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Development of a wireless sensory system for long-term monitoring of large-scale civil structures

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ABSTRACT

In this study, dynamic performance of one of the most significant infrastructures in New Zealand, the Newmarket Viaduct, is assessed using a new wireless sensory system developed to address the limitations associated with wired Structural Health Monitoring (SHM) systems. The new system is a part of an integrated SHM system to collect ambient and earthquake-induced vibrations from civil structures. The main aims of the design are to lower cost, improve power consumption compared to the wired sensory systems, and to achieve higher performance compared to the existing wireless sensory systems. Another goal of this development is to control the hardware parts of the system for different SHM applications. To show the system performance for large-scale structures, it is installed on one span of the Newmarket Viaduct to measure dynamic characteristics of the superstructure. For long-term monitoring of the bridge performance, the identified natural frequencies are compared to the counterparts measured during three ambient vibration tests, Test 1, Test 2, and Test 3, carried out on 2011, 2012 and 2014, respectively. The comparison between modal parameters is carried out to reveal any significant changes in structural performance over time. The consistency in dynamic features of the bridge measured during different tests indicates a reliable performance of the developed system in terms of resolution, sensitivity and wireless communication for long-term structural monitoring. The dynamic characteristics extracted from vibration data collected at different test setups indicate no obvious changes in the structural performance after several years of operation.

1 INTRODUCTION

In today's world, the need for quick damage assessment of structures after severe events such as earthquakes and the ability to regularly monitor the structural integrity is becoming considerably significant from both

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economic and life-safety viewpoints. Vibration-based methods are among most widely-used techniques by researchers to assess the integrity of civil structures (Huang 2018). To use such valuable methods for reliable and accurate structural assessment, the dynamic characteristics of structures such as natural frequencies, mode shapes, and modal damping ratios need to be precisely measured. To accomplish this task, ambient vibration and forced vibration tests can be carried out (Beskhyroun et al. 2013; Navabian et al. 2016). Utilisation of sensor technology integrated within structures could extremely increase the efficiency of the inspection procedure through rapid in-situ data collection and processing. However, traditional sensory systems use wires to connect the sensors to a central server. Such systems usually incur high installation costs and long setup times especially for large civil infrastructures. Due to the high cost and complexity of traditional wired sensory systems, the improvement in Micro-Electro-Mechanical System (MEMS) provides researchers with great opportunities to develop sensor nodes with sensing capabilities, wireless communication and data processing options for reliable SHM applications. This improvement could provide a successful implementation of large sensing networks throughout large civil structures by limiting the complexity and high cost associated with the traditional wired sensory systems (Çelebi 2000; Pakzad 2008). In this study, the performance of one of the most significant civil infrastructures in New Zealand, Newmarket viaduct, is investigated using a new wireless sensory system. This system has been developed to address the limitations associated with wired sensory systems designed for SHM applications. The new wireless SHM system is a part of an integrated SHM system that is able to collect ambient and earthquake-induced vibrations from large-scale civil infrastructures. To show the performance of the system, it was installed on one span of the Newmarket Viaduct to measure dynamic characteristics of the bridge. In addition, for long-term monitoring of the bridge performance, the identified natural frequencies are compared to the counterparts measured during three construction stages.

2 NEWMARKET VIADUCT

Newmarket viaduct is one of the most distinctive engineering features' of New Zealand. The bridge is a seven-lane state highway viaduct in Auckland with the length of 690m and up to 20m high in places. It is a horizontally and vertically curved, post-tensioned concrete box bridge, comprising two parallel twin bridges. The Northbound and Southbound Bridges are supported on independent pylons and joined together via a cast in-situ concrete 'stich'. The 700m bridge has twelve different spans ranging in length from 38.67m to 62.65m and average length of approximately 60m (Chen et al. 2013). The views of the viaduct are shown in Figure 1.

Figure 1: Newmarket Viaduct (Auckland Motorways 2013).

