Reconfigurable wireless monitoring systems for bridges: validation on the Yeondae Bridge

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ABSTRACT

The installation of a structural monitoring system on a medium- to large-span bridge can be a challenging undertaking due to high system costs and time consuming installations. However, these historical challenges can be eliminated by using wireless sensors as the primary building block of a structural monitoring system. Wireless sensors are low-cost data acquisition nodes that utilize wireless communication to transfer data from the sensor to the data repository. Another advantageous characteristic of wireless sensors is their ability to be easily removed and reinstalled in another sensor location on the same structure; this installation modularity is highlighted in this study. Wireless sensor nodes designed for structural monitoring applications are installed on the 180 m long Yeondae Bridge (Korea) to measure the dynamic response of the bridge to controlled truck loading. To attain a high nodal density with a small number (20) of wireless sensors, the wireless sensor network is installed three times with each installation concentrating sensors in one portion of the bridge. Using forced and free vibration response data from the three installations, the modal properties of the bridge are accurately identified. Intentional nodal overlapping of the three different sensor installations allows mode shapes from each installation to be stitched together into global mode shapes. Specifically, modal properties of the Yeondae Bridge are derived off-line using frequency domain decomposition (FDD) modal analysis methods.

Keywords: structural monitoring, wireless sensor, modal analysis, FDD

1. INTRODUCTION

In most developed nations, bridges are inspected on an annual or semi-annual basis. For example, bridges are semi-annually inspected in the United States through the National Bridge Inspection Program (NBIP) [1]. While programs like the NBIP have done a good job ensuring the safety of bridges, visual inspection of bridges suffer from some drawbacks. First, inspections are labor intensive and costly. Furthermore, there is a high degree of subjectivity in the inspection process leading to uncertainty in the decision making of the bridge owner. In recent years, greater objectivity has been added to the inspection process through the adoption of nondestructive evaluation (NDE) technologies. While manually operated NDE instrumentation has helped to improve the quality of inspections, more permanent automated sensing is envisioned for future bridge management. A permanently installed structural monitoring system can be used to provide empirical evidence of a bridge’s response to operational (e.g., traffic) and environmental (e.g., temperature variations) loads. Once engineers understand the normal behavior of a bridge based on response data collected by the monitoring system, only then can they begin to formulate automated data interrogation methods aimed towards identifying degradation or structural damage.

The architecture of the traditional structural monitoring system consists of three parts: sensors to measure structural responses, a centralized server for system operation and data storage, and coaxial wiring for the communication of data from the sensors to the central server. Unfortunately, the extensive wiring required for the communication of sensed data can drive the cost of the monitoring system high [2]. To reduce this high cost, wireless sensors have been proposed for structural monitoring [2-4]. Recent installations of wireless monitoring systems in actual operational bridges (Alamosa Canyon Bridge, New Mexico[5]; Geumdang Bridge, Korea [6]; Gi-Lu Bridge, Taiwan [7]; Wright Bridge, 

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New York [8]) have revealed the potential of wireless sensors for accurate and reliable data collection in the field.

In this study, a wireless monitoring system is installed on the Yeondae Bridge (Korea) to monitor its behavior during forced excitation using a speeding truck. The bridge is 180 m long and is designed as a continuous steel box girder supported by piers along its length. Low-cost wireless sensor nodes using microelectromechanical system (MEMS) accelerometers are installed to measure the vertical acceleration of the bridge under controlled traffic loading. To provide a high nodal density using a small number of sensor nodes (20), the system is installed three separate times with sensors concentrated in three overlapping regions along the bridge length. A total of 50 unique sensor locations are utilized providing a rich set of data for modal analysis. Frequency domain decomposition modal estimation (FDD) is carried out using the response data collected by the wireless monitoring system to identify modal frequencies and mode shapes.

