LONG-TERM STRUCTURAL HEALTH MONITORING SYSTEM OF A CABLE-STAYED BRIDGE BASED ON WIRELESS SMART SENSOR NETWORKS AND ENERGY HARVESTING TECHNIQUES

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Abstract

A long-term structural health monitoring (SHM) system using wireless smart sensor networks (WSSNs) for civil infrastructure such as a cable-stayed bridge is investigated. The hardware and software for the SHM system and its components have been developed for low-cost, efficient, and autonomous monitoring of the bridge. A total of 70 sensor nodes and two base station computers have been deployed to assess the integrity of a bridge using an autonomous SHM application with consideration of harsh outdoor environments. The 2nd Jindo Bridge located in Korea is considered as a test bed structure, which is an in-service cable-stayed bridge with the total length of 484 m (i.e., a 344-m main span and two 70-m side spans). In addition, the power supply problem, which is one of the critical issues to be solved for continuously operating the long-term SHM system, is addressed. To this end, two types of approaches have been introduced, which are effective power management strategies and energy harvesting techniques using solar cells and complementary small-size wind turbine generators, respectively.

Introduction

Civil infrastructure is widespread and it has great impact on the quality of our daily lives. Monitoring the safety and functionality of the civil infrastructure such as the world's buildings and bridges is critical to minimize the cost associated with repair and ultimately improving public safety. Structural health monitoring (SHM) plays an important role for capturing structural response as well as assessing structural condition.

However, the high cost associated with installation and maintenance is still being a limitation of wide spread adoption of SHM system. With the rapid advancement in electronics, smart wireless sensor system which have capabilities of on-board computation and wireless data transmission has emerged as a powerful alternative to existing SHM system by substituting expensive accelerometers with low-cost digital sensors and long cables with wireless transmission. This novel system enables a dense deployment of sensor so that it will provide more accurate information of a large infrastructure.

To validate smart wireless system as a long-term SHM system, the 2nd Jindo cable-stayed bridge was selected as a test bed. The test bed bridge has a 344-m main span and two 70-m side spans, connecting mainland South Korea with Jindo Island across the sea. The Crossbow's Imote2s are utilized in corporation with multi-scale sensor boards designed for SHM of civil infrastructure. A total of 70 sensors are deployed on the bridge to capture its global ambient dynamic characteristics.

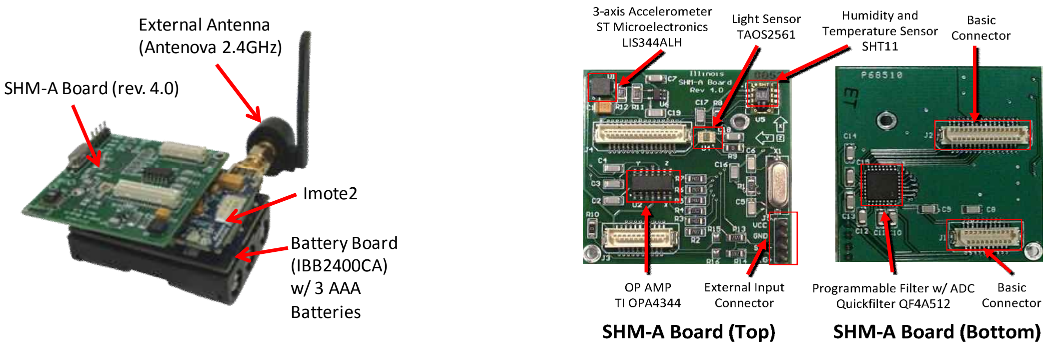
Figure 1. 1st (right) and 2nd (left) Jindo Bridges (Jang *et al*. 2010)

Smart Wireless Sensors

The smart wireless sensors consist of an Imote2, a multi-scale sensing board, and a battery board with three 1.5 V batteries. The Imote2 is a high-performance wireless smart sensor platform, having Intel's PXA271 XScale® processor running at 13-416 MHz and an MMX DSP Coprocessor (Crossbow 2007). The imote2 has memory size of 256kB SRAM, 32MB FLASH, and 32MB SDRAM, which enables longer measurements than previous motes, as well as the on-board computation.

The multi-scale sensor board, SHM-A sensor board, has been designed. The SHM-A sensor board has been designed for monitoring civil infrastructure through the Illinois SHM Project for monitoring civil infrastructure through the Illinois SHM Project and is compatible with Imote2 through two basic connectors. This sensor board is able to capture 3-axis acceleration, temperature, humidity, light, and external input voltage between 0-3.3 V as shown in Figure 2. Also, a programmable low-pass filter is embedded to prevent anti-aliasing of measured dynamic data. The TinyOS is employed as an operating system on the Imote2.

