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Rapid full-scale expansion joint monitoring using wireless hybrid sensor

Shinae Jang*, Sushil Dahal and Jingcheng Li

Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT 06269, USA

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Abstract. Condition assessment and monitoring of bridges is critical for safe passenger travel, public transportation, and efficient freight. In monitoring, displacement measurement capability is important to keep track of performance of bridge, in part or as whole. One of the most important parts of a bridge is the expansion joint, which accommodates continuous cyclic thermal expansion of the whole bridge. Though expansion joint is critical for bridge performance, its inspection and monitoring has not been considered significantly because the monitoring requires long-term data using cost intensive equipment. Recently, a wireless smart sensor network (WSSN) has drawn significant attention for transportation infrastructure monitoring because of its merits in low cost, easy installation, and versatile on-board computation capability. In this paper, a rapid wireless displacement monitoring system, wireless hybrid sensor (WHS), has been developed to monitor displacement of expansion joints of bridges. The WHS has been calibrated for both static and dynamic displacement measurement in laboratory environment, and deployed on an in-service highway bridge to demonstrate rapid expansion joint monitoring. The test-bed is a continuous steel girder bridge, the Founders Bridge, in East Hartford, Connecticut. Using the WHS system, the static and dynamic displacement of the expansion joint has been measured. The short-term displacement trend in terms of temperature is calculated. With the WHS system, approximately 6% of the time has been spent for installation, and 94% of time for the measurement showing strong potential of the developed system for rapid displacement monitoring.

Keywords: structural health monitoring; wireless smart sensor; displacement measurement; bridge expansion joint; temperature

1. Introduction

More than 25 percent of the Nation's 600,000 bridges have been rated as structurally deficient or functionally obsolete (Report Card for America's Infrastructure 2009, Bridge Preservation Guide 2011). This number is only to grow as more than 30 percent of existing bridges have exceeded their 50-year theoretical design life and are in need of various levels of repairs, rehabilitation, or replacement. Increasing travel demands, limited funding, and increasing costs of labor and materials have compelled the bridge owners to act towards structural health monitoring (SHM) and condition assessment of their bridges to prevent sudden and catastrophic failure.

*Corresponding author, Professor, E-mail: sjang@engr.uconn.edu

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SHM has drawn significant attention due to the possibility to provide early alarm on structural condition. To date, numerous researchers have spent great efforts in past three decades related to SHM (Doebling *et al*. 1996, Sohn *et al*. 2003). Some researchers investigated various sensing technologies on displacement measurement using optic device (Wahbeh *et al*. 2003, Lee *et al*. 2007), GPS (Nakamura 2000), Laser Doppler Vibrometer (Nassif 2005), etc. However, challenges remain before such methods can be applied routinely to bridge structures in the field. In reality, the number of the sensors in an installation is limited due to the cost of the sensors, data acquisition systems, and system installation. Also, the cost of installation and maintenance of traditional wired sensors is high. Furthermore, management of the data acquisition system is difficult because of large quantities of raw data streaming continuously. Therefore, a cost effective sensor with reliable data acquisition capability which can overcome the limitations of the conventional wired sensors is desirable.

With the recent advancements on the MEMS technology, more sophisticated and advanced systems have been developed in the field of SHM. Among them, wireless smart sensor network (WSSN) is a potential candidate to overcome the drawbacks of wired SHM system due to its cost effectiveness and versatility. Easier installation, effective data management, lower initial and maintenance cost are the attractive features of WSSN. Moreover, WSS have on-board computation capability that can help to mitigate the problem of data inundation that is intrinsic to densely instrumented structures. Recently, some researchers implemented WSSN to monitor vibrations of bridge structures (Jang *et al*. 2010, Jang *et al*. 2011, Kim *et al*. 2007, Lynch *et al*. 2006, Nagayama 2007, Pakzad 2008, Rice and Sepencer 2009, Jo *et al*. 2011). Still, research to measure displacement of bridge structures is quite limited.

