INTERNATIONAL COLLABORATION TO DEVELOP A STRUCTURAL HEALTH MONITORING SYSTEM UTILIZING WIRELESS SMART SENSOR NETWORK AND ITS DEPLOYMENT ON A CABLE-STAYED BRIDGE

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Abstract

Wireless smart sensors (WSS) equipped with on-board computation and wireless communication capabilities are expected to provide rich information for structural health monitoring (SHM). While a large number of researchers have been contributing their efforts toward the realization of wireless smart sensor networks (WSSN), full-fledged implementation of WSSN for SHM has not yet been materialized. WSSN systems for SHM involve various research fields and require understanding in respective areas. Therefore, collaboration among researchers plays an important role in pursuing this inter-disciplinary research. Recent prevalence of inexpensive telecommunication systems facilitates close collaboration among international research groups. The authors in Japan, Korea, and the U.S. with respective research strengths have been closely collaborating in WSSN development and its deployment on a cable-stayed bridge in Korea. This tri-lateral collaboration involves frequent teleconferences to coordinate research efforts, system component development in each group, and joint visits to the bridge site. Seventy WSS have been installed on the bridge. The dynamic behavior of the girder, cable, and pylons were remotely observed and recorded over the internet. The sensor operational conditions such as battery voltage have also been monitored. Obtained data sets have been analyzed among the three groups and were fed back to system developments.

Introduction

Wireless smart sensors equipped with computational and wireless communication capabilities are expected to provide rich information for structural health monitoring (SHM). Inexpensive nature of sensors nodes and wireless communication allow dense sensor instrumentation over structures. Densely instrumented sensors can capture large structures' dynamic behaviors in detail in the space domain. Investigation of dynamic characteristics from spatial perspectives has been pursued for SHM; mode shape curvature and mode shape phase, for example, are considered to reflect structural conditions (Pandey et al 1991; Nagayama et al. 2005). Furthermore, there are a variety of damage detection algorithms assuming dynamic measurements at arrays of sensor nodes. The possibility of dense deployment is indeed an attractive feature of wireless smart sensors.

Nagayama and Spencer (2007) has demonstrated the possibility of SHM using WSSN through implementation of synchronized vibration sensing capabilities and online damage diagnosis on a wireless sensor platform. A set of functionalities such as reliable communication and synchronized sensing have been identified as fundamental to SHM applications and were substantialized as middleware services, i.e. software that functions at an intermediate layer between applications and the operation system. Damage identification and localization applications based on vibration measurements were built upon these services and the damage diagnosis capability was experimentally verified using a scale-model truss.

Though the system demonstrated the future use of WSSN for SHM, its applications to full-scale structures require substantive technical advances and considerations. Communication ranges can be smaller than the size of structures. Battery power may not be enough to carry out measurements, communication, and data analysis for the expected life of WSSN. Monitoring of full-scale structures thus involves various research fields and requires understanding in respective areas. Therefore, collaboration among researchers plays an important role in pursuing this inter-disciplinary research.

The authors in Japan, Korea, and the U.S. with respective research strength have been closely collaborating to move from the scale-model experiment phase toward full-scale structure monitoring. The international and interdisciplinary collaboration includes the Illinois SHM Project (ISHMP) organized by the civil engineering and computer science researchers at the University of Illinois at Urbana-Champaign (http://shm.cs.uiuc.edu/), preliminary wireless vibration measurements of a pedestrian bridge in Mahomet, IL USA by the US and Japan researchers (Nagayama et al 2009), and the trilateral research project to monitor a cable-stayed bridge in Korea (Cho et al 2010; Jang et al 2010). Recent prevalence of inexpensive telecommunication systems facilitates close collaboration among the international research groups. Research plan elaboration and coordination among these collaborators were realized through frequent IP-based teleconferences, information and data sharing through emails and data servers, and occasional meetings and site visits.

This paper describes the authors' international collaboration to develop a SHM system using WSSN and its deployment on the cable-stayed bridge in Korea. The developed system is first described with the emphasis on the trilateral collaboration. The system deployment on the cable-stayed bridge is then explained. The measured structural vibrations as well as the wind velocity are analyzed to show the validity of the developed system.