2. YEONDAE BRIDGE

In 1998, the Korea Highway Corporation (KHC) initiated construction of a state-of-the-art test road to study the impact of Korean truck traffic on pavement systems designed by current Korean design codes [9]. The test road is 7.7 km long and is designed to carry two lanes of southbound traffic of the Jungbu Inland Highway. A unique aspect of the design of the test road is that it serves as a redundant section of the existing southbound highway; this allows the road to be opened and closed by the KHC without interfering with the flow of traffic on the main highway. In total, 1897 sensors (e.g., strain gages, soil pressure sensors, and thermocouples) are installed within the pavement and soil system along the entire length of the test road. Along the length of the highway are three bridges: Samsenung Bridge, Yeondae Bridge, and Geumdang Bridge. The bridges are not instrumented with sensors and are only intended to carry traffic over a number of irrigation valleys. At the time of completion of the road construction, the KHC partnered with the Smart Infrastructures Technology Center (SISTeC) to explore ways to utilize the bridges for benchmarking the performance of sensing and data interrogation technologies under development for structural health monitoring (SHM). Since that time, a large number of studies have utilized the three test road bridges to validate a variety of new sensor technologies in the field [6, 9-11].

In this study, the Yeondae Bridge is selected to validate the performance of a reconfigurable monitoring system designed using wireless sensor nodes (termed Narada) that are under development at the University of Michigan. The Yeondae Bridge is a curved, but continuous steel box girder bridge that is 180 m long (Fig. 1). The bridge is divided into 4 identical spans with three concrete piers located every 45 m and concrete abutment structures situated at the northern and southern-most ends of the bridge. The box girder is supported at the piers and abutments using stacks of elastomeric pads. The concrete deck of the bridge is roughly 27 cm thick and 12.6 m wide. The cross section of the bridge reveals two identical trapezoidal steel box girders roughly 2.2 m tall with top and bottom widths of 3.3 and 2.1 m, respectively. The design of the box girder varies along the length of the bridge depending upon the flexural moment imposed on the
section. For example, in the center of the bridge spans where the bending moment is positive, the box girders are open with the concrete deck taking the compressive stress of the bridge section. However, in locations where the bending moment is negative (e.g., over the bridge piers), the box girders are closed with steel plates welded to the top of the box girders to take the tensile action.

3. INSTRUMENTATION OF THE YEONDAE BRIDGE

Due to the complex geometric features of the Yeondae Bridge, it is anticipated that the bridge will exhibit some unique modal properties. To calculate the bridge mode shapes, a dense instrumentation of vibration sensors are sought. Wireless sensors are selected for instrumentation because of their cost advantages over traditional structural monitoring systems that require extensive wiring. Specifically, the Narada wireless sensor node [12] is adopted to record data from accelerometers installed along the bridge length.

3.1 Narada Wireless Sensor

The Narada wireless sensor has been designed explicitly for smart structure applications where sensing, actuation and computing are desired functionalities. The wireless sensor supports data collection from analog sensors that output voltage signals between 0 and 5 V. Up to 4 different sensors can be interfaced to the wireless sensor at one time with sensor data digitized using a 16-bit analog-to-digital converter (Texas Instruments ADS8341). This converter is also capable of sampling at rates as high as 100 kHz. Data collected by the sensing interface is managed by a low-power microcontroller (Atmel ATmega128). The ATmega128 is a fixed-point processor with an 8-bit internal architecture. With 128 kB of on-chip flash memory, software is embedded in the microcontroller to automate its operation including the collection of data, the packetizing of data for communication, and the execution of data interrogation algorithms. To provide the wireless sensor node with memory for storing sensor data, an additional 128 kB of random access memory is interfaced to the microcontroller. To communicate data between wireless sensor nodes, a 2.4 GHz transceiver that complies with the IEEE802.15.4 communication standard is selected. The Chipcon CC2420 can communicate 250 kilobits per second. However, one drawback of the standard configuration of the Chipcon CC2420 is its communication range. At roughly 30 m, the short range of the transceiver might prove challenging in most civil engineering structures that have geometric dimensions in the hundreds of meters. For the Narada wireless sensor node, a separate radio board is designed for the Chipcon CC2420 radio. A unique feature of the board is the inclusion of a power amplifier that amplifies the radio output to achieve reliable communication ranges of 300 m or greater. While beyond the scope of this study, the wireless sensor is capable of actuation using a 12-bit digital-to-analog converter (Texas Instruments DAC7612) [13].