2.1 Previous ambient vibration tests

The southbound of the viaduct, spans 8 and 9, was instrumented by a continuous monitoring system on 2009 including 20 vibrating wire strain gauges, 42 embedded temperature sensors, two external temperature and humidity sensors, and four baseline systems measuring deflections (Chen et al. 2013). A series of ambient vibration testing was performed on the Newmarket Viaduct. The first test (Test 1) was carried out on November 28th and 29th 2011 before casting the concrete 'stich' on the Southbound and the next testing

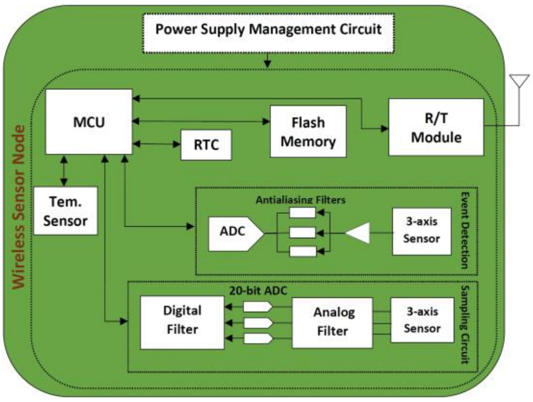
(Test 2) was carried out on November 29th and 30th 2012 immediately after casting the concrete 'stich' on both Northbound and Southbound. Also, on December 2nd and 3rd 2014, another set of ambient vibration testing was performed on Northbound and Southbound of the bridge to investigate the condition of the bridge after two years of operation. A number of MEMS accelerometers was used to measure the vibration induced by traffic on the bridge during all the tests. The results measured from these setups are used in the study for long- term monitoring of the superstructure.

3 WIRELESS MONITORING SYSTEM

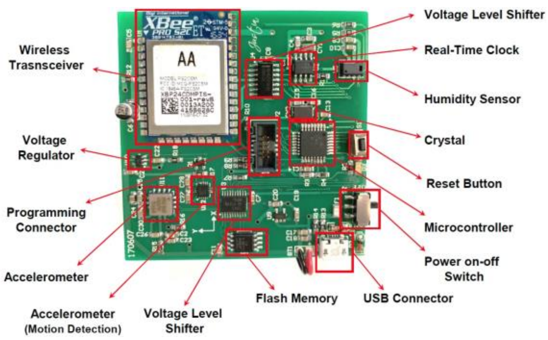
In this part, the wireless SHM system, which has been designed and installed on the Newmarket Viaduct, will be introduced and presented. The system consists of two major parts including sensor nodes and the base station unit. The base station unit is the heart of the system and consists of an industrial grade PC, a Mobile Wi-Fi modem for remote access to the system, and an XBee Pro Series 2C module, all enclosed by a weatherproof plastic enclosure. One of the critical components is the Intel Core i7-7600U Processor selected due to its high power, fanless design, and high storage capacity. In this research, three different versions of wireless sensor nodes were designed. The first and second versions were designed to measure earthquake- induced and ambient vibrations from structures, respectively. The features of the first two wireless sensor nodes were combined into a new sensor board to make a new versatile wireless sensor node for vibration-based structural health monitoring. Third generation of wireless sensor node is able to record both low-amplitude ambient vibrations and high-amplitude earthquake-induced vibrations from large-scale structures. Figure 2 shows the development process of the third version of wireless sensor node at AUT electrical lab.

Figure 2: Manufacturing of the third version of wireless sensor node at AUT electrical lab.

Figure 3 shows the schematic design and the components of the third version of wireless sensor node. As is obvious, the main components of the sensor node are: (1) a pico-power microcontroller, 2) a XBee S^2C RadioFrequency (RF) module (3) an external flash memory for data storage, (4) a highly sensitive Real-Time Clock (RTC) for time synchronisation between sensor nodes, (5) a humidity and temperature sensor, (6) a 3- axis ultralow noise density accelerometer with an integrated 20-bit Analogue-to-Digital Converter (ADC), (7) an ultralow power 3-axis MEMS accelerometer with motion detection feature, and 8) a USB connector. Atmel picoPower microcontroller was selected due to its low power consumption in active and sleep modes and its low cost. The XBEE S^2C 802.15.4 RF module was selected for wireless communication between sensor nodes and the gateway unit. In addition, a 64-Mbit SPI external flash memory was selected to temporarily store the vibrations before wireless transmission. A Battery-backed I^2C Real-Time clock/calendar was embedded to the board design to synchronise the sensors in the network. The sensor board has two sensing components for measuring the ambient parameters. One is a fully calibrated humidity and temperature sensor with low power consumption. Second is a highly sensitive and low power 3-axis digital accelerometer with selectable measurement ranges. This low power chip has an ultralow noise density of 25 µg/√Hz in all axes and internal 20-bit ADC to digitise the filtered analogue signal. This accelerometer uses an analogue, low- pass, antialiasing filter and an additional digital filtering option including low-pass and high-pass digital filters. For measuring earthquake-induced vibration, an event-detection accelerometer was added to the board design to trigger the sensor board to log the earthquake-induced vibration.



