Validation case studies of wireless monitoring systems in civil structures

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ABSTRACT: Growing interest in smart structure technologies has motivated researchers to explore wireless sensor networks for structural monitoring applications. Wireless sensors offer significant cost savings and functionality enhancements compared to traditional cable-based monitoring technologies. First, wireless communication eradicates the need to undertake installation of wires in a structure, thereby saving major costs. Second, embedded computing technologies are integrated with wireless sensors to offer opportunities to locally process measurement data. This paper summarizes two validation case studies where wireless sensors are installed within realistic civil structures. The first case study describes the installation of a wireless monitoring system upon the Geumdang Bridge. The second case study describes the application of wireless sensors to a three-story steel structure excited with base motion. In both case studies, the wireless monitoring system is shown to provide equivalent accuracy compared to baseline cable-based monitoring systems simultaneously installed. Furthermore, the computational power integrated with the wireless sensor prototypes is utilized for real-time data interrogation.

1 INTRODUCTION

Wireless sensor networks tailored for structural monitoring applications have grown in popularity since their initial introduction in the mid-1990s. Wireless sensors have the potential to radically change how future civil structures are managed and maintained. Initial interest in wireless sensors was prompted by the use of wireless communication for data transfer in the monitoring system; by eliminating the extensive lengths of cables often required in traditional tethered monitoring systems, wireless monitoring systems offer lower installation and upkeep costs. However, to successfully integrate digital wireless radios with sensors, some of the functionality traditionally residing in the centralized data server must be migrated to the sensor. In particular, analog-to-digital conversion must be performed at the sensor so that response data is digitized prior to communication on the wireless channel. To assist in this task, embedded microcontrollers are another key element within wireless sensor architectures. The computing power offered by the embedded microcontroller can simultaneously be used for local data interrogation of response data. This computing feature is what sets wireless sensors apart from traditional sensors interfaced to a cable-based monitoring system.

With wireless sensors offering low installation costs and a distributed computing paradigm, many researchers have considered their use within structural monitoring systems. Straser and Kiremidjian (1998) first proposed the design of a low-cost wireless sensor for monitoring the response of civil structures to ambient and seismic excitations. Since their initial study, additional academic prototypes have been proposed by Lynch *et al*. (2001), Lynch (2002), Casciati *et al.* (2003), Shinozuka (2003), and Wang, Lynch and Law (2005). In addition to these efforts, others have explored the application of generic wireless sensor solutions offered by the commercial sector to civil structures. In particular, a wireless sensor platform termed the Mote system which was developed at UC-Berkeley and commercialized by companies such as Crossbow and Intel, has been especially popular. Researchers such as Tanner *et al.* (2002), Ou and Li (2003), Ruiz-Sandoval, Spencer Jr., and Kurata (2003), Spencer (2003) and Glaser (2004) have applied Crossbow MICA Mote wireless sensors to structures dynamically excited in the laboratory. All of these studies illustrate the utility of wireless sensors for structural monitoring.

To quantify the quality and robustness of wireless sensors within realistic structural monitoring systems, installations of wireless sensors in full-scale civil structures are needed. The complex and harsh

Figure 1. Fully assembled wireless sensing unit prototype (battery and external container not shown for clarity).

environment of a structure in the field can provide a true measure of a wireless monitoring system's performance. In this study, a wireless monitoring system assembled from wireless sensing units initially proposed by Wang, Lynch and Law (2005) are installed within two full-scale civil structures. The first test structure is the Geumdang Bridge located in Icheon, Korea. This structure is a pre-cast concrete box girder bridge whose total span length is 122 m. The second structure is a three-story steel frame structure whose base is mounted to a large shaking table. White noise and seismic base motions are applied to the steel structure. A common feature of both case studies is the large number of sensing channels employed. For example, the wireless monitoring system installed in the Geumdang Bridge has 14 sensing channels. In a similar fashion, 20 sensing channels are employed in the base-excited steel frame structure. In both validation studies, the data quality of the wireless monitoring system's response data is compared to that of a cable-based monitoring system installed in parallel. Furthermore, the studies provide an opportunity to showcase the local data processing capabilities of the wireless sensing units.