Among many parts of bridges, expansion joint plays an important role in bridge performance and safety. An expansion joint is an assembly designed to safely accommodate the deformation of bridge deck caused by heat-induced expansion and contraction of various construction materials, to absorb vibration, to hold certain parts together, or to allow movement due to ground settlement or earthquakes without imposing significant secondary stresses on the super structure (Dornsife 2000). Because failure of the expansion joint may affect functionality of the whole structure, it is important to keep track of the status of the expansion joint with monitoring. The displacement of the expansion joint is primarily due to cyclic thermal expansion and contraction that occur throughout the life of the structure. Once a correlation pattern between displacement and temperature is established as a baseline, the comparison of deviation in future would be used as early alarm on the condition of the expansion joint. By comparing the monitoring data with design values, verification on the design can be provided. In addition, an accurate monitoring system can offer reliable information for decision making on repairing or replacing the expansion joints to prevent structure failure.

Due to lack of monitoring the expansion joints performance, failures of the expansion joints have caused some severely bridge collapse. For example, the Mianus river bridge carries I-95 over the Mianus River in Greenwich, Connecticut collapsed in 1983 (Graybeal *et al*. 2007). Rust formation within the bearing on the pin, exerting a force on the hanger which was beyond design limits started a fatigue crack at a sharp corner on the pin. When two heavy trucks and a car entered the section, the expansion joint failed, and the bridge deck crashed into the river. In addition, a highway bridge in Montreal, Canada was collapse one hour after the inspection in 2006 (Charron 2006). The reason was the road salts used for melting snow causing heavy corrosion of support below the leaked expansion joint.

Yet, the technology for inspecting expansion joints is limited. On-site inspection of expansion joints was performed by at Vasco da Dama Bridge (Guerreiro *et al*. 2011). The evaluation was based on visual inspection complemented by sound responses to determine where maintenance was needed for the expansion joints. A long-term assessment of bridge expansion joints displacement and temperature was presented by Ni *et al*. (2004) for the cable-stayed Bridge, the Ting Kau Bridge. A procedure for predicting and verification of the maximum displacement range, extreme temperature, and cumulative movement of the expansion joints was established. All sensor channels for this research were wired sensors, which involved with expensive cost for sensors, computer, and wires, as well as long installation time because of long wires. Therefore, a wireless, long-term, robust expansion joint monitoring system is lacking.

In this paper, a wireless displacement monitoring system which can check the displacement of expansion joint with low cost and rapid installation has been developed. To do that, the wireless data transmission functionality of WSSN, and accurate analog displacement sensor has been combined into a wireless hybrid sensing (WHS) system. The WHS system has been employed to measure the real-time static and dynamic displacement of the expansion joint of an in-service highway bridge. For completeness, the schematics and calibration of the WHS system are described, followed by the laboratory-scale experiments to measure simulated thermal expansion of a truss bridge. Finally, the WHS system has been deployed on an in-service highway bridge, the Founder’s Bridge in Connecticut, to demonstrate its performance in rapid displacement sensing of an expansion joint. The developed system shows the potential of WSSN for field transportation system monitoring with cost and time efficiency.

Table 1 Comparison of sensor boards

Criteria		SHM-A Sensor Board*	UConn Sensor Board
Acceleration	Resolution	0.06 mg	0.045 mg
	Range	± 2 g	± 1.5 g
	Sensitivity	0.66 V/g	0.8 V/g
Temperature	Range	-40 to 123 C	-40 to 120 C
	Accuracy	± 0.3 C	± 0.4 C
Humidity	Range	0 to 100% RH	0 to 100% RH
	Accuracy	± 3.0% RH	± 3.0% RH
Light	Range	0.1 to 40000 Lux	0.1 to 40000 Lux
	Resolution	0.61 Lux	0.61 Lux
External Input	Channel 4	0 V to 3.3 V	-10 V to 10 V

