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Comparison of structural health monitoring systems on the Hwamyung bridge

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ABSTRACT

The purpose of these experiments was to test our new system of wireless accelerometers on civil engineering structures. The system was developed to detect leakages in water distribution networks by analyzing the vibrations of the pipe walls. Design sampling frequency had to reach up to 1 kHz. Instead, in these experiments the system is used for the structural health monitoring of the Hwamyung bridge, which is a cable stayed bridge in Korea. The sampling frequency was reduced less than 100 Hz. Different experiments were conducted on the bridge over a period of two years. The system was improved with each new experiment. Furthermore, different layouts of the SHM system were deployed on the bridge. The results shows the reliability of the current system, the weaknesses and strengths of the various layouts, the solid knowledge acquired about the bridge behavior, and its modal properties, which include natural frequencies, mode shapes, and damping ratios.

1. INTRODUCTION

Structural health monitoring (SHM) of civil infrastructure system is an ever growing research field. In the last decades, many ideas from other applications have been used in SHM. For example, the development and worldwide deployment of Wi-Fi has been exploited by researchers to deploy SHM systems free of data transmission cables Lynch (2003), Park (2005), Cho (2008), among others. The research and development in solar panel technology and wind turbine technology has been exploited in SHM to deploy SHM systems free of power transmission cables Kim (2011), Ho (2012), Ho (2012). Different system identification techniques have been used to analyze the output data of SHM systems, such as: fast Fourier transform (FFT), stochastic subspace identification (SSI) Van Overschee (1996), frequency domain decomposition (FDD) Brincker (2000), Autoregressive with exogenous inputs (ARX).

Throughout the years, these technologies have been combined together in many different SHM systems for civil engineering applications. Each system has its own power supply, such as: external power, local energy harvester, local wind turbine, local corrosion. Each system has its own data transmission hardware and protocol, such as: XStream, XBee Pro, Wi-Fi, and Ethernet. In this study, the results of two completely different SHM systems that have been deployed on the same structure were compared to show the difference in the results, their accuracy, and the overall reliability of the different technologies employed.

The structure is the Hwamyung bridge, which is a cable stayed bridge. The bridge was instrumented with two different systems based on two different technologies over a period of two years. Furthermore, the layout of the two systems has been changed throughout the experiment to achieve different goals, including: monitoring the longitudinal modal properties, transverse modal properties, torsional modal properties, modal properties and behavior of the cables.

2. Hwamyung bridge

Hwamgyung bridge (Fig. 1) is a cable stayed bridge on the Nakdong river. It was built to connect the west bank, where the town of Gimhae is, with the east bank, where the city of Busan is. The bridge is 500 m long, it has a main span of 270 m and two side spans of 115 m each (Fig. 2). Two towers that are 65 m tall support the 72 cables that carry the bridge load. This is the longest cable-stayed bridge with prestressed concrete box-girder in Korea. The bridge was a convenient location to test the two new SHM systems because it was still under construction and close to traffic. The bridge was built by Hyundai Engineering & Construction Co. and it was open to public in April 2012.

