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Wireless Structural Monitoring of the Geumdang Bridge using Resolution Enhancing Signal Conditioning

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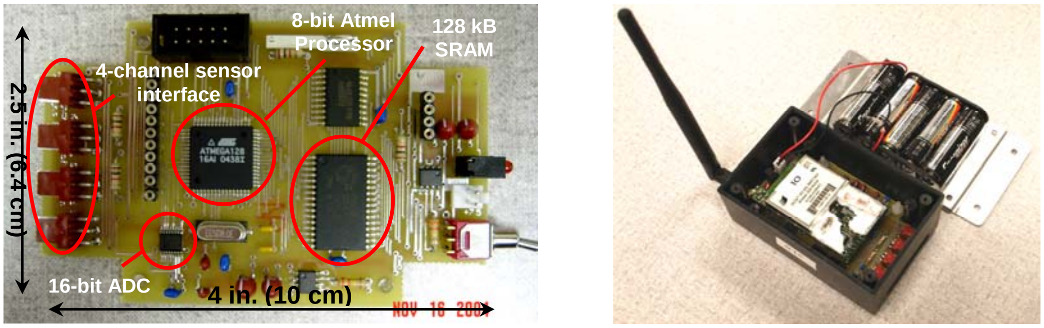
ABSTRACT

Field deployment of wireless sensors is a necessary first-step towards validating their performance within the complex and challenging environments posed by civil structures. In this study, a wireless structural monitoring system, assembled from low-cost wireless sensor prototypes, is deployed upon the Geumdang Bridge, Korea. The wireless monitoring system is installed on the concrete box girder bridge on two separate occasions. During the first installation, the wireless system is shown to be capable of collecting acceleration response data using a network of fourteen wireless sensors. However, higher than expected noise is observed in the sensor data. To improve the resolution of the wireless monitoring system, a signal conditioning circuit is proposed for band-pass filtering and amplification of accelerometer outputs before connecting to the wireless sensors. With the signal conditioning circuit greatly enhancing the resolution of the wireless monitoring system, the Geumdang Bridge is again utilized for validation. During this phase of the study, response data collected by the wireless monitoring system is compared to that collected from a traditional wired monitoring system. The result is high-resolution data that can be used to accurately identify modal frequencies and mode shapes of the bridge.

INTRODUCTION

Wireless sensors have been proposed for use in structural monitoring and structural health monitoring systems. Wireless sensors are particularly attractive for civil structures because they eliminate the need for extensive lengths of coaxial wires common to traditional monitoring systems. To date, a number of academic and commercial wireless sensor platforms have been proposed for structural monitoring [1-4]. The wireless sensors proposed are all designed with three major functional components. First, to collect data from sensors



(a) (b)

Figure 1 – (a) Wireless sensor circuit; (b) fully assembled with radio and battery source shown

installed in a structure (*e.g.* accelerometers, strain gages, LVDTs), wireless sensors include analog-to-digital converters that convert continuous analog sensor signals into discretely sampled digital signals. Second, wireless transceivers are necessary components of wireless sensors since they allow sensors to communicate data to the remainder of the wireless sensor network. The last major functional element of most wireless sensors is a microcontroller. The microcontroller is primarily responsible for autonomous operation of the wireless sensor, encoding data for communication and local interrogation of response data. While the popularity of wireless sensors has been largely fueled by their low installation costs, the integration of mobile computing power with the sensing transducer represents a major paradigm shift in the monitoring domain. The embedded computational power allows wireless sensors to interrogate their own measurement data. This capability can be used by the monitoring system to carry out system identification and/or damage detection analyses.