(a)



(b)

Figure 3: (a) Schematic diagram, and (b) components of the third version of wireless sensor node.

4 AMBIENT VIBRATION TESTS

4.1 Ambient vibration testing procedure

In order to monitor the bridge condition and to investigate the performance of the developed wireless sensory system in an outdoor environment, the wireless sensory system was installed on span 9 of the Newmarket Viaduct (Figure 4). The field testing was conducted on December 1, 2018 under operational conditions, which did not interfere with the flow of the traffic over the viaduct. The dynamic characteristics, such as natural frequencies, of the bridge and the post-tensioning cables were obtained using the vibration recorded by the sensory system. A total of 20 measurement points were selected inside the box girders on both sides of the span for placing the accelerometers. Figure 5 shows the locations of the sensors and the base station unit inside the concrete box. 14 sensor nodes, Ch.1-Ch.14, were attached to the internal surface of the bridge deck to measure the ambient vibration induced by the traffic. The remaining 6 sensor nodes, Ch.15-Ch.20, were fastened to the post-tensioning cables to measure the vibration of the cables due to the operational uses.

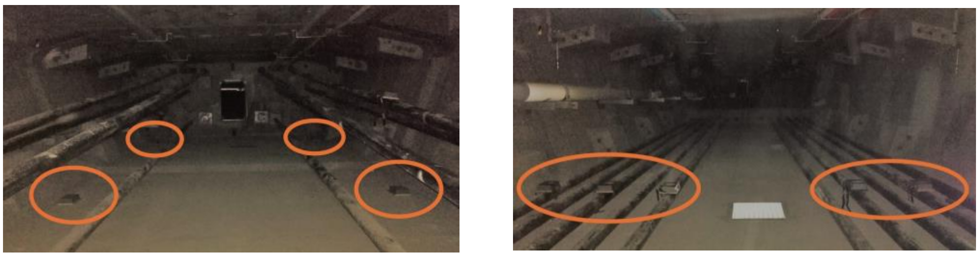


Figure 4: Bridge instrumentation using the wireless sensory system.

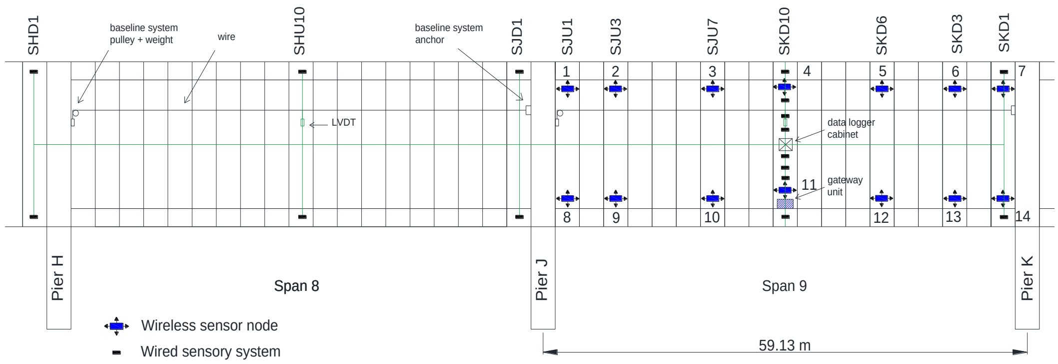


Figure 5: Locations of the wireless SHM system inside the concrete box of the bridge (Span 9).

