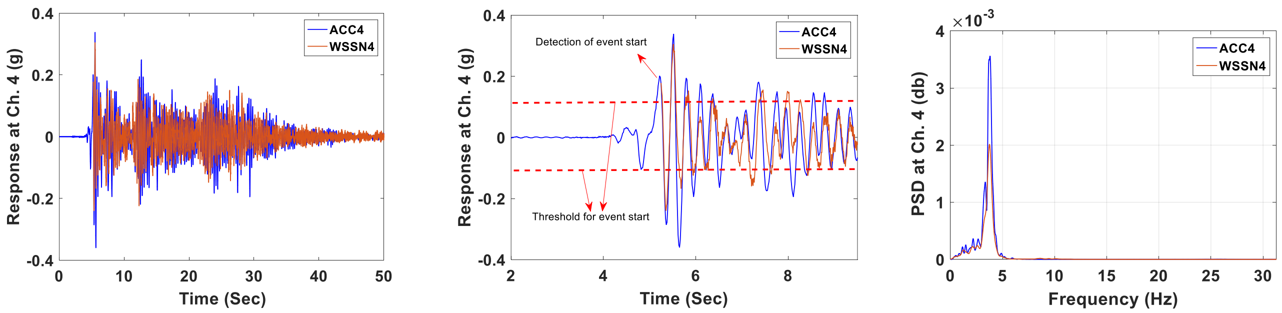
Figures 6(a) and (b) show a time window of acceleration time histories and the corresponding Power Spectral Density (PSD) values measured using WSSN3 and ACC3 located in mid-span of the bridge, respectively. During this test, the bridge was subjected to a sine sweep wave with peak amplitude of 0.2 mm and frequency range of 6 to 6.4 Hz. As is clear from the result, there is a perfect match between the time domain and frequency domain results measured using the developed wireless sensor node and the reference wired accelerometer. In another attempt, the structure was excited with a high-amplitude real ground motion. El Centro Earthquake with an amplitude of 85 mm was subjected to the structure. The acceleration time histories and the PSD values measured using channel 1 in both transverse and longitudinal directions are shown in Fig.7. There is a near to perfect match between acceleration and natural frequencies obtained using wireless smart sensor node and the wired accelerometer in both directions of the bridge model. It should be mentioned that both wireless and wired sensor were set to sample the vibrations at 62.5 Hz.



(a) X direction (longitudinal) (b) Y direction (Transverse)

Fig. 7 - Acceleration time histories and PSD values recorded by wireless and wired accelerometers.

To evaluate the event-triggered sampling mode of the wireless smart sensor nodes, they were set to event-triggered sampling mode. In this sampling mode, the sensors are able to log and sample the event-triggered vibrations at 125 Hz. For an accurate comparison, the wired accelerometer sensors were also set to sample the vibrations at 125 Hz. El Centro Earthquake with peak amplitude of 85 mm was simulated using the shake table as the sudden event. The vibration threshold was set to 100 mg for this vibration test. It means that in the case of occurrence of any event that has greater amplitude than 100 mg, the ADXL362 accelerometer wakes up the sensor board to start sampling the event using the high-performance ADXL355 accelerometer. Figure 8 shows the acceleration time histories of the earthquake-induced vibration and the PSD values measured using wired and wireless sensors by channel 4. As is clear, after the first peak greater than 100 mg, WSSN4 was awakened to log the structural response. The acceleration time histories and the PSD values measured using the wireless nodes and the reference wired sensor matched well showing capability of the wireless smart sensor nodes to detect and record the event with a high precision.

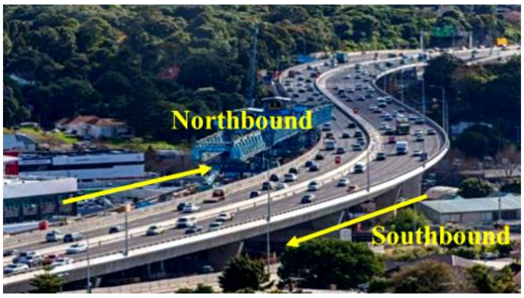


(a) (b) (c)

Fig. 8 - (a) Acceleration time histories, (b) acceleration time histories for the event start, and (c) PSD values.