Fig. 1 Hwamyung bridge

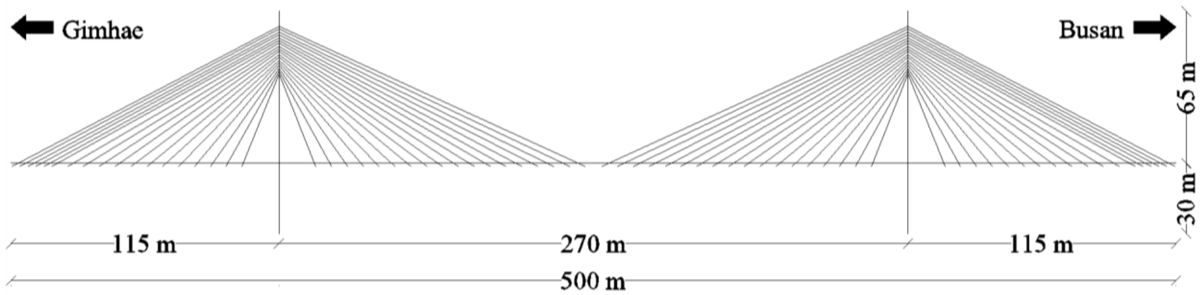


Fig. 2 Layout of the bridge

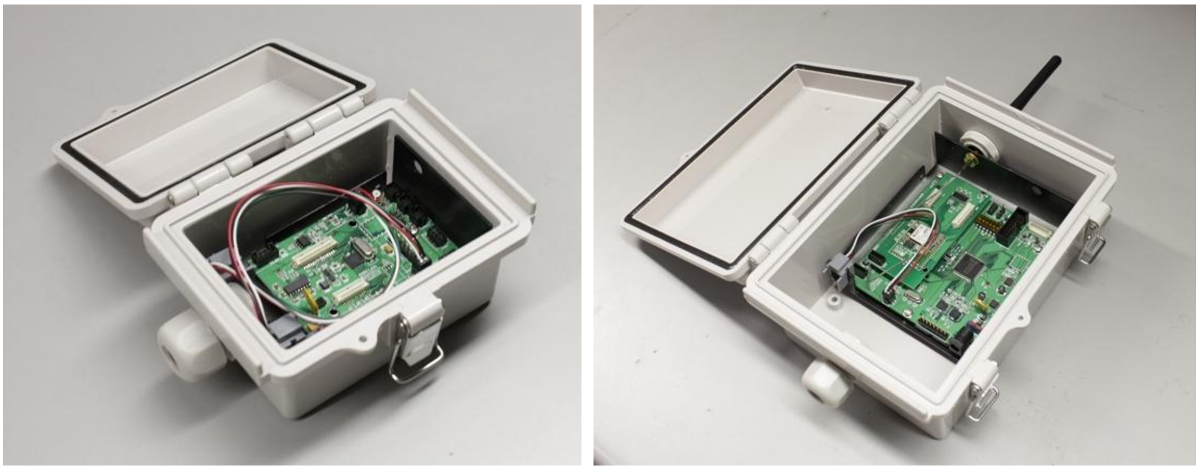
The base station of both experiments, which we will call the UCI experiment and the PKNU experiment, was located inside the deck next to the west tower. The two experiments have: different base station technology, different system identification tools, different data transmission systems, different sensors system, different sampling rate. They share only the same external power supply line, the same 3G remote connection, and the same analog digital converter (ADC) chip, 4 channels 16 bits.

3. UCI experiment: Duramote system

Duramote is a SHM system of wireless accelerometers. Initially, it was developed to detect rupture and leakage of buried pipe of water distribution networks by measuring the vibrations of the pipe wall. The characteristic of the buried pipe required two components at each node: a sensor unit and a data aggregator unit. The sensor unit (Fig. 3a) is attached to the wall of the pipe and is equipped with up to 3 SD1221L-002 accelerometers. The data aggregator unit (Fig. 3b) is placed on the surface, it provides power to the sensor unit, and it handles the data collection and transmission from the sensor unit through a RJ5 cable and CAN-bus technology.

The data aggregator unit transmits the data through wireless to a base station. Different wireless technologies are supported: Wi-Fi, cellular network, WiMAX, or WiBro. Each technology is chosen based on the relative distance between the node and the base station, the presence of other nodes nearby. When they operate a Wi-Fi network the data aggregator units hop the signals between each other up to the base station. Therefore, access points and routers are not necessary to sustain the network.

The experiments to develop the algorithm that detects the leakage or rupture of water pipes through the analysis of the vibrations of the wall were carried out in laboratory. Instead, the wireless network had to be tested on the field but performing experiments on real water distribution networks was too complex and it could have compromised the network functionality. Therefore, the wireless network was tested on civil infrastructure systems and the Duramote system was used to identify and monitor the modal properties of the civil structures, in this case a bridge.