To control and acquire sensing data, the software toolsuite (http://shm.cs.uiuc.edu) has also been developed. The toolsuite includes a reliable communication protocol with acknowledgement-based approach, time synchronization using beacon-signal and resampling-based approach (Nagayama, 2007), service-oriented architecture for SHM software and automonous long-term monitoring software such as snooze-alarm, threshold sentry and automonitor (Jang *et al*. 2010).



(a) Assembled smart wireless sensor

(b) SHM-A board

Figure 2. Smart wireless sensor (Cho *et al*. 2010)

Sensor deployment on 2^{nd} Jindo Bridge

To validate the performance of smart wireless sensor system at site, a total of 70 smart wireless sensors were deployed on the 2nd Jindo Bridge. Each sensor is covered with hardened water-proof enclosures as shown Figure 3. As the transmission range is limited, 70 sensors are divided into two individual groups (37 sensors for Haenam-side and 33 sensors for Jindo-side as in Figure 3) and each of them is controlled by corresponding base stations installed on the tower-piers of the 1st Jindo Bridge.

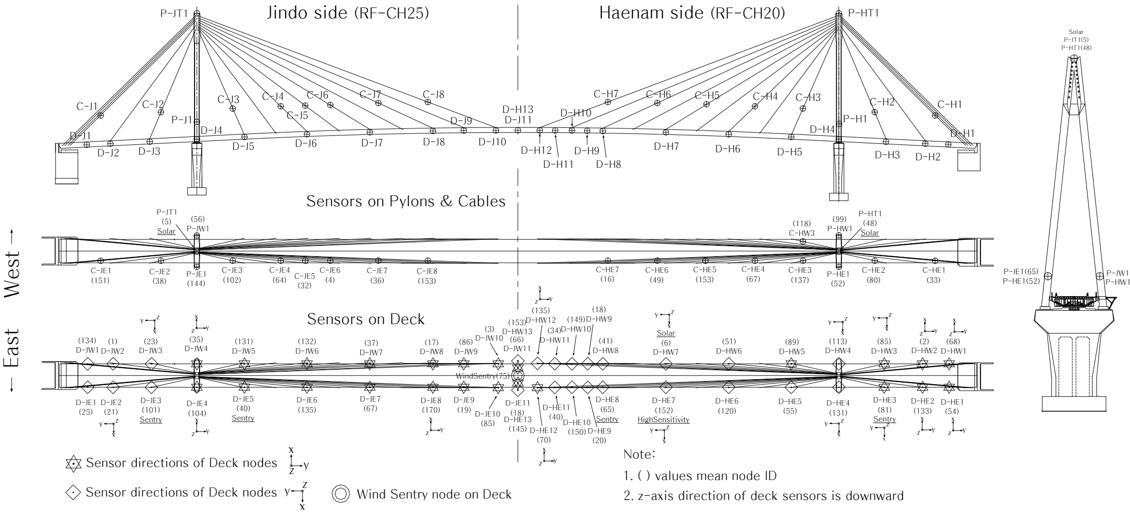


Figure 3. Sensor Deployment (Jang *et al.* 2010)