2.2 Field testing

To test the performance of the wireless smart senor network in an outdoor environment, a series of ambient vibration test was conducted the Newmarket Viaduct, located in Auckland, New Zealand (Fig.9(a)). The structure is a seven-lane state highway viaduct with a length of 690 m and height of up to 20 m. It is a horizontally and vertically curved, post-tensioned concrete box bridge, comprising two parallel twin bridges. The bridge has twelve different spans with an average length of approximately 60 m.

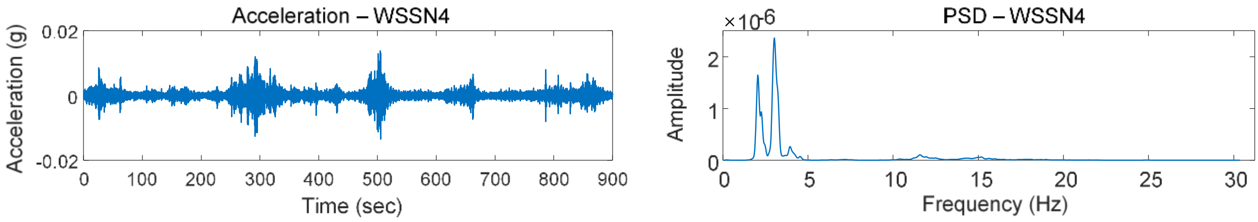


(a)

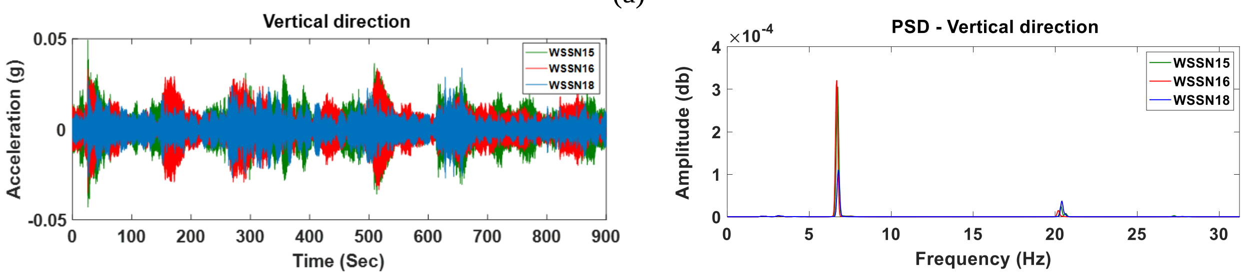
(b)

Fig. 9 - (a) Newmarket viaduct, and (b) installed wireless nodes inside the viaduct.

Span 9 of the bridge was selected for instrumentation, as several ambient vibration tests were already conducted on this span during various construction phases. The field experiments were conducted under operational conditions on November 2018. In total, 20 wireless smart sensor 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 deck and the remaining 6 sensors (WSSN15-WSSN20) were fastened to the post-tensioning cables. Figure 9(b) shows some of the wireless nodes installed inside the box girder. The wireless sensor nodes were programmed to sample the traffic-induced vibrations at 62.5 Hz for 15 minutes. The vibration data recorded by the wireless sensor nodes were transferred to the base station located in middle of span 9.



(a)



(b)

Fig. 10 - Acceleration time histories and PSD values of (a) bridge deck and (b) post-tensioning cables.

The wireless smart sensor nodes are intended to measure dynamic response of the bridge deck and post-tensioning cables when the bridge is subjected to the traffic and wind loading. These measurements help to evaluate the performance of the wireless sensor nodes for condition monitoring of large-scale structures. The vertical acceleration time history and the corresponding PSD value recorded by WSSN4 from the middle of span 9 is shown in Fig.10(a). As is clear, 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 during the test. Despite the low level of the bridge vibration amplitude, the developed wireless smart sensor nodes could record clear and low-noise acceleration time histories induced by traffic on the bridge. Figure 10(b) depicts the acceleration time histories and the natural frequencies measured from three post-tensioning cables in vertical direction using three wireless sensor nodes. The acceleration data measured across the post-tensioning 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. In overall, the results show that the developed wireless accelerometer sensors are able to record very low-amplitude vibrations from full-scale structures for an accurate estimation of dynamic characteristics.