The wireless sensory network records acceleration, humidity and temperature every 4 hours for 15 minutes using time-triggered mode with sampling frequency of 62.5Hz. The system was installed on the bridge for long-term monitoring under operational uses. However, only one week of ambient vibration recorded from 1st Dec to 7th Dec 2018 are analysed here. The base station unit was connected to the bridge electrical system to supply a continuous power. In addition, although the sensor nodes can operate with four 1.5V AA industrial alkaline batteries, they were powered by a 12000mAh USB battery pack to increase the network lifetime.

4.2 Identification of modal parameters

In this part, the results of modal analysis on vibration data recorded from the bridge and the post-tensioning cables are presented. It is noteworthy that the vibration recorded from the bridge in longitudinal direction is ignored from the analysis, as they are not significant for dynamic assessment of the bridge. The analysis was carried out using a system identification toolbox developed in MATLAB (Beskhyroun 2011). After preliminary data manipulation, the mean and trend removal, the Power Spectral Density (PSD) of acceleration recorded from the bridge deck and the post-tensioning cables are obtained. Figure 6 presents the PSD values of acceleration obtained from vibration recorded by Ch.11 at the mid-span of the bridge in both transverse and vertical directions. Figure 7 also depicts the PSD values of acceleration recorded by Ch.18 on cable #7 in vertical direction. The datasets were recorded at 1pm during one week of monitoring period (1Dec-7Dec). The PSD magnitudes obtained from the data recorded from the bridge deck and the post-tensioning cable on weekend (December 1 & 2) are less than the values obtained during weekdays because of less traffic loads on the bridge during the first two days of the monitoring period. The results show a good consistency between the PSD values obtained from different datasets recorded at different days of a week.

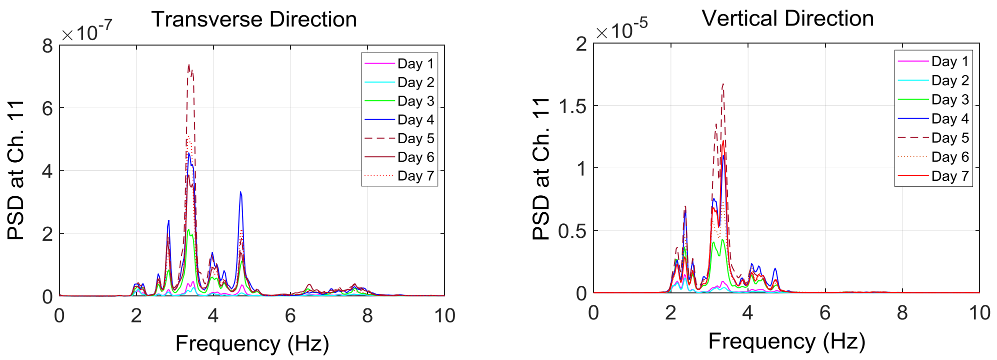


Figure 6: Power spectral densities of acceleration recorded by Ch.11 in Transverse and vertical directions.

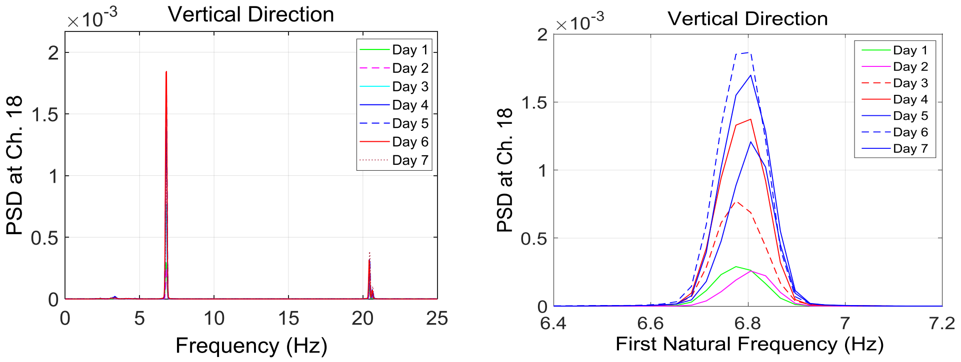


Figure 7: Power spectral densities of acceleration recorded by Ch.18 (cable #7) in vertical direction.