In this study, a wireless sensor proposed for structural health monitoring by Wang, Lynch and Law [5] is adopted. As shown in Figure 1, the wireless sensor is a compact academic prototype fabricated using commercial off-the-shelf electrical components. The wireless sensor is intended to be an autonomous data acquisition node to which structural sensors can be easily interfaced. To collect data from the interfaced sensors, a four channel 16-bit analog-to-digital converter (ADC) is included in the design of the wireless sensor. The Texas Instruments ADS8341 ADC has a maximum sample rate of 100 kHz. After the outputs from interfaced sensors are digitized, a microcontroller included in the wireless sensor design is responsible for storing data in memory and preparing data for transmission. An 8-bit low-power Atmel ATmega128 microcontroller is selected for the wireless sensor prototype. This microcontroller has sufficient on-chip read-only memory (ROM) (128 kB) for the storage of embedded software. However, with only 4 kB of random access memory (RAM), an additional 128 kB of external RAM is included in the wireless sensor design for storage of structural response data. When data is ready for communication, the Maxstream 9XCite wireless transceiver is utilized. Operating on the unlicensed 900 MHz radio band, this modem can communicate with ranges as large as 300 m (line-of-sight). After all of the wireless sensor hardware components are selected, a two-layer printed circuit board is designed to integrate all circuit elements (*e.g.* microcontroller, ADC, voltage regulators) upon a small footprint board (6.4 cm x 10 cm); a picture of the fabricated printed circuit board is shown in Figure 1a. The 9XCite transceiver, consisting of its own printed circuit board, is stacked above the printed circuit board housing the chip components. These stacked printed circuit boards are then combined with a portable power source (5 AA lithium-ion batteries) within a single hardened plastic container that offers protection from the harsh environment encountered in civil structures. The final, fully assembled wireless sensor is presented in Figure 1b.

To assess the performance of wireless sensors designed for structural monitoring, it is important to carry-out validation studies using actual civil structures. Many of the academic and commercial prototypes proposed by the structural engineering community have been successfully installed in bridges and buildings. For example, the Alamosa Canyon Bridge, located in New Mexico, has been used by Straser and Kiremidjian [1] and Lynch *et al.* [2] to validate their wireless sensor prototypes. Chung *et al.* [4] have installed their wireless sensors upon a footbridge on the University of California-Irvine campus to monitor its response under foot-fall excitation. Ou *et al.* [6] report on their use of eight Crossbow MICA Mote wireless sensors to measure the response of the Di Wang Tower in Guangdong, China to wind loading.

A primary focus of this study is the validation of the wireless sensor prototype proposed by Wang, Lynch and

(a) (b)

Figure 2 – Geumdang Bridge, Icheon, Korea: (a) side view; (b) top deck view

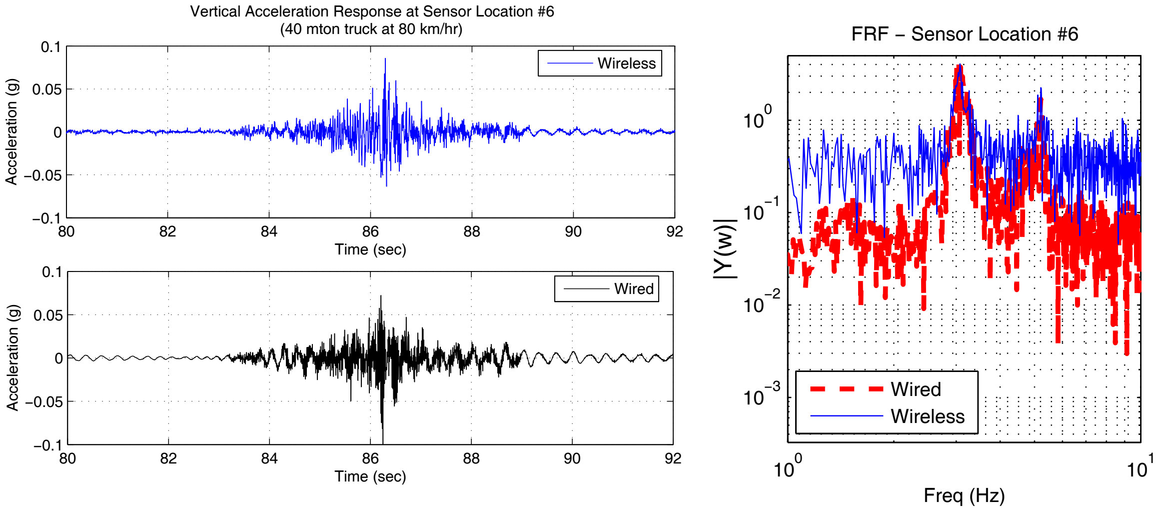
Law [5] using the Geumdang Bridge. During a previous study carried out in December 2004, the same wireless sensor prototype had been used to monitor the vertical acceleration response of the Geumdang Bridge while trucks crossed the bridge at set speeds [7]. While the wireless monitoring system was found to perform well during this study, noise introduced into the response data by quantization error in the wireless sensor's ADC was observed. Since the acceleration response of the bridge due to truck traffic is quite small (< 50 mg), quantization noise was evident in the time-history records collected. To improve the resolution of the wireless monitoring system, a signal conditioning circuit that amplifies low-level sensor outputs is proposed. The primary function of the signal condition circuit is to ensure the amplified noise floor of the sensor is well above the quantization noise introduced in the analog-to-digital conversion process. To validate the performance of the wireless monitoring system with the amplified signal conditioning circuits attached, the Geumdang Bridge is again used as a test-bed structure. Testing carried out in July 2005 will reveal that the performance of the new high-resolution wireless monitoring system is identical to that of a traditional tethered structural monitoring system.