2 PROTOTYPE WIRELESS MONITORING SYSTEM

In this study, a wireless structural monitoring system is designed and constructed primarily using commercial off-the-shelf (COTS) embedded system components. The fundamental component of the wireless monitoring system is the wireless sensing unit. The wireless sensing unit is not a sensor *per se*; rather, it is an autonomous data acquisition node to which a variety of sensing transducers (*e.g.* accelerometers, strain gages, linear displacement transducers) can be attached. The wireless sensor is responsible for analog-to-digital conversion, data aggregation, data processing and wireless communication of raw and processed sensor data. In addition to the wireless sensing unit, this study includes the design of two analog signal conditioning circuits that will permit the interface of sensors with low-output signals (*e.g.* low-noise capacitive accelerometers) and metal foil strain gages.

2.1 *Wireless sensing units for structural monitoring*

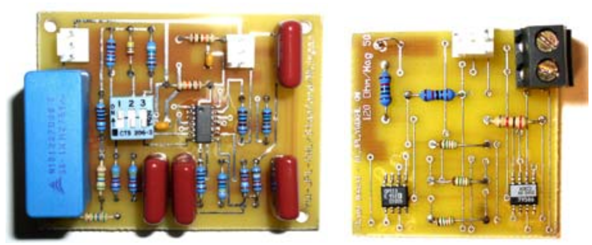
The wireless sensor prototype, designed by Wang, Lynch and Law (2005), is adopted as the fundamental building block of the wireless monitoring systems deployed in the two validation structures. The wireless sensing unit is designed explicitly for monitoring civil structures. The primary function of the wireless sensing unit is to collect data from interfaced sensors. To execute this task, a 4-channel analog-to-digital converter (ADC) is included in the design of the prototype. The Texas Instruments ADS8341 ADC has a resolution of 16-bits and is capable of sampling as high as 100 kHZ. The ADC is controlled by the wireless sensing unit's 8-bit Atmel ATmega128 microcontroller. This microcontroller is selected because it offers convenient peripherals (*e.g.* timers, input/output ports, serial interfaces). With 128 kB read only memory (ROM), the ATmega128 can have many different algorithms embedded for execution. The microcontroller has an insufficient amount of random access memory (RAM) for sensor data storage. In response to this limitation, 128 kB of off-chip RAM is included in the design of the wireless sensing unit computational core. After sensor data has been obtained by the microcontroller, the data is readied for transmission on the wireless channel. The Maxstream 9XCite wireless transceiver is integrated with the wireless sensing unit architecture. This 900 MHz radio can communicate up to 300 m line-of-sight with an over-the-air data rate of 38.4 Kbps. An additional benefit of this radio is that it employs frequency hopping spread spectrum encoding, resulting in a highly reliable wireless communication channel.

The fully assembled wireless sensing unit prototype is shown in Fig. 1. The unit is powered by a 7.5 V battery supply assembled from 5 AA lithium batteries. A hardened external container is used to protect the wireless sensing unit from potentially harsh field conditions. The assembled unit is compact in size with a volume of 130 cm^3.

After the wireless sensing unit prototypes are fully assembled, they are programmed with a multitasking operating system as described by Wang, Lynch and Law (2005). In addition to the embedded operating system, engineering algorithms are programmed and stored in the wireless sensing units. Algorithms including a fast Fourier transform (FFT) and autoregressive (AR) model fitting, are implemented for execution during field testing.

2.2 *Interface circuit for low-output sensors*

The majority of structural sensors envisioned for use with the wireless sensing unit modulate their sensor reading upon a voltage signal. The wireless sensing unit ADC is capable of reading voltage signals that span from 0 to 5 V. Some sensors output positive and negative voltage signals with a zero mean; the



(a) (b)

Figure 2. (a) Signal condition circuit for mean-shifting, amplifying and anti-aliasing sensor output signals; (b) signal conditioning circuit for metal foil strain gages interfaced to the wireless sensing unit.

current ADC would not be able to read the negative output of these sensors. Another limitation of the ADC is its conversion resolution. The 16-bit resolution can only discriminate voltage signals above 7.63 x 10^{-5} V. For ambient structural monitoring, accelerometers used to measure the low-level acceleration response of the structure would output very small changes in the output voltage. As a result, this small variation in output voltage requires a higher ADC conversion resolution. Alternatively, the sensor output can be amplified so that the 16-bit ADC resolution offers sufficient measurement fidelity.