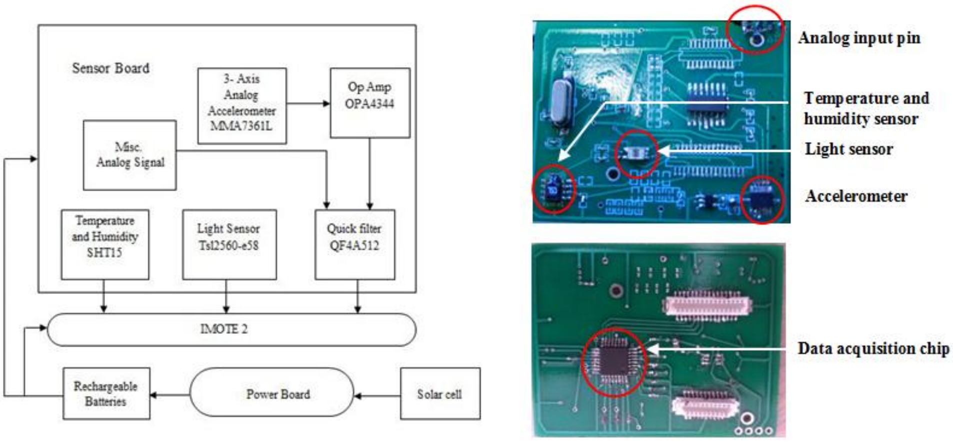
2. Wireless hybrid sensing system

2.1 Multi-scale wireless sensor board

A multi-scale wireless sensor board (Jang *et al*. 2012) has been developed at University of Connecticut, based on the SHM-A board, developed by Rice and Spencer (2009). The developed sensor board is dedicated for SHM applications and is capable of providing the information required for comprehensive infrastructure monitoring. The sensor board was designed to interface with the Imote2 smart sensor platform, providing three axes of acceleration as well as light, temperature and humidity measurements. The developed sensor board was also designed as an analog/digital hybrid design which implements a tri-axial accelerometer and digital light, temperature, and humidity sensors. In addition, the 4-channel analog to digital converter (ADC) can accommodate the addition of one external analog input signal which can read any sensors including strain sensor, anemometer, or displacement sensors. However, compare to SHM-A sensor board, it has higher resolution, better accuracy. Most importantly, it increases the external input voltage range which makes it much suitable for implementing addition analog input signal.

Those improvements were shown as highlighted in Table 1.

Fig. 1(a) shows the block diagram of the developed multi-scale sensor board (Jang *et al*. 2012). The measurement from analog accelerometer is passed through the operational amplifier which is fed into the signal conditioner consisting of 16-bit analog to digital converter. The signal conditioner implements anti-aliasing filters and finite-input response filter which help to reduce internal and external noise and also possible data error. From the signal conditioner, the signal is passed to Imote2 from where it is transmitted wirelessly. Since the temperature, humidity and light sensors are digital, those signals are sent to the Imote2 directly from where they are transmitted by wireless transmission. Fig. 1(b) shows the detail design of the sensor board. Therefore, a new multi-scale wireless sensor board has been designed and fabricated.



(a) Block diagram of wireless sensor board (b) Wireless sensor board

Fig. 1 Multi-scale wireless sensor board

2.2 Development of the WHS system

The wireless hybrid sensor (WHS) system has been developed by combining the Imote2, the multi-scale wireless sensor board and a high-resolution displacement transducer (Jang *et al*. 2012). The Imote2 was chosen because of the fast CPU speed (416 MHz maximum), and abundant memory size of 256 kB of SRAM, 32MB of FLASH and 32MB of SDRAM, suitable for demanding SHM application reported by Rice and Spencer (2009). This board is programmed to interact with the sensor board using TinyOS 1.x, an open source software currently used to program the Imote2. TinyOS 1.x is a Linux based operating system generally used to program sensors and sensor boards. This program is designed to be used on a Linux platform; however, it can be used on a Windows computer, such as the computers in the lab, through Cygwin. For operating Imote2, a NesC® -based software toolsuite, the Illinois SHM Project Services Toolsuite v.2.0 was employed (http://shm.cs.uiuc.edu/software.html).