The fully assembled Narada wireless sensor node is compact with a footprint of 6 by 6 cm² and a height of 1 cm (Fig. 2a). The modified, long-range CC2420 transceiver is designed on its own circuit board (3 by 3 cm²) and is attached to the main wireless sensor circuit using standard header pins. The design of the wireless sensor intentionally keeps the radio on its own circuit board so that it can be replaced by a shorter-range version of the radio when shorter
communication ranges (50 m or less) are desired. As a result, the overall power consumption of the wireless sensor node can be reduced by using the shorter range radio for such applications. Sensors are interfaced to the wireless sensor using the four connectors (i.e., each connector corresponds to one channel of the analog-to-digital converter) located on one side of the wireless sensor printed circuit board. The wireless sensor is powered using a standard battery pack that provides a nominal voltage of 7.5 V. While any type of battery can be used (e.g., alkaline, lithium-ion), past experiences reveal that lithium-ion batteries provide the best performance. The total power consumed by the wireless sensor when utilizing the transceiver for the communication of data is roughly 250 mW.

3.2 Accelerometer and Signal Conditioning

In this study, accelerometers are selected to measure the vibration response of the Yeondae Bridge during traffic excitation. To keep the cost of the instrumentation down, two low-cost accelerometers that employ capacitive read-out mechanisms are selected. The accelerometers selected are: Crossbow CXL02 and PCB Piezotronics 3801D1FB3G. Both accelerometers are fabricated using microelectromechanical system (MEMS) methods which keeps the cost of the accelerometers comparatively low (< $300). The Crossbow CXL02 is the more sensitive accelerometer of the two with a sensitivity of 1 V/g (compared to 0.7 V/g for the PCB 3801D1FB3G). However, the noise floor of the PCB 3801D1FB3G accelerometer is superior at 0.15 mg; the noise floor of the Crossbow CXL02 is greater at 0.5 mg. The dynamic ranges of both accelerometers (2g and 3g for the Crossbow CXL02 and PCB 3801D1FB3G, respectively) are well above the anticipated level of acceleration in the Yeondae Bridge. In total, 14 Crossbow CXL02 and 6 PCB 3801D1FB3G accelerometers are procured for the purposes of this study.

While the nominal resolution of the wireless sensor’s analog-to-digital converter is 16-bits, electrical noise in the circuit reduces the effective resolution to fall somewhere between 14- and 15-bits [6]. If the effective resolution is 14-bits, the minimum resolution of the analog-to-digital converter is 0.305 mV. In terms of the two accelerometers selected, this translates into a minimum acceleration resolution of 0.305 mg and 0.214 mg for the Crossbow CXL02 and PCB 3801D1FB3G accelerometer, respectively. Since the quantization error is in the vicinity of the accelerometer noise floors, the quality of data collected by the wireless sensor can be drastically improved if the outputs of the accelerometers are amplified before digitization. A custom-designed amplification (with an amplification factor of 20) and band-passing (with a pass band of 0.014 to 25 Hz) circuit is therefore adopted in this study (Fig. 2b). This signal conditioning board is used to filter the accelerometer outputs before interfacing to the Narada wireless sensor node.

3.3 Sensor Configurations

The wireless monitoring system deployed on the Yeondae Bridge employs 20 Narada wireless sensor nodes with one accelerometer (Crossbow CXL02 or PCB 3801D1FB3G) interfaced to each sensing node. The single-axis accelerometers are oriented to measure the vertical acceleration of the bridge deck. As previously mentioned, a signal conditioning board that amplifies the sensor output by a factor of 20 is used with each accelerometer-wireless sensor node pair. Instead of installing all 20 wireless sensors across the entire length of the bridge, the system is first deployed with a dense instrumentation of sensors concentrated on the northern-most 70 m of the bridge (Fig. 3). This allows 10 wireless sensors to be installed on each side of the bridge; in this configuration, the wireless sensors are longitudinally separated by 7.65 m.

A benefit of using wireless sensors is the ease by which they can be conveniently moved; this feature is taken full advantage of in this study. Once a sufficient amount of data is collected by the first installation, the wireless sensors are moved to the center section of the bridge. Again, 10 sensors are installed on each side of the bridge with the same longitudinal distance preserved between nodes. After data is collected by the second installation, the system is again reconfigured to form a third installation that records the response of the southern-most portion of the Yeondae Bridge. It should be noted that four sensor locations are always shared between the different network installations. For example, sensor location 9 in the first network installation is the same as sensor location 1 in the second network configuration (Fig. 3). This intentional overlap between the three different network installations ensures the global mode shapes of the bridge can be assembled by stitching together localized mode shapes calculated from each installation of the wireless monitoring system.