INSTRUMENTATION OF THE GEUMDANG BRIDGE

The Geumdang Bridge, pictured in Figure 2, is located in Icheon, Korea and is part of a special redundant segment of the Jungbu Inland Highway that is densely instrumented with sensors that monitor the performance of the highway pavement system. The Geumdang Bridge, spanning 273 m, carries southbound traffic across an irrigated farming valley. The southern-most portion of the Geumdang Bridge is constructed from pre-cast concrete box girder sections. The concrete box girder span is 122 m long and is supported by three piers and one retaining wall abutment structure. The northern portion of the Geumdang Bridge spans 151 m and is constructed from four concrete I-beam sections supported by four piers and an abutment. Although the bridge is an integral element of the instrumented highway segment, no sensors are installed on the bridge. However, the Geumdang Bridge can serve as a convenient test-bed for validating wireless monitoring systems because the Korea Highway Corporation is able to close the instrumented Jungbu Inland Highway segment to regular traffic.

During December 2004, the Geumdang Bridge was closed to traffic and a wireless monitoring system installed. As reported by Lynch *et al.* [7], fourteen wireless sensor prototypes were installed within the interior spaces of the concrete girder span. Interfaced to each wireless sensor was the PCB Piezotronics 3801 capacitive accelerometer. Installed in 14 different locations along the span length, each PCB3801 accelerometer was interfaced to a wireless sensor to measure the vertical acceleration response of the bridge during forced vibration testing. The PCB3801 accelerometer is a low-cost capacitive accelerometer with a ± 3g dynamic range, 0.5 mg noise floor, and 0.7 V/g sensitivity. The accelerometer was selected for two reasons: it is low-cost (~$300) and could be easily interfaced to the wireless sensor nodes.

Installed in parallel to the wireless monitoring system was a traditional tethered structural monitoring system. Similar to the wireless monitoring system, 14 separate piezoelectric accelerometers (PCB Piezotronics 393 accelerometers) were installed adjacent to the wireless monitoring system's PCB3801 accelerometers. Coaxial wires were then run from the sensors to a centralized data collection point consisting of a 16-channel PCB Piezotronics 481A03 signal conditioner interfaced to a 12-bit National Instruments data acquisition system. The 481A03 signal conditioning system converted the charge output of the piezoelectric accelerometers to



(a) (b)

Figure 3 – (a) Guemdang Bridge vertical acceleration response to truck loading [7]; (b) Fourier amplitude spectra at sensor location #6 [7]

amplified voltage signals (10x amplification in this study) before sending the signals to the 12-bit data acquisition system.

Vibrations were introduced in the Geumdang Bridge using trucks of known weight crossing the bridge at fixed speeds. The wireless and wired monitoring systems were configured to collect the bridge response data at a sample rate of 200 Hz. Shown in Figure 3a are time-history responses collected by both systems at the center of the 122 m span. Close investigation of the time-history data reveals the wireless monitoring system's measured acceleration response to be noisier than that of the response measured by the wired monitoring system. The elevated noise floor of the wireless monitoring system is evident when transforming data to the frequency-domain. Figure 3b represents the Fourier amplitude spectra for the time histories presented in Figure 3a. While the first two modal frequencies of the bridge can easily be identified, the Fourier amplitude spectrum from the wireless monitoring system is noisier. The white noise present in the wireless monitoring system time-history data results in the Fourier amplitude spectrum's flat portions occurring at higher amplitudes than that of the wired monitoring system.