The analog device chosen for the development of this hybrid sensing system is the Linear Variable Differential Transformer (LVDT). The LVDT used for this research is manufactured by TRANS-TEK, Inc. model number 356-000 DC gazing LVDT with the range of ±7.62 cm measurement range. The power is supplied to LVDT with a transducer manufactured by TRANS-TEK, Inc. Model number 1002.

The connection of the WHS system is shown in Fig. 2. The physical displacement sensor, LVDT, is connected to the power supply and signal conditioner. The signal from the signal conditioner is feed to the 4th channel of the multi-scale wireless sensor board for analog to digital conversion and accurate data acquisition. The measured signal is transferred to the Imote2 for data storage as an ascii file, and the subsequent post processing. The power supply is currently connected with stable AC power source, and inside the supply, the AC power is converted to 12 V DC power; however, this will be eventually replaced by 12 V car battery, or rechargeable battery system with solar panels. Similar energy harvesting system was applied to Imote2 platform for monitoring a cable-stayed bridge in South Korea (Ho *et al*. 2012). The energy harvesting system is under developing and will not be considered in this paper.

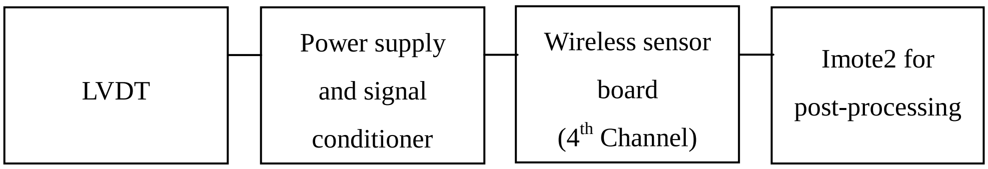


Fig. 2 Connection details for the WHS system

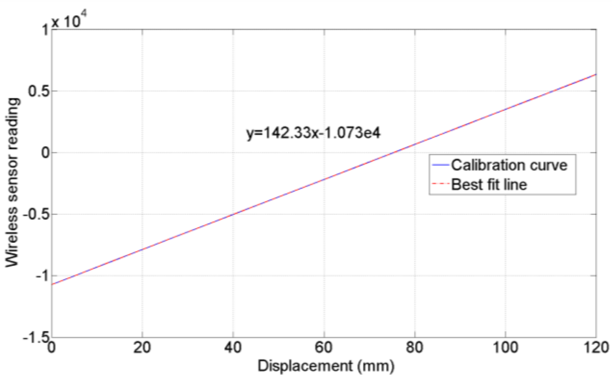


Fig. 3 Calibration from raw voltage to displacement

The digital voltage outputs measured from the WHS system is converted into the physical displacement by post processing with pre-calibration table (Fig. 3). This calibration has been obtained by comparison between the static displacement of the LVDT and the voltage fluctuation from the wireless sensor board. Based on the results, the resolution of the displacement was 0.007 mm, showing the capability to measure small displacement with a reliable precision level. Furthermore, the dynamic performance of the WHS system was also validated using shake table tests. Under a 3 Hz sine excitation, the displacement from WHS was compared with the shake table displacement. Fig. 4 shows the displacement of the shake table and the WHS system matches very well.