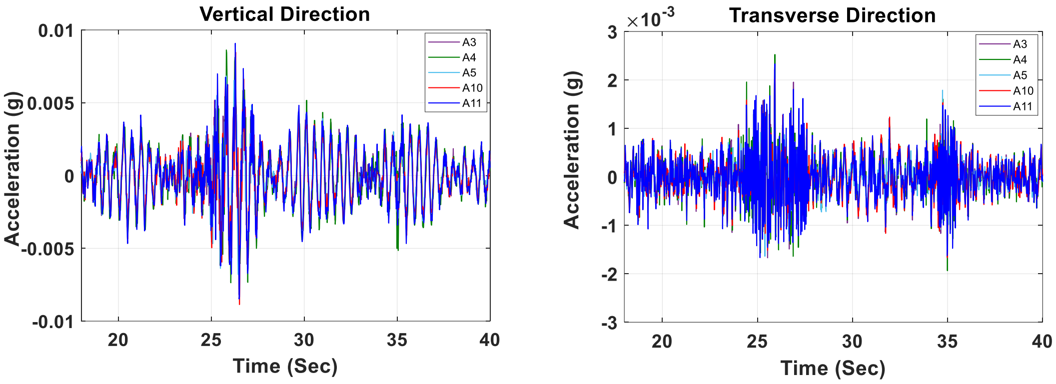


Fig. 11 - Time window overly of acceleration time histories during a traffic event.

As mentioned a common concern regarding the wireless sensor network is time synchronization between different wireless sensor nodes. In such network, each sensor node operates with its internal clock, which owns a unique offset specification. As mentioned, the developed wireless smart sensor 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. As mentioned, a post-processing time synchronization technique was also performed on the vibration measurements using the time offsets of each wireless sensor nodes. Figure 11 shows a time window of acceleration time histories measured during a traffic event by five wireless smart sensor nodes installed on different locations of the bridge in both vertical and transverse directions. The results confirm that the wireless smart nodes maintained phase among themselves with a maximum synchronization error of 1 to 2 milliseconds and the data can be reliably used for a precise estimation of the bridge modal characteristics, such as mode shapes. It is noteworthy that the data management and analysis on both laboratory and field experimental data were conducted using the MATLAB-based toolbox.

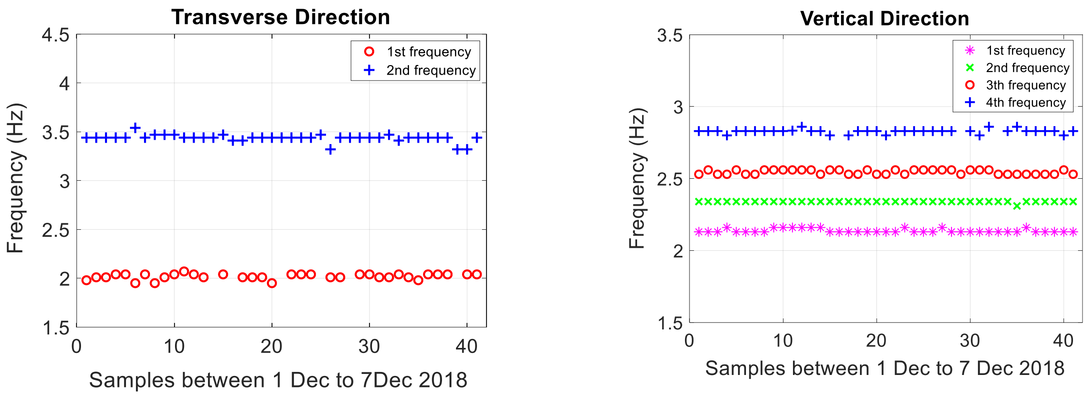


Fig. 12 - Variation of bridge modal frequencies measured during one week of monitoring period.