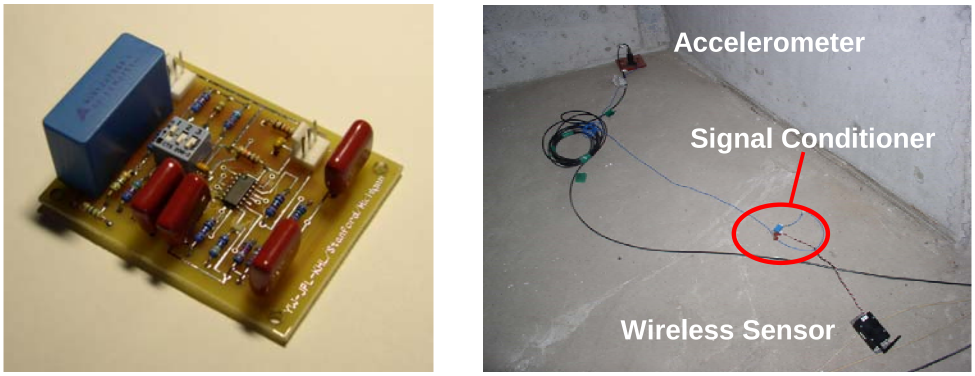
SIGNAL CONDITIONING INTERFACE BOARD

To better understand the source of the noise observed in the wireless monitoring system response data, consider the environment in which the analog-to-digital converter operates. The wireless sensor prototype is fabricated using a two layer printed circuit board. The two layer printed circuit board design approach does not allow analog portions of the circuit (*e.g.* ADC) to be isolated from the digital integrated circuit elements (*e.g.* microcontroller, wireless transceiver). As a result, the opening and closing of transistors in the digital components flood charge into the wireless sensor's electrical ground, resulting in noise in the analog portion of the system; this can result in a degradation of the resolution of the ADC. The Texas Instruments ADS8341 is a four channel 16-bit ADC; however, due to digital circuit noise, the true resolution is lower than 16-bits. Previous study of analog-to-digital converters placed on two-layer printed circuit boards reveals that 16-bit ADC resolutions can be reduced by as much as 2 or 3-bits [8].

If the effective resolution of an ADC is 13-bits (reduced from 16-bits due to the digital circuit components), then the quantization noise present in the ADC conversion can be calculated based on the measurable voltage range of the ADC (0 to 5V):

$$V_{NOISE}=\frac{5V}{2^{13}}=\pm 6.1x10^{-4}V \tag{1}$$

During forced vibration testing of the Geumdang Bridge, the PCB3801 accelerometer was interfaced to the wireless sensor's 16-bit ADC. The sensitivity of this accelerometer is 0.7 V/g, which implies that the



(a) (b)

Figure 4 – (a) Signal conditioning circuitry for band-pass filtering and amplification of sensor outputs; (b) installation of a signal conditioning circuit with a wireless sensor in the Geumdang Bridge

quanitization error of the ADC conversion is 0.87 mg. When compared to the specified internal noise floor of the PCB3801, we see the quantization noise of 0.87 mg is greater than the accelerometer's internal 0.5 mg noise floor. As a result, quantization noise controls the overall quality of the measurement data.

To enhance the effective resolution of the wireless sensor, a signal conditioning circuit is proposed. The signal conditioning circuit is designed externally to the wireless sensor and would be an intermediate element in the connection between the sensor (accelerometer) and the wireless sensing unit. The primary objective of the signal conditioning circuit is to amplify sensor outputs to improve the ADC resolution. For example, if the PCB3801 accelerometer output is amplified by a factor of 20, the effective sensitivity of the sensor would then be 14 V/g. This would suggest that the 0.5 mg noise floor of the accelerometer is at a voltage of 70 x 10^{-4} V; this voltage is 11 times larger than the quantization noise of the 13-bit effective resolution ADC (6.1 x 10^{-4} V). As a result, the noise floor of the accelerometer would control the quality of the time-history response recorded by the wireless sensor. To provide a flexible amplification circuit that can be used with different structural sensors, three amplification factors, 5, 10 and 20, are included in the signal conditioning circuit. In addition to amplification, a 4-pole Bessel band-pass analog filter is included in the signal conditioning circuit. The high- and low-pass cutoff frequencies are designed to be 0.014 and 25 Hz, respectively. A Bessel band-pass filter is selected because of its constant group delay in the pass band. The completed signal conditioning circuit is shown in Figure 4a.