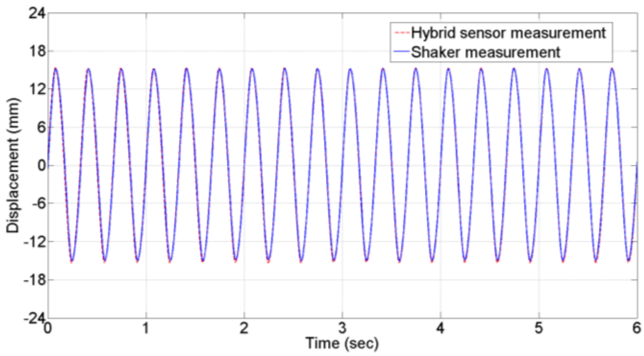


Fig. 4 Dynamic performance validation using a shake table

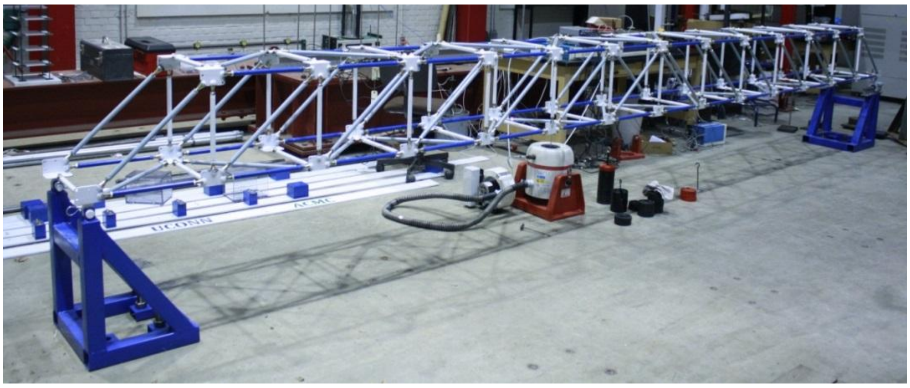


Fig. 5 Three Dimensional 21 feet long 14 bay truss structure

3. Lab-scale validation

The performance of the WHS system has been investigated to measure the displacement of the expansion joints of a lab-scale truss bridge. The testbed is a 14 bay three dimensional truss structure at the Smart Infrastructure Laboratory of the University of Connecticut (see Fig. 5). The truss bridge was simply supported with 14 bays, each of a width of 0.4572 m in length and sits on two rigid supports, connected to the strong floor. The purpose of this lab-scale experiment was to show the high-resolution displacement measurement capability of the WHS system under simulated thermal loads. Because the temperature in the laboratory environment was relatively constant, the temperature effect was simulated by gradual increase of static weights. The WHS system was installed on one of the roller support of the truss bridge and the static load was vertically applied at the mid-span of the truss. The displacement of the support was measured by increasing the load from 0 to 49.9 kg.

Fig. 6 shows the measured displacement in terms of increased static loads in the middle span of the truss bridge. Though the displacement was small with a maximum measurement of 0.254 mm, the WHS system was able to measure the static displacement under the applied loads. This confirms the accuracy of the displacement measurement capability of the WHS system. With the validation of accuracy, the WHS system was considered for the field implementation of thermal expansion measurement of in-service highway bridge.

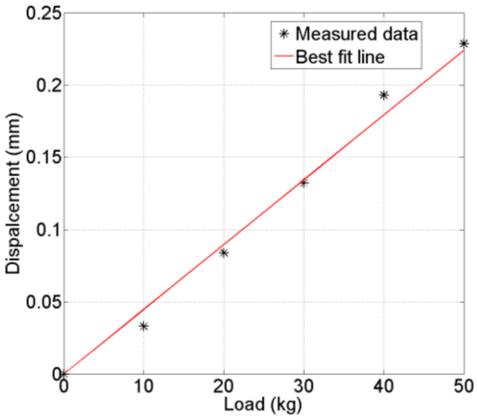


Fig. 6 Displacement vs applied loads

4. Field validation

4.1 Testbed description

The testbed to demonstrate the WHS system is the Founders Bridge in East Hartford, Connecticut (see Fig. 7 (a)). This bridge is a steel stringer bridge carrying Route 2 expressway and I-91 (ConnDOT, 2005). The total length of the bridge is 358.1 m, and the width is 26.2 m. As of 2005, the average daily traffic of the bridge was 29,200. This bridge was chosen for testbed because of simple geometry, exposed expansion joints, and the proximity to campus. Fig. 7(b) shows the expansion joint gap of the bridge to accommodate the displacement of the bridge due to various factors such as thermal expansion, shrinkage, displacement due to the dynamic effect of traffic, etc. Because the expansion joint is accessible without a ladder or bucket truck, the deployment of WHS system is convenient. With permission from the Connecticut Department of Transportation, who maintains this bridge, the deployment the WHS system has been conducted.