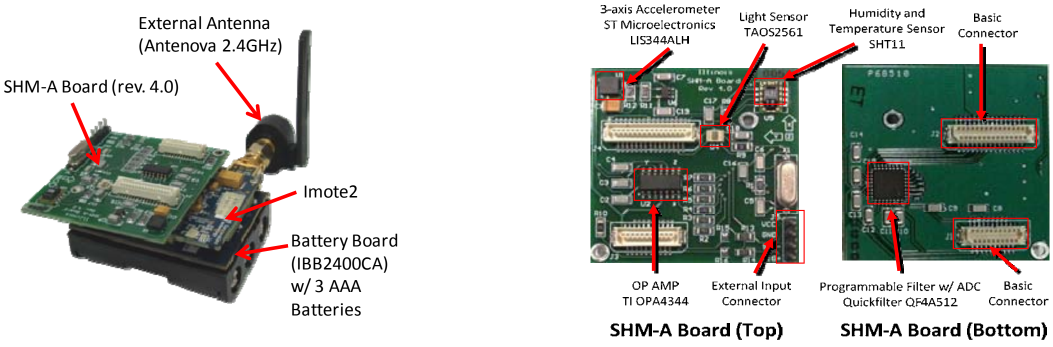
System development

A SHM system is developed based on the system proposed by Nagayama and Spencer (2007). The system utilizes the Imote2 wireless sensor module (MEMSIC 2010). The module, as well as its battery board and sensor board envisioning environmental monitoring, is commercially available. Though the scale-model experiments reported in Nagayama and Spencer (2007) were performed using these commercially available components, application to the full-scale structures require hardware customization to capture small ambient vibration, to allow long battery life, and to provide environmental hardening. These hardware customizations as well as development of middleware services and applications carried out by the three groups are described in this section.

Hardware development

The key hardware components of a wireless smart sensor node are the Imote2, sensor board, and battery board (Figure 1a). The Imote2 is one of high-performance wireless computing modules, built on PXA271 XScale® processor (Marvel Semiconductor Inc., 2010) running at 13-416 MHz and an MMX DSP coprocessor. The chip is equipped with 256kB SRAM, 32MB FLASH, and 32MB SDRAM, which enable to buffer and store long-time measurement data as well as complex on-board manipulation of the measured data. The Imote2 has an onboard antenna for 2.4GHz IEEE 802.15.4 wireless communication. Alternatively, a 2.4GHz antenna can be connected to the board; an external antenna with appropriate characteristics potentially elongates the communication range.

Sensor boards connected to the Imote2 through its two connectors are customized. The improvement of vibration measurement resolution and timing control over the commercially available sensor boards, ITS400CA and ITS400CB (MEMSIC 2010), is the main objective. The boards include the SHM-A (structural health monitoring-acceleration) board to measure multi-metric data and SHM-W (structural health monitoring-wind) board to measure wind speed and direction by interfacing with a 3-axis anemometer. As shown in Figure 1(b), the SHM-A board has a tri-axial accelerometer (ST Microelectronic's LIS344ALH), and the 4-channel 16-bit analog to digital converter (ADC) equipped with analog and digital filters (Quickfilter QF4A512). While three of the four ADC channels are used for acceleration measurements, one is available for general analog signal reading. The Quickfilter chip allows sampling rate up to 2Msps with appropriate filters. Four sampling frequencies (10, 25, 50, 100 Hz) have been pre-programmed on the SHM-A board. The SHM-A board also contains temperature, humidity, and light sensors. The SHM-W board (Figure 1c) is based on the SHM-A board design; three input channels of the Quickfilter chip is interfaced with a 3-D ultrasonic anemometer. The RM Young Model 81000 3-D ultra-sonic anemometer is selected due to its high resolution (wind speed: 0.01m/s, wind direction: 0.1 degree), good accuracy (wind speed: ±1%, wind direction: ±2 degrees), and the long-term durability against harsh outdoor environment..