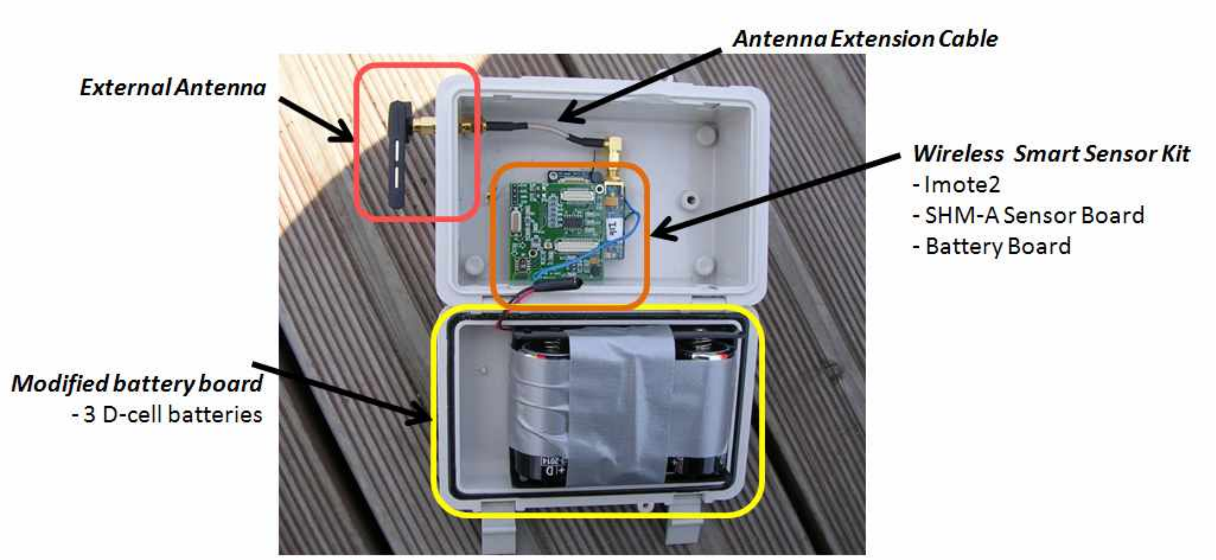


Figure 4. Environment-harden sensor

Results of modal analysis

From the measured acceleration data, modal analysis was carried out to check the performance of the installed system. Figure 5 shows the first three vertical modal properties analyzed from the measured data by the Jindo-side network and those from the FE model of the 2nd Jindo Bridge constructed from the detailed drawings depicted in small square box. It can be said that the modal properties from the measured data show excellent agreement with those from the FE model.

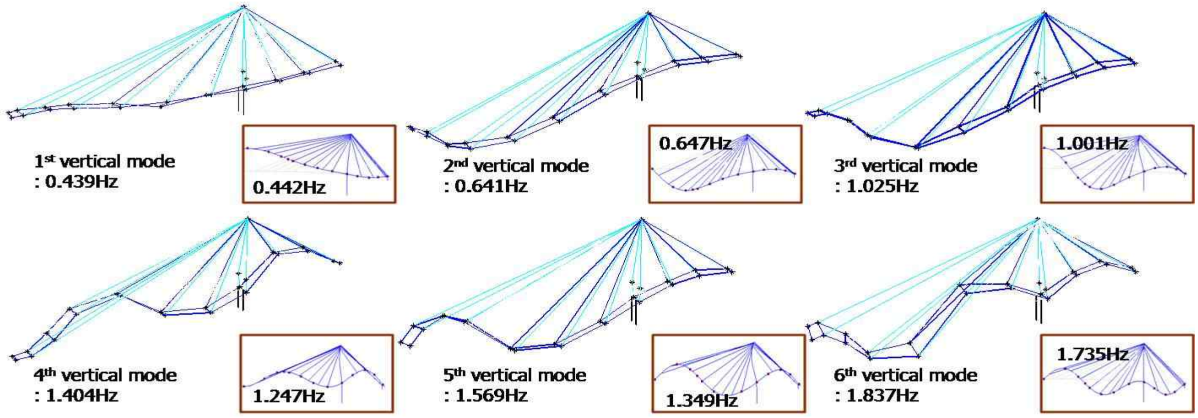


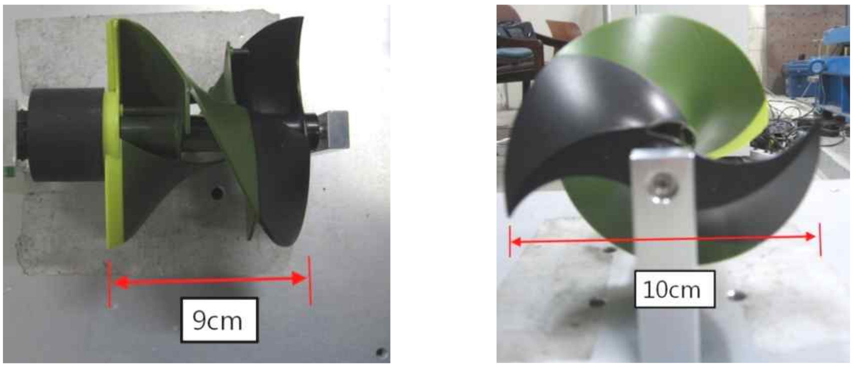
Figure 5. Extracted modal properties

Wind powered energy harvesting

The power supply has been one of the critical issues to be solved for continuously operating the long-term SHM system, is addressed. As an effort to address power issues on sensors, both power management software and power supplying hardware (i.e., solar panel) were utilized. Totally, five of the sensor nodes on cable is equipped with solar panel as well as one of sensor nodes underneath the deck. However, solar panel located underneath the deck does not provide sufficient power to the sensor node while others are supply proper power. Thereby, small wind turbine is motivated to supply power to the nodes by making use of plenty of wind energy around the bridge. As such, feasibility of small wind turbine is investigated in this study.