4.2 Deployment

The WHS system was deployed on the central expansion joint of the Founders Bridge. The complete test set up for the WHS can be found in Fig. 8. The equipment includes the WHS system, a laptop, and a power supply. The LVDT was installed at the nearest cross beam to the expansion joint. The enclosure of the LVDT was made of a PVC pipe and two magnets with 10800 gauss strength, to provide environmental protection and fast installation capability without damaging the bridge surface. The Imote2 and the multi-scale wireless sensor board were inside a PVC case (see Fig. 8 (b)). The measure displacement data of the expansion joint was record by the multi-scale sensor, and transmitted back to base station as well as tri-axial vibration data using wireless communication. The temperature of the central stringer was also measured to correlate the displacement of the expansion joint. It only took 15 minutes to deploy the whole system showing the rapid feature of the developed system.

(a)

(b)

Fig. 7 Founders bridge over Connecticut River: (a) Bridge view seen from East Hartford side and (b) Expansion joint

(a)

(b)

Fig. 8 Test setup: (a) Base station and LVDT and (b) Vibration measurement node

4.3 Static displacement

After the rapid deployment of the WHS system, the displacement of the expansion joint has been measured in 30 minute intervals from 8 AM to 4 PM. To correlate the dynamic displacement and acceleration, 100 seconds of dynamic displacement has been recorded, and the mean displacement was calculated and plotted in Fig. 9. The initial increase of displacement during 8 AM to 9 AM was minimal possibly due to the time for heat convection from the top surface to the stringers underneath. As the day advances, the displacement of the expansion joint gradually increased.

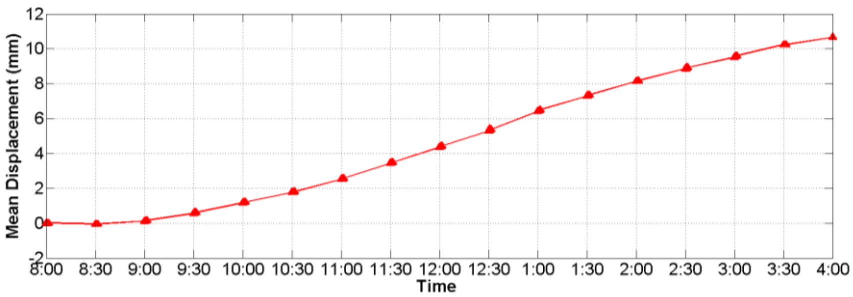


Fig. 9 Displacement of expansion joint

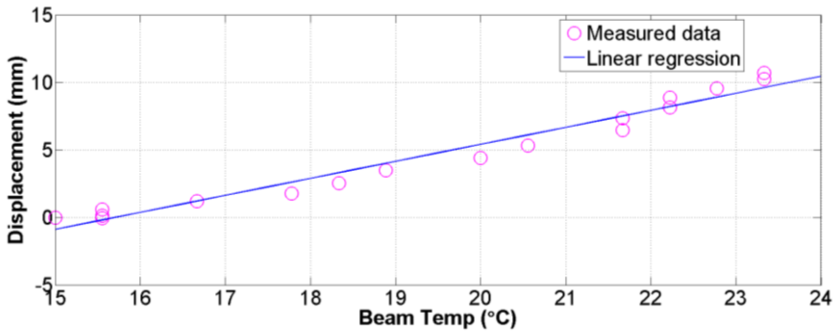


Fig. 10 Linear regression of beam temperature and expansion joint displacement

Based on the displacement and temperature measurement, the correlation between displacement of the expansion joints and the central stringer has been obtained (see Fig. 10). Overall, the displacement is linearly proportional to the temperature, showing the main source of the displacement is thermal expansion of the bridge. The thermal expansion is estimated as linear regression such that