FORCED VIBRATION TESTING OF THE GEUMDANG BRIDGE – JULY 2005

Adoption of the proposed signal amplification circuit can significantly improve the resolution of the wireless monitoring system. To illustrate the performance of the high-resolution wireless monitoring system, the system is again installed in the Geumdang Bridge in late-July 2005. In this study, fourteen wireless sensors are installed in the interior spaces of the Geumdang Bridge concrete box girder span. Attached to each wireless sensor is a signal conditioning board and PCB3801 accelerometer, as shown in Figure 4b. The amplification signal conditioning board is configured to amplify the PCB3801 accelerometer output by a factor of 20. The wireless sensors are evenly distributed along the span with a higher concentration of sensors installed in the center of the span between Pier 5 and 6. The locations of the fourteen wireless sensors are presented in Figure 5 and are numbered from #2 to 21. A centralized data server (laptop) is placed in the vicinity of sensor location #16 to coordinate the operation of the wireless sensor network and to receive measurement data for permanent storage. In addition to the wireless monitoring system, the wired data acquisition system (PCB Piezotronics 481A03 signal conditioning and National Instruments 12-bit data acquisition systems) previously adopted is employed to record the bridge response using the PCB393 accelerometers. Again, both monitoring systems are sampled at a rate of 200 Hz.

To excite the instrumented bridge, a 40 ton truck with four wheel axels is driven across the bridge at fixed speeds (40, 60 and 80 km/hr). The corresponding response of the bridge is recorded by the wireless and wired monitoring systems. For the 40 ton truck crossing the bridge at 80 km/hr, the measured time-history response of the bridge is presented in Figure 6 for accelerometer locations #2, 4, 5 and 6. The responses measured by both monitoring systems are superimposed to facilitate visual comparison. As can be seen at all four sensor locations, the response of the bridge measured by both monitoring systems is identical. Figure 7

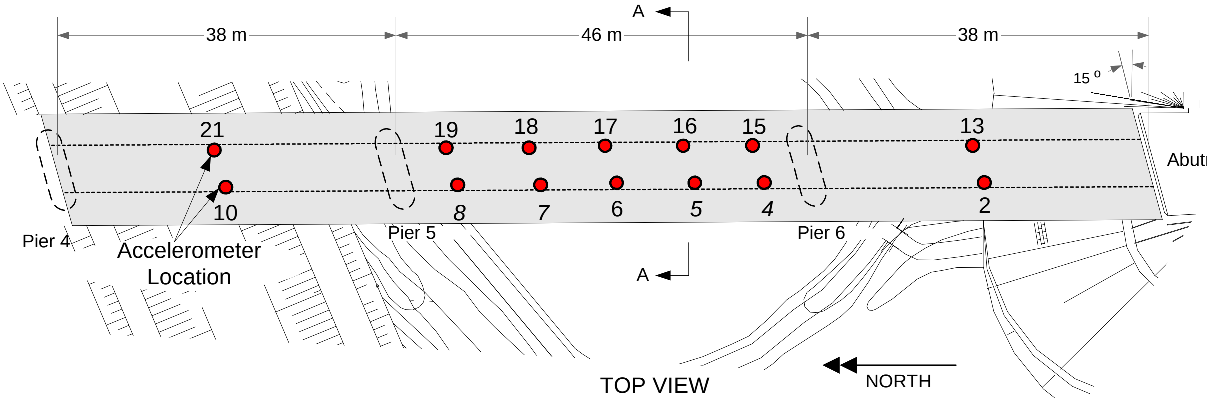


Figure 5 – Location of accelerometers along the Geumdang Bridge span during July 2005 vibration study