To render the sensing interface of the wireless sensing unit more versatile to a broader class of sensors, a special signal condition circuit is designed and constructed. The circuit has three primary tasks: 1) to move all sensor outputs to have an output mean of 2.5 V, 2) amplification of the sensor output, and 3) anti-alias filtering. The circuit is designed using discrete analog circuit elements and ordinary operational amplifiers. Adopting a three-way switch, three amplification factors are provided to the user: 5, 10 and 20. Furthermore, a 50 Hz anti-alias filter is included in the circuit design. A picture of the signal conditioning circuit is shown in Fig. 2a.

2.3 *Interface circuit for metal foil strain gages*

Metal foil strain gages do not directly output a voltage signal that can be read by the wireless sensing unit. The primary readout mechanism of a strain gage is a change in foil resistance that varies in proportion to strain. As a result, metal foil strain gages are often installed within a Wheatstone bridge circuit so that changes in the strain gage resistance are converted to a change in bridge voltage. Unfortunately, Wheatstone bridge voltage changes can be small for strain gages; therefore, most strain gage Wheatstone bridge circuits adopt an instrumentation amplifier to amplify the voltage change to a reasonable level.

To interface a metal foil strain gage to the proposed wireless sensing unit, a Wheatstone bridge-amplification circuit is designed. Lynch (2002) has previously proposed the design of a strain gage interface circuit for wireless sensors. The circuit designed in this study is nearly identical to this original bridge circuit except for one change. The strain circuit initially proposed employed a dual-supply instrumentation amplifier (Analog Devices AD620) that necessitated the use of two 9V alkaline batteries for power. In this study, this instrumentation amplifier is replaced with a single-supply instrumentation amplifier (Analog Devices AD623) that can be powered directly from the wireless sensing unit. Anticipating the use of metal foil strain gages with a nominal resistance of 120 Ω, the strain gage circuit proposed in this study is designed with 120 Ω 1% resistors on three sides of the bridge circuit. The bridge voltage is amplified by a factor of 50 in the circuit design. A picture of the final strain gage interface circuit is shown in Fig. 2b.

3 GEUMDANG BRIDGE STUDY

The first structure in which the proposed wireless monitoring system is installed is the Geumdang Bridge (Lynch *et al.* 2005). Located in Icheon, Korea, the Geumdang Bridge spans 273 m and carries two south-bound lanes of Jungbu Inland Highway traffic (including commercial truck traffic). Recently constructed in 2002, the bridge is designed using two different types of structural systems. The northernmost portion of the bridge (151 m) is constructed from 4 precast concrete I-beam sections supporting a 27 cm concrete bridge deck. The southernmost span (122 m) is constructed as a continuous pre-cast concrete box girder system supported by one abutment and three concrete piers. In this study, only the concrete box girder span is instrumented with wireless sensors. Fig. 3 summarizes the dimensions of the concrete box girder.

A wireless monitoring system, assembled from wireless sensing unit prototypes, is installed within the interior spaces of the concrete box girder span. In total, 14 wireless sensing units are installed along the length of the span. Attached to each wireless sensing unit is one capacitive low-noise accelerometer that is intended to record the vertical acceleration of the bridge. The accelerometer selected in this study is the PCB Piezotronics 3801 accelerometer because of its low 0.5 mg noise floor. The performance specifications of the PCB3801 include a sensitivity of 0.7 V/g, linear range of ± 3 g, and an 80 Hz bandwidth. During installation, the accelerometers are fixed to mounting plates that have been aligned orthogonal to gravity.