$$\Delta = 1.261T - 19.815 \tag{1}$$

where, Δ is displacement of the expansion joint in mm, T is the temperature of the central stringer in ℃. The coefficient of the thermal expansion of steel member is 12×10^{-6}/℃, and the span length to contribute to the displacement of this expansion joint is 137.16 m. The measured coefficient of thermal expansion is under-estimated possibly due to friction of bearing, changes in vertical deflections, and other uncertain factors. Further long-term displacement monitoring of this bridge is still underway. Nonetheless, the WHS system has shown its stable performance in the field for measuring thermal expansion effectively.

4.4 Dynamic displacement

The dynamic displacement of the expansion joint has been correlated with acceleration to demonstrate accurate displacement measurement under traffic loading condition (see Fig. 11). The ambient vibration without any traffic is approximately ~2 mg, while the maximum vibration level of the bridge due to the traffic loading is approximately 16 mg at 51 second, and 17 mg at 62 second, respectively. At these two peak acceleration points, the dynamic displacement of the expansion joint abruptly increased by 0.013 cm and 0.015 cm, respectively, showing stable performance of the expansion joint. Though the dynamic displacement due to traffic loadings is small, it may be used to monitor the performance of the expansion joint. After the test, the retrieval of the whole system took 15 minutes, showing the potential of the WHS system for rapid displacement monitoring of expansion joint.

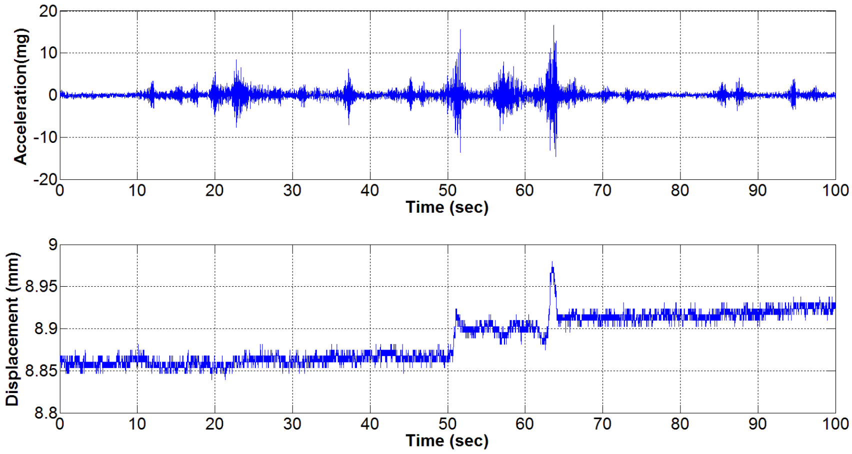


Fig. 11 Dynamic displacement with acceleration at 2:30 pm

5. Conclusions

A rapid displacement monitoring system using hybrid wireless sensor system was developed for bridge expansion joint measurement and its performance was successfully demonstrated in both laboratory and field environments. The WHS system has high resolution of 0.007 mm, which is suitable for expansion joint measurement under thermal expansion and traffic loading. Based on the simulated thermal expansion experiments on the laboratory-scale truss bridge, the accuracy of the developed system was successfully demonstrated. The measurement of the expansion joint of an in-service bridge also demonstrated the efficacy of the WHS system for rapid displacement monitoring purposes. This paper showed a short-term deployment and validation of the developed system on displacement measurement. The total experiment time was 8 hours and 30 minutes, and only 30 minutes (6%) was spent for the deployment and retrieval, and it should be reduced with respect to the increased measurement time. Therefore, the performance of the WHS system for rapid displacement monitoring of bridge expansion joint was successfully demonstrated. Further study on long-term deployment and implementation of a solar power energy harvesting system is still underway.

Acknowledgements

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