(a) (b)

Fig. 3 (a) Sensor node unit, (b) Data aggregator unit

The first layout of the Duramote system was installed on the structure in June 2011 (Fig. 4) Torbol (2013). Sensors were placed on the center line of the deck, both on the main span and the side spans; sensors were also placed on 4 cables and on top of the towers. The modal properties to be identified were: the longitudinal natural frequencies and mode shapes, the transversal natural frequencies and mode shapes, the natural frequencies of 4 cables of different length, and the natural frequencies of the towers. The sensors had to be placed along the center line of the bridge due to limitations from the on-going construction. Therefore, it was impossible to detect the torsional natural frequencies and mode shapes of the bridge. The sampling frequency in this first experiment was 450 Hz.

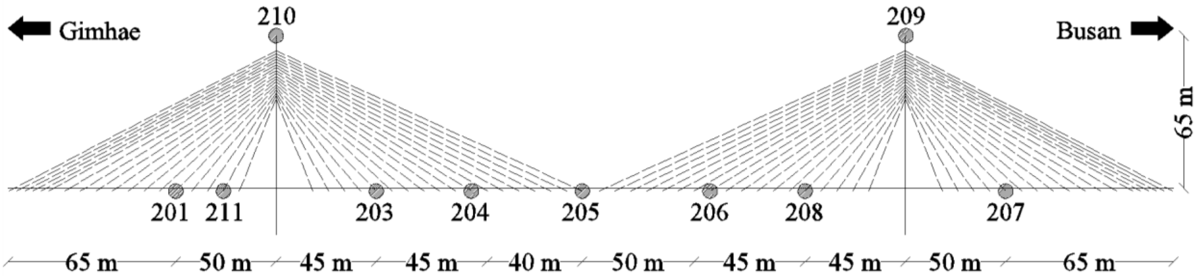


Fig. 4 1st experiment layout (UCI)

The second layout of the Duramote system was installed on the structure in Feb 2012 (Fig. 5) Torbol (2013). During this experiment the sensors were placed inside the deck. Each node includes a data aggregator unit, which is located near the center of the deck, and 2 sensor nodes, which are located on the lateral walls of the deck (Fig. 6). This setup can identify and monitor the torsional modal properties of the structure. The sampling frequency for this second experiment was 100 Hz but the closed environment of the reinforced concrete box girder made Wi-Fi transmission a challenge.

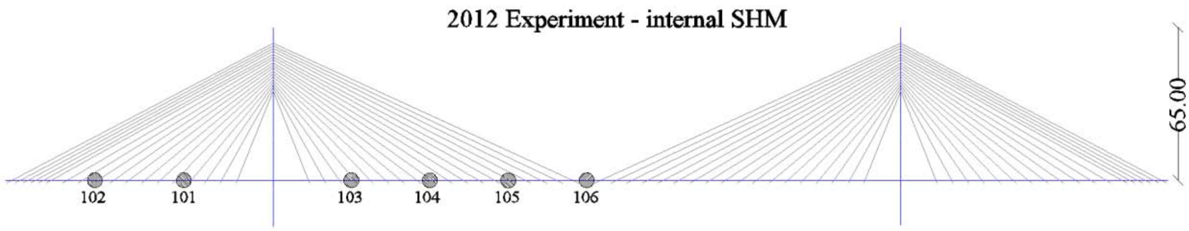


Fig. 5 2nd experiment layout (UCI)

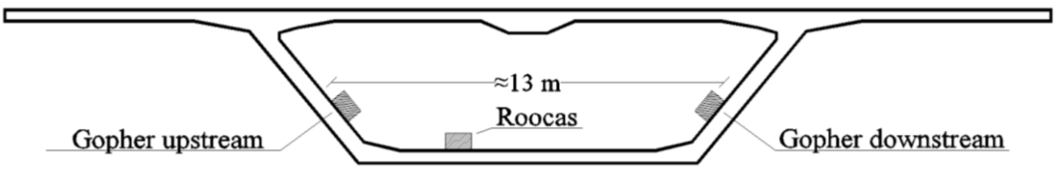


Fig. 6 Transverse layout

4. SHM system based on Imote2

The PKNU group deployed their own sensor system on the bridge during the same period Ho (2012). This sensor system is based on the Imote2 platform and two different configurations were used: SHM-A and SHM-B Jo (2010), Rice (2010). The SHM-A node includes a tri-axial accelerometer LIS344ALH. 6 nodes were deployed on the center line of the deck along half the bridge length and on top of the tower. Instead, the SHM-B node includes SD1221L-002 accelerometers, which is the same accelerometer used in the sensor unit of the Duramote system. 5 nodes were deployed on specific cables.