(a) Wireless sensor node

(b) SHM-A Board

(c) SHM-W Board and Anemometer
(RM Young Model 81000)

(d) Solar panel (SPE-350-6) and lithium-polymer rechargeable battery for energy harvesting

Figure 1. Hardware components of wireless smart sensor

The IBB2400CA battery board is modified to connect a solar panel and rechargeable battery. The Imote2 contains a power management integrated circuit (PMIC) which provides multiple voltage domains and allows battery charging and monitoring options. The IBB2400 board, compatible with this Imote2 PMIC, is utilized to accommodate the solar system. The Solarworld SPE-350-6 solar panel (9V-350mA) and the Powerizer lithium-polymer rechargeable battery are employed as the system components. The battery has the capacity of 10,000 mAh and supplies 4.2V when fully-charged.

All the components of a wireless smart sensor is stacked and contained in a hardened plastic enclosure to be protected from harsh outdoor environment. The RF antenna of the Imote2 is switched from the onboard antenna to an external dipole antenna (Antenova gigaNova Titanis 2.4 GHz antenna), which is fixed outside the enclosure, to elongate the communication range.

Middleware development

The middleware services are a set of program providing functionalities utilized by applications or other middleware services. Functionalities not provided by OS are developed as middleware services, including time synchronization and reliable communication. These middleware services are originally proposed and programmed by Nagayama and Spencer (2007) and integrated as versatile services into the ISHMP Services Toolsuite, which is open-source software available at http://shm.cs.uiuc.edu/software.html. The detailed information regarding this software can be found in Rice et al. (2010).

The time synchronization middleware service employs the Flooding Time Synchronization Protocol (Maroti et al. 2004). The implementation on the Imote2 is evaluated for the synchronization accuracy, which is estimated to be about 20 μs when nodes are in a single-hop range. This synchronization services is prepared as a middleware component so that the service can be utilized by simply wiring this component to the application.

While the time synchronization estimates the difference among local clocks of sensor nodes, sampling process is not necessarily controlled precisely based on the clocks. Even when the clocks are synchronized with each other, sampling timing is not synchronized. Nagayama and Spencer (2007) proposed a resampling-based approach, where sampling is performed with precise time stamps which is utilized for post-process resampling. This approach can achieve synchronized sensing with an accuracy of about 30 μs. This service is included as a middleware component as well.

Another middleware service is to allow reliable communication by utilizing a selective NACK approach. All packets are first sent without acknowledgement for fast data transfer. Packet ID numbers corresponding to missing ones are sent back for retransmission. In this manner, the number of acknowledgement packets is reduced and communication speed is kept modest. Reliable communication middleware for multicast is implemented as well. This communication service has been updated for the full-scale monitoring to provide more reliability and faster data transfer. This middleware service can be integrated into applications or other middleware services by wiring the corresponding component.

Application development

Application software incorporating the middleware and other services is developed to monitor the structural response and wind velocity and direction. Continuous and autonomous monitoring is realized as the AutoMonitor application program, which combines RemoteSensing, ThresholdSentry, and SnoozeAlarm applications described in Rice and Spencer (2009). SnoozeAlarm is a strategy that allows the network to sleep most of the time, thus improving energy efficiency and allowing long-term system deployment. To wake the network for an important event, the ThresholdSentry application defines a specified number of the leaf nodes as sentry nodes. The sentry nodes wake up at predefined times and measure a short period of acceleration or wind data. When the measured data exceeds a pre-defined threshold, the sentry node sends an alarm to the gateway node, which subsequently wakes the entire network for synchronized data measurement. In this way, AutoMonitor enables the automatic, continuous monitoring with reduced power consumption.

The application software is also available as a part of the ISHMP Services Toolsuite. The components in the toolsuite are categorized into foundation services, application services, tools and utilities, and continuous and autonomous monitoring services. The foundation services include the middleware services and provide the fundamental functionalities to measure synchronized sensor data reliably (Mechitov et al., 2004; Nagayama and Spencer, 2007; Rice et al. 2008). The application services are the numerical algorithms to implement SHM applications on the Imote2, including modal identification and damage detection algorithms. The tools and utilities support network maintenance and debugging. This category has essential services for full-scale monitoring as well as sensor maintenance. For example, tools for RF range tests and remaining battery level check are included. The continuous and autonomous monitoring services include the AutoMonitor and RemoteSensing applications.