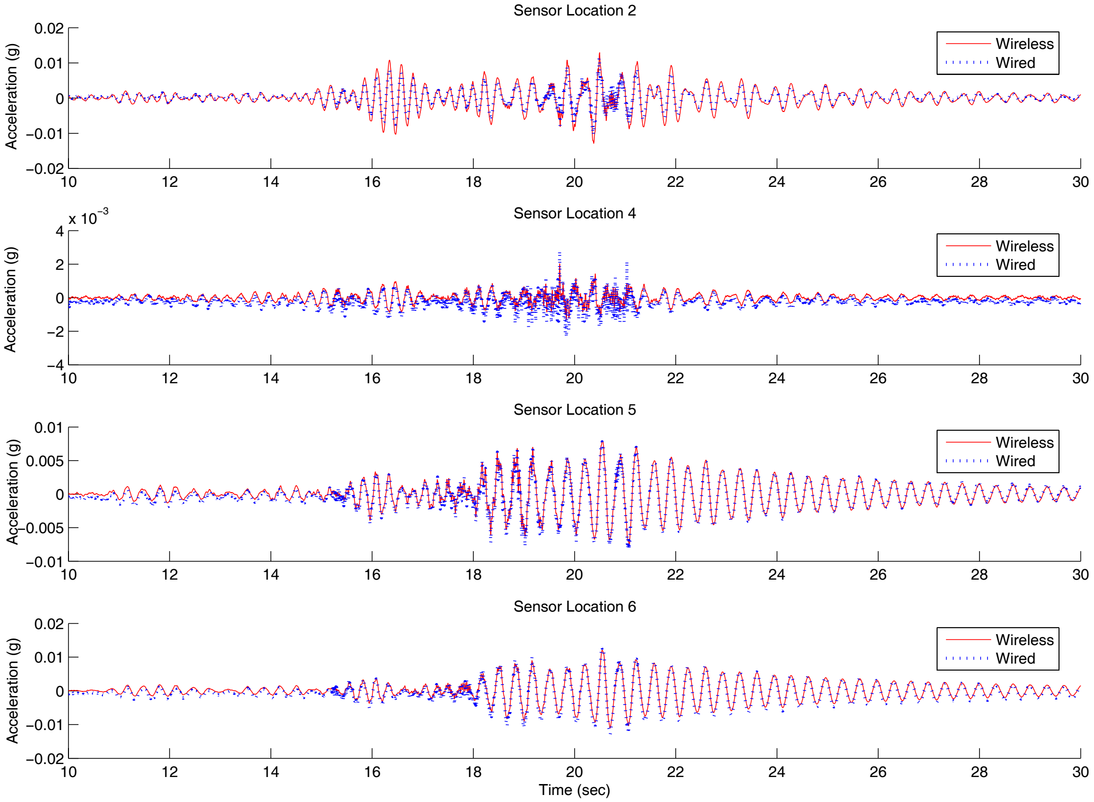


Figure 6 – Complete Guemdang Bridge vertical acceleration response to 40 ton truck loading with signal conditioning circuit installed to improve wireless sensor resolution

presents a five second segment (17 to 22 sec) of the complete time-history shown in Figure 6; as can be seen, the two response records align perfectly. The wireless monitoring system acceleration response appears to have less high-frequency content than the response recorded by the wired monitoring system, an artifact of the Bessel filter.

The recorded time-history records can be converted from the time-domain to the frequency-domain through the use of a fast Fourier transform (FFT). The wireless sensor prototype has the Cooley-Tukey implementation of the FFT encoded in its computational core [2]. Upon command by the central data server, each wireless sensor is capable of calculating a 4096-point FFT of a recorded response time-history. In this study, the complex-valued Fourier spectrum is calculated by each wireless sensor and wirelessly transmitted to the central data server. Figure 8 presents the Fourier amplitude spectra for sensor location #5 and 6 as