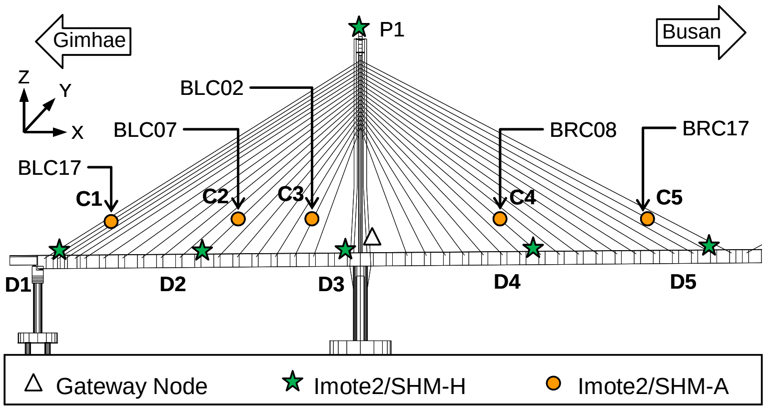


Fig. 7 Imote2 experiment layout (PKNU)

5. Results

In all experiment the different systems were capable of detecting the modal properties of the bridge including natural frequencies and mode shapes. The bridge was subject to different typhoons causing loss of power, loss of remote connection, loss of functionality of some nodes. Table 1 shows the identified natural frequencies in each experiment and the difference between the two.

The torsional natural frequencies were computed from the second UCI experiment. Instead, PKNU group used too different system ID technique: FDD and SSI. Although the sampling frequencies, the accelerometers, the transmission systems, and data processing are different the results are in general within 5% from each other.

Tab 1 Natural frequencies of the bridge

Frequency	UCI (FDD)	PKNU (FDD)	PKNU (SSI)	Difference (abs value)
Vertical	0.465 Hz	0.446 Hz	0.444 Hz	4.52 %
Transverse	0.413 Hz	0.464 Hz	0.454 Hz	9.93 %
Transverse	0.797 Hz	0.665 Hz	0.666 Hz	16.44 %
vertical	0.752 Hz	0.720 Hz	0.720 Hz	4.26 %
vertical	/	/	1.028 Hz	/
vertical	1.072 Hz	1.087 Hz	1.084 Hz	1.12 %
transverse	/	1.172 Hz	1.169 Hz	/
vertical	1.134 Hz	/	1.171 Hz	3.26 %
vertical	1.522 Hz	1.465 Hz	1.462 Hz	3.94 %
transverse	1.472 Hz	/	/	/
torsional	2.421 Hz	/	/	/
torsional	2.740 Hz	/	/	/

6. Conclusion

The different modal properties were identified by the different systems and system identification methods. However, the first two natural frequencies in each direction, vertical transverse and torsional were detected by every system. These are the important natural frequencies and they have the highest mass participation factor; they are also the most excited by traffic load, wind load and seismic load, which is not a concern because the bridge is located in a low level seismic region.

In regards to system identification, frequency domain decomposition (FDD) and stochastic subspace (SSI) are both valid and successfully identified the first few natural frequencies of the bridge. However, FDD becomes unreliable for higher natural frequencies because these are not excited as much by ambient vibrations. Higher frequencies have poor signal to noise ratio when FDD is plotted in frequency domain. Instead, both data driven SSI and covariance driven SSI can identified every natural frequency. Furthermore, by changing the model order of the SSI model the results can be refined.

In the future, the bridge will be equipped with a fixed SHM for long term monitoring to perform life-cycle cost analysis (LCC), structural degradation, damage detection, and damage assessment with special attention on cables and loss of prestress.

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