Deployment on the second Jindo Bridge

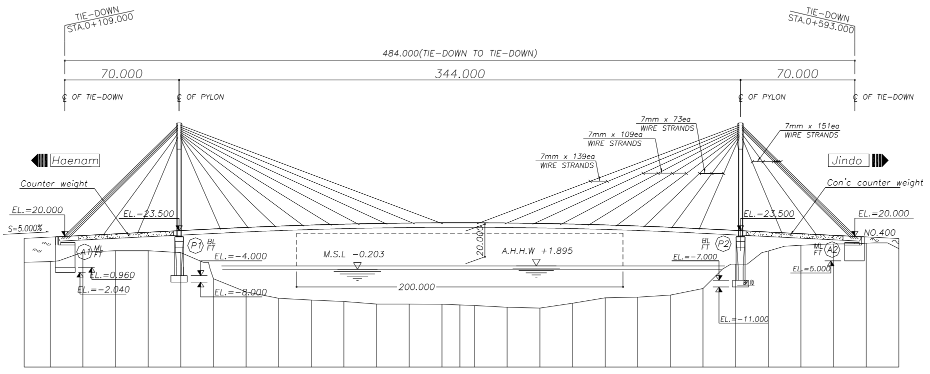
Bridge description

The Jindo Bridges are twin cable-stayed bridges connecting Haenam on the mainland with the Jindo Island (see Figure 2). The Jindo Island is the third largest island in South Korea, and Haenam, which is located in the south-west tip of the Korean peninsula. Each of these bridges consists of three continuous spans, with a 344-m central main span and two 70-m side spans.

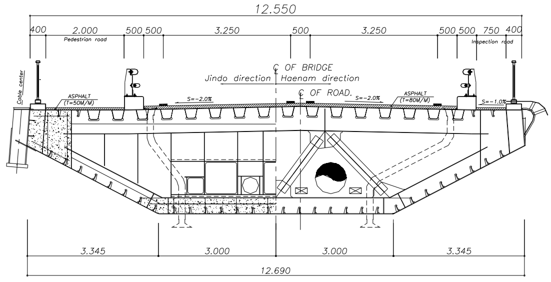
The original Jindo Bridge, constructed in 1984 by Hyundai Engineering & Construction Co., Ltd., is the first cable-stayed bridge in South Korea. The design traffic velocity is 60 km/hr, and the design live load is based on AASHTO HS-20-44 (DB-18). The second Jindo Bridge was constructed in 2006 by Hyundai Engineering & Construction Co., Ltd., Daelim Industrial Co., Ltd., and Namhei Co., Ltd. The traffic design velocity is 70 km/hr, and the design live load is based on AASHTO HS-20-44 (DB-24, DL-24). The streamlined steel box girder is supported by 60 high-strength steel cables connected to two pylons. The structural drawing of the bridge is shown in Figure 3.

Wired sensor systems are installed on both bridges. The first Jindo Bridge has 38 strain gages, four inclinometers, two anemometers, two seismic accelerometers, five uniaxial capacitive accelerometers, and 15 uniaxial piezoelectric accelerometers. The second Jindo Bridge has 15 thermometers, 15 strain gages, four biaxial inclinometers, two string pots, two laser displacement meters, 24 Fiber Bragg Grating sensors, 20 uniaxial capacitive accelerometers, two biaxial force balance type accelerometers, and three triaxial seismic accelerometers. Among two bridges, the second Jindo Bridge is selected as the test bed for this research, for two primary reasons: (i) the existing SHM system is quite versatile, including accelerometers and fiber optic sensors, and (ii) the design and construction documents are more complete.

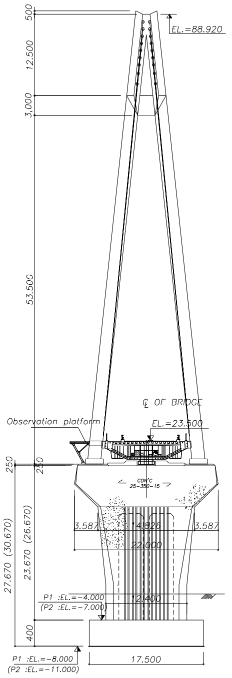
Figure. 2. 1st (right) and 2nd (left) Jindo Bridges (Jang et al 2010).