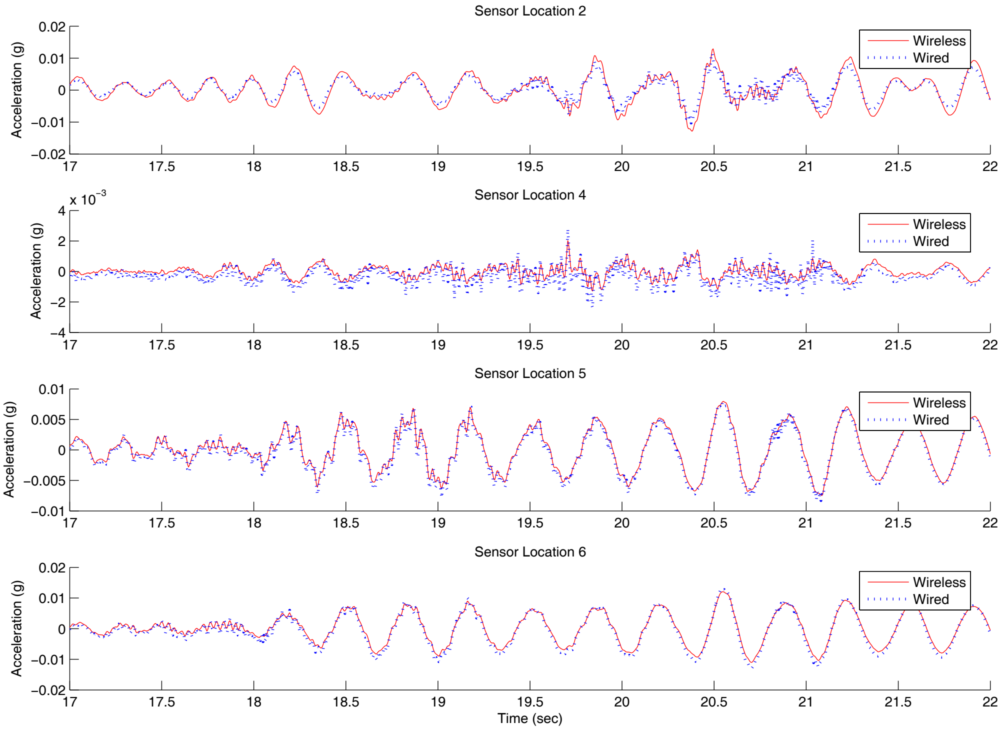


Figure 7 – Five second segment of the Guemdang Bridge vertical acceleration response to 40 ton truck crossing bridge at 80 km/hr

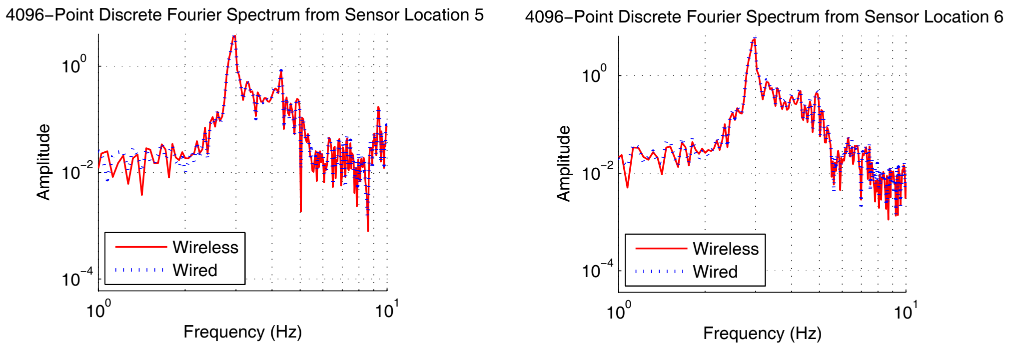


Figure 8 – Fourier amplitude spectra calculated by wireless sensors at sensor location 5 and 6 (Fourier amplitude spectra calculated off-line using the wired monitoring system shown for comparison)

calculated by the wireless sensors at those two locations. For comparison, the Fourier amplitude spectra are calculated off-line for the same sensor locations using the acceleration response data collected by the wired data acquisition. As can be seen in Figure 8, the Fourier amplitude spectra are almost identical. In stark contrast to Figure 3b, the noise floor of the wireless sensor (with the signal conditioning circuit interfaced) is identical to that of the wired data acquisition system. The first two modal frequencies of the Geumdang Bridge can be identified in the Fourier amplitude spectrum (2.98 and 4.28 Hz).

CONCLUSIONS

In this study, a wireless sensor prototype is adopted as a building block of a wireless structural monitoring system. Previous installation of the wireless monitoring system upon the Geumdang Bridge revealed the effects of a reduced ADC resolution. The 16-bit ADC, when placed upon a two-layer printed circuit board, experiences a reduction in its true resolution. To overcome this limitation, a signal conditioning circuit is proposed to amplify and band-pass the voltage output of structural sensors. For sensors whose intrinsic noise floor is below the quantization noise of the ADC, the signal conditioning circuit can amplify the sensor output so that the noise floor of the sensor controls the quality of the measured data. The signal conditioning circuit proposed in this paper offers three amplification factors (5, 10 and 20), in addition to a 0.014 to 25 Hz Bessel filter pass band. The wireless monitoring system was again installed upon the Geumdang Bridge to assess the performance of the wireless monitoring system using the signal conditioning circuit. Due to the signal conditioning, the quality of data collected by the wireless monitoring system is on par with that of the wired data acquisition system.

Future work will consider the design of wireless sensors using four-layer printed circuit boards. This will allow the power and ground planes for the analog and digital circuits to be separated. In addition, automated variable amplification is being considered for inclusion in the wireless sensor design as opposed to a separate signal conditioning board. To further validate the performance and reliability of the wireless monitoring system, additional field validation studies are being undertaken. For example, the wireless monitoring system is currently being installed upon the Grove Street Bridge in Ypsilanti, Michigan to monitor the bridge acceleration response to routine traffic loading.

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