During each network installation, a single receiver is used to control the operation of the wireless monitoring system as well as to collect data from the wireless sensor nodes. For this purpose, a laptop computer with a Chipcon CC2420 transceiver connected is selected. The laptop is placed on the top deck of the bridge in the vicinity of the northern abutment. From this location, the laptop has a direct line of sight with every wireless sensor installed on the road surface. Hence, wireless communication between the laptop and the wireless sensor nodes should be very reliable.
4. RESULTS

4.1 Forced Bridge Excitation

The Yeondae Bridge is excited through the use of a heavy truck driven across the bridge at fixed speeds. The truck (Fig. 4a) utilized in this study has three axles and a total weight of 25 metric tons. The truck can be driven across the bridge at any desired speed; however, this study limits the speed of the truck to be from 30 to 70 km/hr in increments of 10 km/hr. For each monitoring system configuration, the truck is driven over the bridge using the five established truck speeds. Different truck speeds are used to excite the bridge in order to ascertain if truck speeds have any effect on the modal estimation process.

Each time the truck is driven over the bridge, the wireless monitoring system is used to collect the vertical acceleration response of the deck. Prior to the truck’s arrival, the wireless monitoring system initiates the data collection operation by first time synchronizing the network. Due to the star network topology adopted in each network configuration, a beacon approach is used to achieve tight time synchronization between the wireless sensors and the centralized laptop. Past studies reveal the error inherent in this time synchronization approach is 10 ms or less [6]. Once the network is synchronized, each wireless sensor collects the acceleration response of the bridge using a sample rate of 100 Hz. A total of 90 seconds of acceleration data is collected by the wireless monitoring system during each run. The 16-bit integer data streaming from the analog-to-digital converter is stored in the Narada random access memory bank. For 90 seconds worth of time history data, this only occupies 18 kB of the available memory (128 kB). After each wireless sensor has collected 90 seconds worth of data, the centralized repository wirelessly queries the network for the stored time-history records. The repository stores the synchronized time history data from each wireless sensor one-by-one.
Fig. 5 presents the time synchronized time history response of the Yeondae Bridge when the truck is driven at 30 km/hr with the first sensor installation collecting bridge response data. Similarly, Fig. 6 presents the response of the bridge for the same installation but for a truck speed of 70 km/hr. As can be observed in the time history figures, the wireless monitoring system proves reliable with no data lost during wireless communications. Furthermore, the time history response is time synchronized with the initiation of bridge response occurring at the same time for each truck excitation. When comparing the absolute peak acceleration response, the higher speed truck induces a significantly higher response of 46.6 mg (occurring at 24.34 seconds in the time history record measured at sensor S4 (Fig. 6)) compared to 19.1 mg (occurring at 31.35 seconds in the time history record measured at sensor S20 (Fig. 5)) for the 30 km/hr truck. Similar results are obtained for the other two sensor installations.

4.2 Modal analysis

Modal analysis is conducted on the bridge response data to derive mode shapes. In particular, the frequency domain decomposition (FDD) method proposed by Brinker et al. [14] is used for this purpose. The FDD technique is attractive for use in this study because it is an output-only modal analysis method. While some information is known about the bridge loading (e.g., the weight and speed of the truck), only measurements of the bridge response are available for analysis. FDD is a straightforward modal analysis method that is based on the output power spectral density (PSD) matrix, $G_{yy}(\omega)$. If the excitation to the system is broadband white noise, then the output PSD matrix is proportional to the frequency response function (FRF) product, $H(\omega)H^H(\omega)$. Even if the excitation is not broadband, the output PSD matrix is often considered as a close approximation to the FRF product and used for modal analysis. Singular value decomposition (SVD) is then used to decompose the PSD into its singular values, $\lambda$, and vectors, $u$: $G_{yy} = U\Sigma U^H$ where $U = [u_1 u_2 \ldots u_n]$ and $\Sigma = \text{diag}[\lambda_1 \lambda_2 \ldots \lambda_n]$. Singular vectors corresponding to large singular values are correlated to the mode shapes of the structure. An attractive feature of the FDD algorithm when compared to classical peak picking approaches is that closely spaced but lightly damped modes can be identified through decomposition of the output PSD matrix.