(a) Elevation



(b) Typical Girder Section



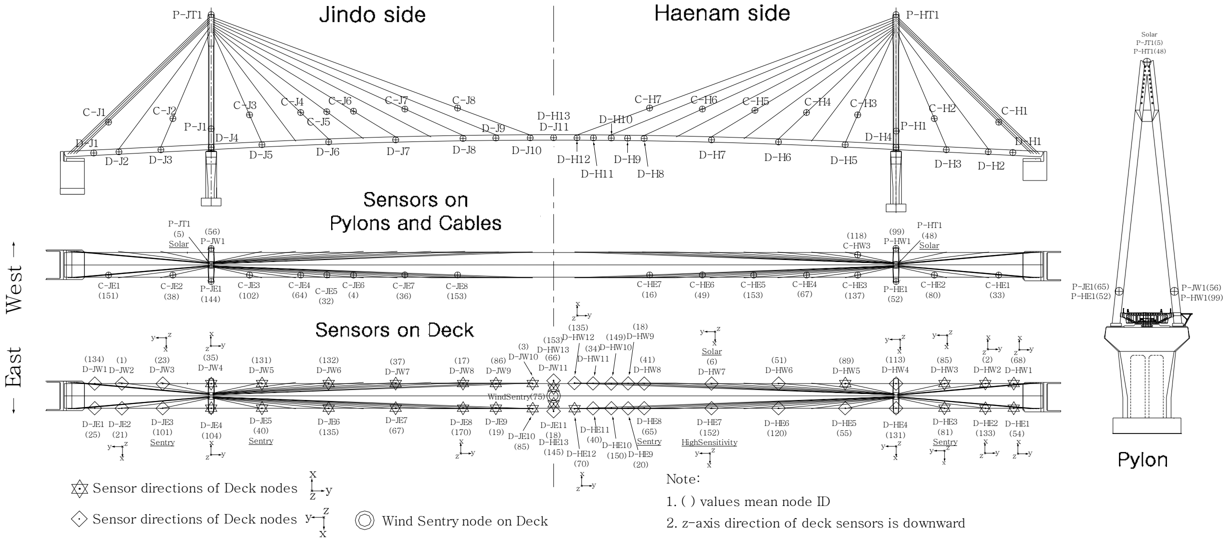
(c) Pylon

Figure 3. The second Jingo Bridge (Jang et al 2010).

Deployment

The developed hardware and software framework described previously has been deployed on the 2nd Jindo Bridge to realize a large-scale and autonomous SHM system using WSSN. The network topology was carefully determined to ensure the reliable communication on the bridge. After communication range tests on site, the communication range of Imote2 with an external antenna is estimated to be about 200m shorter than the total length of the bridge. The network was divided into two single-hop sub-networks with different radio channels: one on the Jindo side and the other on the Haenam side. A total of 70 leaf nodes were deployed on the bridge (see Figure 4). Most of the sensor nodes are equipped with SHM-A sensor boards to measure 3-axis acceleration, while one node is connected to the SHM-W board. The Jindo sub-network consists of 33 nodes with 22 nodes on the deck, 3 nodes on the pylon, and 8 nodes on the cables. The Haenam sub-network consists of 37 nodes with 26 nodes on the deck, 3 nodes on the pylon, and 7 nodes on the cables. One sensor in each sub-network is used as reference sensor; these nodes are installed next to each other so that the same vibration is measured by the two nodes and the signal is utilized to synchronize the two sub-networks (see Figure 5(e)).

Figures 4 and 5 show the locations of 70 leaf nodes and photos of various types of nodes. They were enclosed in water-tight plastic enclosures for protection from moisture and dust of harsh outdoor environment. The deck/pylon nodes were mounted using one-directional magnets attached on the bottom of enclosures, and the cable nodes were mounted on aluminum plates with round interface to fit the round cables. An anemometer was installed on a 5m-tall steel bar at the center of deck to prevent any interruption of the bridge on the wind measurement, while the leaf node with SHM-W board incorporating the anemometer was installed underneath of the deck to secure the line-of-sight to the base station.