In next step, the vibration datasets recorded during one week are analysed using Enhanced Frequency Domain Decomposition (EFDD) method to identify the dynamic characteristics of the bridge after several years of operation. The first three natural frequencies of the bridge measured in vertical direction using different wireless sensor nodes are presented in Table 1. There is a perfect match between the results obtained using various channels which is an indication of reliable performance of the sensor nodes for recording low- amplitude ambient vibration from large-scale structures. Figure 8 shows the variation of modal frequencies in vertical and transverse directions using the vibrations sampled by Ch.4 during one week. A good consistency in natural frequencies 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: Vertical natural frequencies measured using different sensors located on the bridge deck (Hz).

Mode	**Ch.1**	**Ch.2**	**Ch.3**	**Ch.4**	**Ch.5**	**Ch.6**	**Ch.7**	**Ch.8**	**Ch.9**	**Ch.10**	**Ch.11**	**Ch.12**
1	2.04	2.03	2.03	2.03	2.04	2.03	2.04	2.04	2.04	2.03	2.03	2.03
2	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13
3	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34

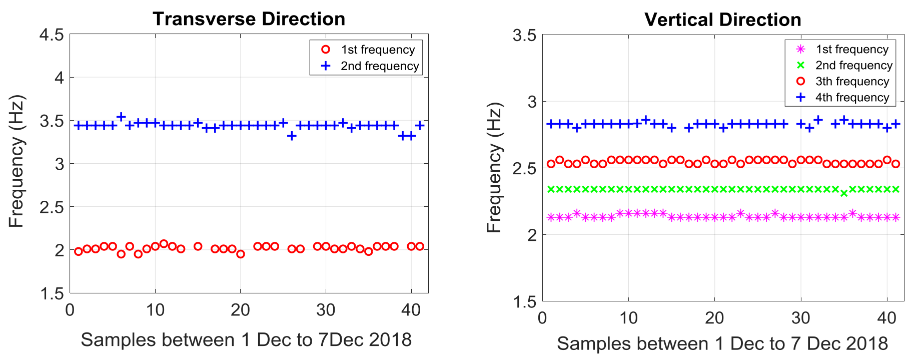


Figure 8: Variation of bridge modal frequencies measured by Ch.4 during one week of monitoring period.

In this part, the results obtained during the ambient vibration test (T4) carried out using the developed system are compared to the results measured during T1, T2 and T3. Table 2 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.

This consistency in dynamic characteristics of the bridge shows there is no significant changes in the bridge dynamic performance after several years of operation. A small difference between the results of T1 and T2-T4 is due to the fact that they were conducted on the viaduct at different construction phases.

Table 2: Natural frequencies measured during four stages of ambient vibration tests on the bridge.

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)

In this part, the effect of amplitude of vibration on the frequency of the post-tensioning cables is investigated. To do, vibration method using multiple modes developed by Shimada is used (Shimada 1994). This method starts with the equation of motion of a cable with bending rigidity (Eq. 1).

$$m\frac{\partial^2 z}{\partial t^2} + EI\frac{\partial^4 z}{\partial x^4} - T\frac{\partial^2 z}{\partial x^2} = 0 \qquad (1)$$

where z is vertical displacement, x is longitudinal coordinate, m is the unit mass, EI is the bending stiffness of the cable and T is the cable tension in the direction of cable length. Then by assuming that EI and T are constant along the cable length and the hinged boundary condition at both ends, the above equation can be present as:

$$T = 4ml^2\left(\frac{f_n}{n}\right)^2 - \frac{EI\pi^2}{l^2}n^2 \qquad (2)$$

where l is the length and f_n is the n^{th} natural frequency of the cable. The relation between $\left(\frac{f_n}{n}\right)^2$ and n^2 can be rearranged as:

$$\left(\frac{f_n}{n}\right)^2 = \frac{EI\pi^2}{4ml^4}n^2 + \frac{T}{4ml^2} = \mathrm{a}.n^2 + b \qquad (3)$$