In this study, the excitation (i.e., the moving truck) is clearly not broadband. Hence, the FDD approach might not yield accurate mode shapes if the response of the bridge during forced vibration is used as the input to the analysis. To utilize FDD for an accurate calculation of bridge mode shapes, the free vibration response of the bridge is used exclusively. Time history responses are first divided into two portions: forced and free vibrations. Forced vibrations correspond to the portion of the acceleration time history when the truck is on the structure. After the truck has exited the structure, the bridge continues to vibrate due to its free vibration behavior. Fig. 7 shows the acceleration time history response to the 30 km/hr truck excitation measured at sensor locations S1 and S20 (in the first network installation). Given sensor S1’s...
location (it is only 0.55 m away from the expansion joint between the bridge deck and the northern bridge approach), it can be used to identify when the truck first enters the bridge. For the example shown in Fig. 7, truck enters the bridge at
15.9 seconds. With the vehicle travelling across the bridge at 30 km/hr, the truck would exit the bridge at roughly 37.5 seconds. Hence, the response measured between 15.9 and 37.5 seconds corresponds to the forced vibration response of the bridge. To proceed with modal analysis, the response after 40 seconds is considered as the bridge’s free vibration response.

Before mode shapes can be estimated, the modal frequencies of the bridge must be identified first. The singular values corresponding to the output PSD matrix can prove valuable for identification of modal frequencies [15]. For example, consider plots of the singular value as a function of frequency for the first four singular values calculated using response data from the 30 km/hr excitation (Fig. 8). Two observations can be made when considering the singular value plots for the three network installations. First, the first singular value is significantly larger than the other remaining singular values suggesting there is no interference between modes. Second, the peaks in the first singular values correspond to the modal frequencies of the system which are independent of network installation. Based on Fig. 8, the first five modal frequencies are identified at 2.25, 2.64, 3.47, 4.05 and 4.1 Hz.

With the first five modal frequencies identified, the modes of the structure are calculated by SVD of the free vibration output PSD matrix. This calculation is conducted for each sensor configuration using the same type of excitation source.
Due to the geometric overlap in the network installations, mode shapes calculated for the three installations can be “stitched” or “glued” together by normalizing each mode to be in agreement with the other in the overlap region. The resulting modes are the global modes of the Yeondae Bridge and are shown in Fig. 9.

The first three mode shapes are flexural bending modes that correspond to modes calculated off-line using a finite element model of the bridge [16]. The fifth mode is a torsional mode also in strong agreement with the finite element model.

5. CONCLUSIONS

A wireless monitoring system consisting of *Narada* wireless sensors and MEMS accelerometers is installed upon the Yeondae Bridge to measure its dynamic response to a 3-axel truck driving across the bridge at fixed speeds. In total, 20 wireless sensor-accelerometer pairs are available for installation in the bridge. To maximize the amount of data available for modal analysis, the wireless monitoring is reconfigured during forced vibration testing in order to acquire bridge response data from 50 unique sensor locations. Specifically, the monitoring system is installed using three different spatial configurations with each installation concentrating sensors in one specific region of the bridge (i.e., northern, central, and southern regions). The system is reconfigured with ease due to the fact that the sensors are wireless. During testing, the wireless monitoring system is found to be reliable (with no data loss encountered) and provided accurate response measurements. To highlight the quality of the data collected, modal analysis using the FDD modal estimation method is conducted. Five mode shapes are estimated by FDD analysis corresponding to modal frequencies of 2.25, 2.64, 3.47, 4.05 and 4.93 Hz). These modes are consistent with modes predicted by a finite element model of the Yeondae Bridge. The authors’ current focus is on the design of a permanent wireless monitoring system for the Yeondae Bridge. Findings from this study will be used to shape the design of the permanent monitoring system. Furthermore, automated modal analysis is being explored as a functionality to be embedded in the wireless monitoring system.

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Fig. 9. FDD derived mode shapes using free response data corresponding to a 30 km/hr truck excitation.
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