Note:
1. ( ) values mean node ID
2. z-axis direction of deck sensors is downward

Figure 4. Sensor installation locations

(a) Node under deck (b) Node on the pylon top (c) Node on cable (d) Anemometer at center of deck (e) Reference sensors

Figure 5. Wireless sensor nodes

Evaluation of the system

Battery power consumption

The battery voltage levels of leaf nodes without solar panel have been monitored for two month using RemoteVbat command, provided by the ISHMP Services Toolsuite, and they are shown in Figure 6. The average voltage with three brand-new D-cell batteries on each node was about 4.6V. From 27 August to 8 September, a series of measurements were carried out to optimize network performance, which results in the rapid drop of battery power as shown in Figure 6(a). After 8 September, the AutoMonitor application has controlled the network and the power consumption has become approximately linear. The minimum onboard voltage required for sensing is about 3.6V so that it can be concluded that three D-cell batteries are able to run the node for about 2 months.

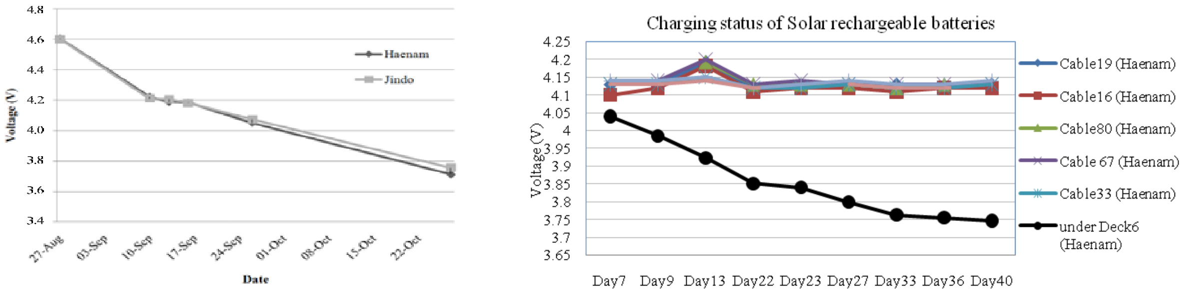
The voltage levels of 8 nodes powered by solar panels and rechargeable batteries (5 on cables, 2 on pylon tops, and 1 under the deck) are also investigated to check the feasibility of solar-based energy harvesting. Figure 6(b) shows the voltage levels of the rechargeable batteries of 6 nodes (for cables and deck) powered by solar panels during 1.5 months of monitoring. It is shown that the voltage levels have stayed around 4.15V, except one node under the deck, whose solar panel faces intentionally downward without being exposed to direct sunlight.

Acceleration and wind measurements

Figure 7 shows examples of the ambient acceleration data measured on the deck, pylon, and cable in three directions. The amplitudes of the acceleration due to the passing traffic on the deck, in particular in the vertical direction, are large. Cho et al. (2010) reported modal identification from these data sets. Similar to the deck, the in-plane (perpendicular to the cable in the vertical plane) vibration of the cable is much larger than the other components. Cho et al. (2010) estimated the cable tension force based on the dominant frequencies of the vibration.

The power spectral densities (PSD) of the vibration data have been investigated. Figure 8 shows PSDs of the deck accelerations obtained from a wireless node and compares it with that from the existing wired monitoring system. The data from wired system was obtained in 2007 while the wireless sensor data is from measurements in 2009. The peak frequencies of two PSDs are close to each other at around 0.44, 0.66, 1.05, and 1.37Hz.