Due to the fact that a cable is a very flexible structure, the multiple natural frequencies can be easily measured using the vibration measurements. By obtaining linear regression between multiple $(f_n/n)^2$ and n^2 and considering b and a as the y-intercept and slop of the linear regression, EI and T can be estimated as:

$$EI = \frac{4ml^4}{\pi^2}\mathrm{a} \quad , \quad T = 4ml^2 b \qquad (4)$$

Two sets of low-amplitude and high-amplitude vibration data recorded at 5:00 AM and 9:00 PM are considered for analysis in this part. Figure 9 shows the time-history recorded from the post-tensioning cable by Ch.18. As is obvious, the data recorded at 9:00 PM has higher amplitude in comparison to the vibration recorded at 5:00 AM. The natural frequency of cable #7 measured using these datasets was obtained using PSD estimation. Then, a linear regression was carried out to find the relation between $(f_n/n)^2$ and n^2 for the low-amplitude and high-amplitude datasets. The results including the first three frequencies of the cable and the associated equations obtained by linear regression are presented in Table 3.

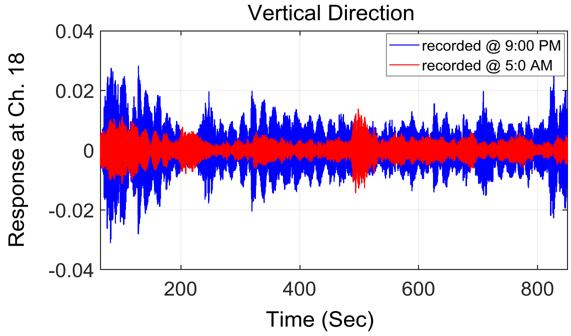


Figure 9: Time-history acceleration recorded by Ch. 18 at 5 AM and 9 PM.

Table 3. Natural frequencies of cable #7 and the corresponding equations obtained from linear regression.

Dataset	Mode number	1	2	3	Equation
Recorded @ 5:00 AM	Frequency (Hz)	6.77	20.42	27.86	$\left(\frac{f_n}{n}\right)^2 = 4.16n^2 + 59.32$
Recorded @ 9:00 PM	Frequency (Hz)	6.80	20.48	27.77	$\left(\frac{f_n}{n}\right)^2 = 4.02n^2 + 60.15$

The first two natural frequencies of the cables, the most dominant ones, increased as the vibration amplitude increased by the traffic loading. Accordingly, term *b* obtained from the linear regression, which represents the tensile force in the cable, was higher for the dataset with higher vibration amplitude. Therefore, natural frequencies of the post-tensioning cables and corresponding tensile forces are proportional to the magnitude of vibration induced by traffic loading. It is noteworthy that using higher modes of vibration could result in more accurate regression between $(f_n/n)^2$ and n^2 for obtaining the tensile force in post-tensioning cables.

5 CONCLUSIONS

In this study, the performance of one the most important superstructures in New Zealand, Newmarket viaduct, is assessed after several years of operation using a new developed wireless SHM system. The new wireless sensory system is developed as a part of an integrated monitoring system for long-term monitoring of large- scale civil structures. To show the system performance, it was installed on one span of the Newmarket Viaduct to identify dynamic characteristics of the structure. During the test, the performance of the wireless sensory system in terms of hardware permanence, wireless communication, power consumption and software stability are investigated for a robust SHM system. Next, for long-term monitoring of the bridge performance, the identified natural frequencies are compared to the counterparts measured during different ambient vibration tests. The analysis of the modal parameters from all the ambient vibration test, separated by one-year, two-year, and four-year intervals, is utilised to investigate any potential changes in the structure performance over time. The natural frequencies extracted from vibration data collected at different construction stages indicate no obvious changes in the performance of the superstructure under operational loading after several years of operation. In addition, the consistency in the dynamic characteristics of the bridge measured during all ambient vibration tests prove the sensitivity and resolution of the sensors and the reliability of wireless communication for SHM application. Further development of the sensory system for long-term monitoring is under progress.

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