4. Condition monitoring of the full-scale bridge

In this part, the overall dynamic performance of the Newmarket viaduct is assessed using its modal parameters. To do so, the modal parameters of the structure obtained using the wireless smart sensor nodes were compared to the counterparts measured during previous tests on the viaduct performed during various construction phases [11]. Test 1 was carried out on the southbound bridge on 28th and 29th of November 2011 before casting the concrete 'stich'. Test 2 was carried out on both northbound and southbound bridges on 29th and 30th of November 2012 immediately after casting the concrete 'stich'. On 2nd and 3rd of December 2014, another set of ambient vibration testing (Test 3) was performed on northbound and southbound bridges to investigate the structural condition after two years of operation. The natural frequencies of the bridge measured during these tests were used in this study to compare the overall condition of the superstructure after several years of operation. The acceleration time histories recorded by wireless smart sensor nodes were analyzed using Enhanced Frequency Domain Decomposition (EFDD) method to measure the natural frequencies of the Newmarket Viaduct. Figure 12 shows the variation of the first two transverse and first four vertical natural frequencies obtained using the vibration data during one week of monitoring period. As is clear from the figure, a good consistency in natural frequencies of both measurement directions was observed during the monitoring period. The small variations between the frequencies could be due to the stationarity of the signal and accuracy of the computational algorithm.

Table 1 - Natural frequencies measured during the ambient vibration tests on the viaduct.

Test	Transverse modes (Hz)		Vertical modes (Hz)				
	T1*	T2	V1	V2	V3	V4	V5
1	1.05±0.00	1.41±0.03	2.12±0.02	2.25±0.01	2.43±0.02	2.66±0.04	2.88±0.02
2	1.25±0.01	1.56±0.00	2.03±0.01	2.15±0.00	2.34±0.00	2.54±0.03	2.82±0.02
3	1.25±0.01	1.56±0.00	2.03±0.00	2.15±0.00	2.34±0.00	2.54±0.00	2.82±0.01
4	1.25±0.03	1.55±0.03	2.04±0.03	2.13±0.03	2.34±0.00	2.56±0.03	2.83±0.03

*T1=transverse mode 1 (V=vertical)

A comparison was made between the results of previous ambient vibration tests and the ambient vibration test (T4) carried out using the wireless nodes. Table 1 shows the first two transverse modes and first four vertical modes measured using different vibration tests. As is obvious, there is a very good match between the transverse and vertical natural frequencies obtained from different ambient vibration tests. The small difference between the results of T1 with other tests is due to the fact that this test was carried out before the casting the concrete 'Stich' and the northbound and southbound bridges were separate from each other. Generally, the consistency observed in dynamic characteristics of the bridge shows that there are no significant changes in the overall dynamic performance of the structure after several years in operation and the bridge has a reliable performance under the traffic loading. It should be mentioned that for more precise estimation of the bridge condition, more vibration datasets should be recorded from the structure.

5. Conclusions

In this paper, an integrated structural health monitoring system for civil structures is introduced. This system includes wireless smart sensor system network and MATLAB-based data management and data analysis toolbox. The wireless smart sensor board was designed to decrease the power consumption and costs associated with existing Structural Health Monitoring System (SHMS) and to increase the accuracy and performance of vibration-based condition assessment. The multipurpose MATLAB-based toolbox was also developed to manage and synchronize time-series data, visualize and process 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. Several laboratory and field experimental tests were conducted on a small-scale bridge model and a post-tensioned balanced cantilever bridge to investigate different features of the developed SHM system. The results of the shake table tests showed that the resolution of the wireless smart sensor nodes are comparable with expensive wired accelerometers. Also, the wireless smart sensor nodes recorded high-fidelity structural responses during the sudden event using high resolution accelerometer. Besides capturing sudden events from structures, this sampling mode helps to save the power source of the wireless smart sensor nodes for long-term SHM applications. In addition, Consistent and precise structural peaks were obtained using the vibration data recorded from the bridge deck and post-tensioning cables. The results showed the reliability of the wireless smart sensor network to estimate dynamic characteristics of the large-scale structure in an outdoor environment. The wireless sensor nodes also maintained phase among themselves and were well synchronized. These results confirmed the reliability of time synchronization techniques and showed their efficiency to be utilized for dynamic characteristics estimation of full-scale structures. The results also showed that the vibration measurements were seamlessly transferred using DigiMesh topology confirming the application of this topology in WSN development for SHM applications. The natural frequencies extracted from vibration data recorded by wireless smart sensor nodes was compared with the counterparts measured during previous vibration tests. The consistency of the results showed that there are no obvious changes in overall dynamic performance of the superstructure after several years in operation.

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