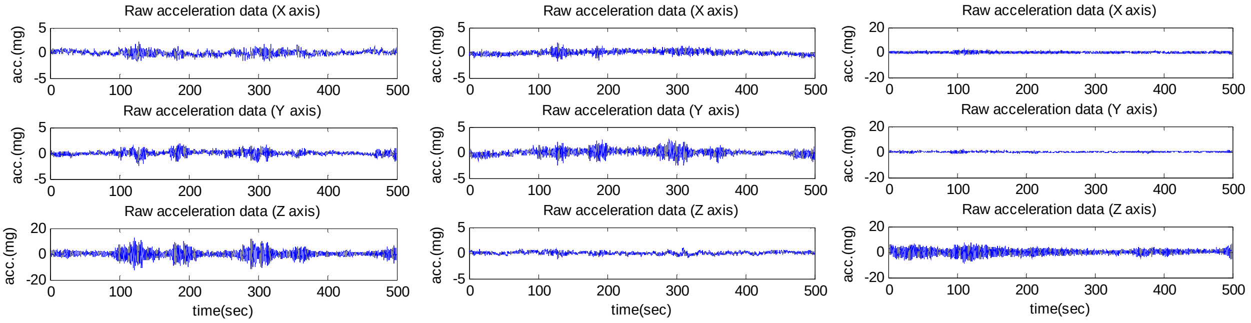
The wind speed and direction has been successfully measured using the 3D ultra-sonic anemometer at the mid span. The data is synchronized with vibration data measured by SHM-A sensor board. Figure 9 shows an example of measured wind speed and direction. In this data set, the wind speed is 4-6 m/sec and the direction is between -10 to 20 degree to the longitudinal direction of the bridge.



(a) Average on-board voltage

(b) Battery status of rechargeable batteries with solar panels

Figure 6. Evaluation of battery and sustainable energy harvesting



(a) On the deck of main span

(b) At the top of a pylon

(c) On a cable

Figure 7. Examples of measured acceleration (Jindo sub-network)

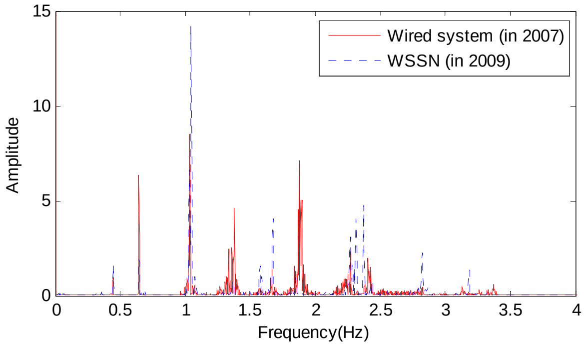


Figure 8. Bridge deck acceleration PSDs estimated from wired and wireless systems

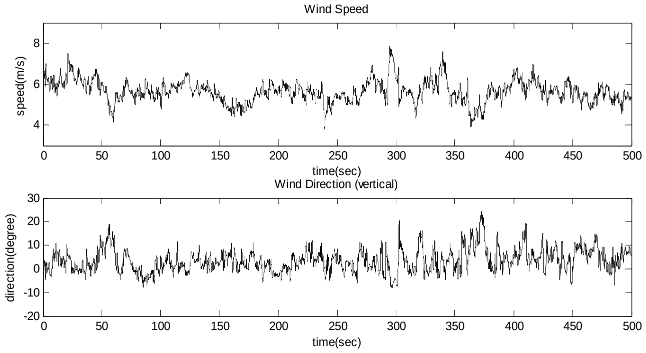


Figure 9. Measured wind velocity and direction

Conclusion

A tri-lateral international collaboration to extend a laboratory-scale wireless sensor vibration measurement system to full-scale bridge monitoring has been reported. The system extension involved hardware, middleware, and application software development as well as deployment issues such as sensor node enclosure, attachment base, sensor installation locations, etc. Researchers at three countries with respective strengths collaborated toward the realization of the full-scale monitoring system. The authors at the University of Illinois at Urbana-Champaign took the initiative in the hardware and software development as well as in the evaluation of the WSSN (e.g. battery status) during and after the deployments. The authors at the University of Tokyo contributed mainly to the communication middleware upgrade. The issues related to the full-scale deployments are addressed mainly by the KAIST authors, who also lead the analysis of the dynamic measurement data. The authors coordinate through IP-based teleconferences, online data and information sharing, and two site visits.

In total, 70 sensor nodes are installed on the Jindo Bridge in two sub-networks to decrease the communication time and to overcome the limit of the radio communication range. The sensor nodes are equipped with SHM-A or SHM-W sensor boards; some nodes are powered from solar panels. The measured data shows a good agreement with data from the existing wired system, which verifies that the data quality of the WSSN is reliable. The successful full-scale deployment of this WSSN demonstrates the suitability of wireless sensor system developments and the effectiveness of the trilateral collaboration. Further system enhancement toward the next deployment at the Jindo Bridge is in progress by the groups at three countries.

Acknowledgements

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