Prior to design wind turbine, it was necessary to investigate the wind environment at 2nd Jindo Bridge site. As a result of wind speed measurement test, the average wind speed of 24 hour was 3.4 m/s so that the small wind turbine was aimed at wind speed of 3.4 m/s for stable power supply.

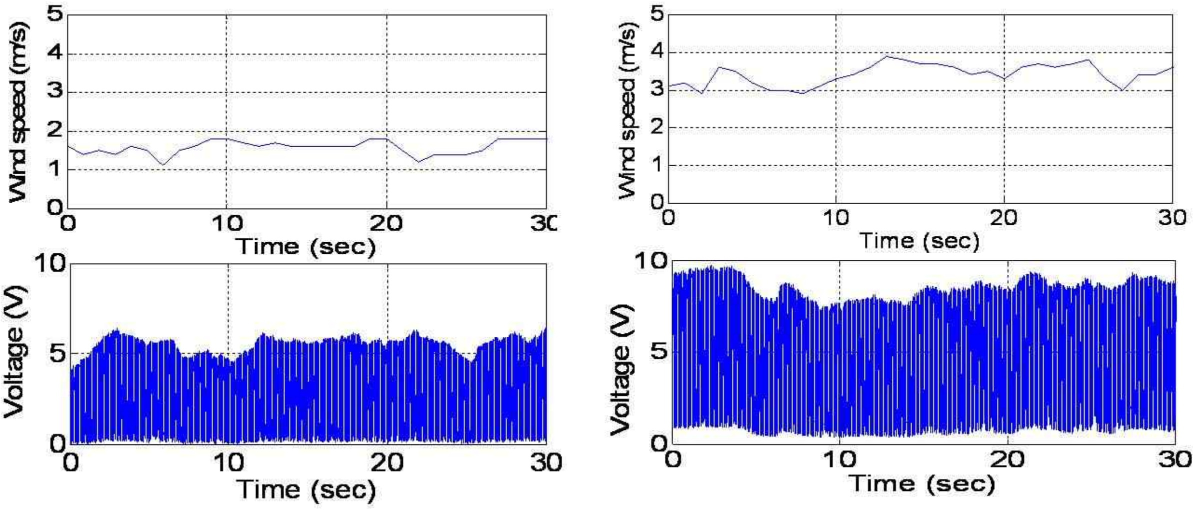
The shape of wind turbine was designed with helical shape to capture omni-directional wind energy as in Figure 6. Inside the turbine, the stator is wound with 0.09 mm copper wire and has 700 turns and resistance of 420 Ω.



(a) Side view **(b) Front view**

Figure 6. Fabricated wind turbine

The small wind turbine was tested with big fan. As the startup wind speed of the device is 1.7 m/s, both 1.7 m/s and 3.4 m/s cases were carried out. As a result of test, the small wind turbine generated 3.86 V and 6.10 V, respectively as shown in Figure 7.



(a) Result of 1.7m/s

(b) Result of 3.4m/s

Figure 7. Generated output voltage

From the result of Figure 7, the maximum generated power can be calculated according to the maximum power transfer theory. As we can get maximum power out of the source if the load resistance is identical to the internal source resistance according to the maximum power transfer theory, the output voltage of 6.10 V coming out from the result of 3.4 m/s and the source resistance 420 Ω makes the maximum power of 18.6 mW. In order to operate the one-cycle sensing of Imote2 per day which consumes 26.14 mWh of energy (Park *et al*, 2010), the required time for generating that energy can be calculated dividing 26.14mWh into 18.6 mW and it becomes 1.4 hours.

Conclusions

A SHM test-bed using smart wireless sensor system has been constructed on the 2nd Jindo cable-stayed bridges in Korea. The hardware for this system is smart wireless sensor nodes with Imote2s and multi-scale sensor boards designed for SHM of civil infrastructures. The software and middleware have the components of the reliable wireless communication, time synchronization, and SHM algorithms to operate and manipulate the smart wireless sensor nodes. In total, 70 smart sensor nodes have been densely deployed on the 2nd Jindo Bridge with two base stations. Modal analysis has been carried out using the measured acceleration data. Finally, the results show good agreements with those from the FE model of the test-bed bridge. Also, the feasibility of a small wind turbine as a power supply was verified through the experimental test. It is demonstrated from the experimental results that it takes about 1.4 hour to generate the electrical energy for one-cycle sensing of the imote2.

Acknowledgements

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