Forced vibration testing of the Geumdang Bridge is done on two separate occasions: December 2004 and July 2005. A separate sensor configuration is adopted on both occasion; as shown in Fig. 3c and d, configurations #1 and #2 are adopted for the December 2004 and July 2005 testing periods, respectively. The wireless sensors are configured to establish communication with a laptop computer serving the role of data repository. The laptop, lo-

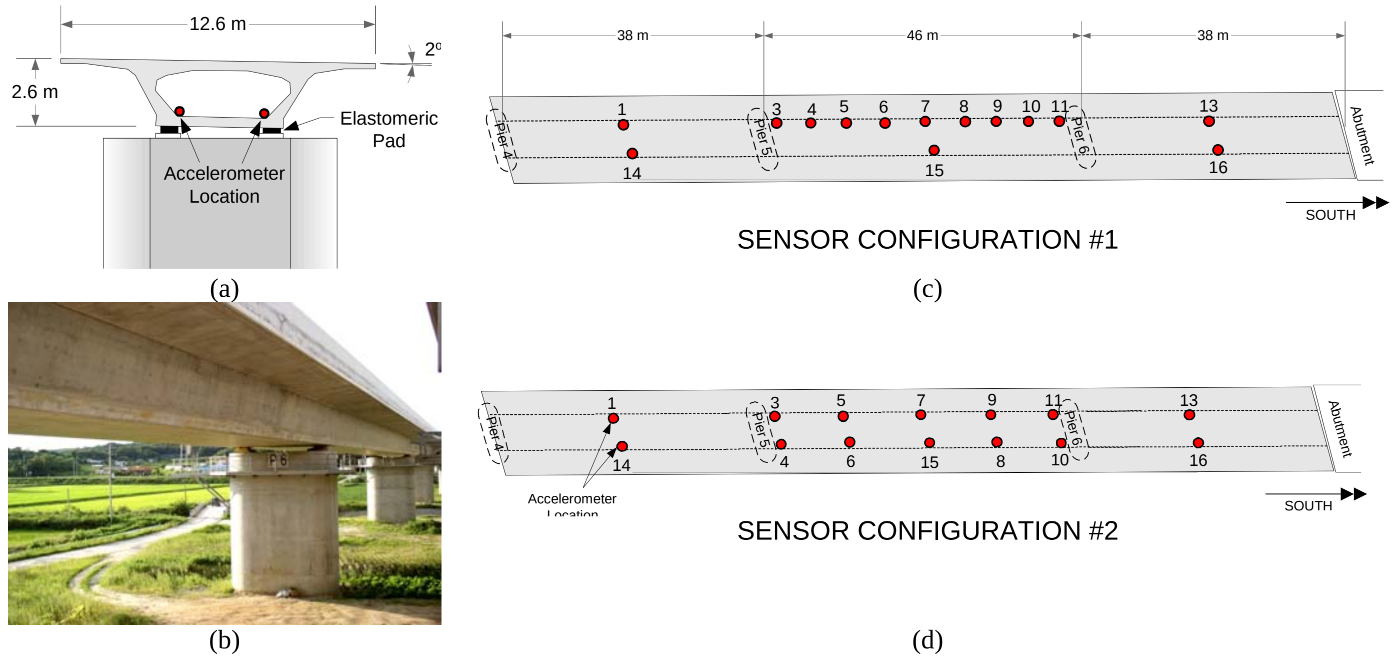


Figure 3. Geumdang Bridge concrete box girder span: a) structural section, b) side view picture, c) sensor configuration #1, and d) sensor configuration #2.

cated in the vicinity of sensor location #7 (on both occasions), has a Maxstream 9XCite transceiver attached.

The Geumdang Bridge is instrumented with a traditional cable-based monitoring system in addition to the wireless monitoring system. The purpose of installing the cable-based monitoring system is to provide a baseline to which the performance of the wireless monitoring system can be compared. Interfaced to the cable-based monitoring system are PCB Piezotronics 393 accelerometers. As piezoelectric-type accelerometers, the PCB393 is well suited for structural monitoring applications. The accelerometer has a low-noise floor (0.05 mg) in addition to a high sensitivity (10 V/g). The linear range of the PCB393 is $\pm$ 0.5 g and has a bandwidth of 2 kHz. The accelerometer is attached to a centralized data acquisition unit consisting of a 16-channel PCB Piezotronics 481A03 signal analyzer. The role of this signal analyzer is to amplify the sensor output by a factor of 10 before passing the sensor signal to a National Instrument 12-bit data acquisition system.

To excite the structure, three trucks with calibrated weights are selected. The trucks are loaded until their total weights are 15, 30 and 40 tons. The bridge is kept closed to normal traffic during testing to ensure the trucks can cross the bridge without interruption. The trucks are commanded to travel across the bridge at fixed speeds ranging from 40 to 80 km/hr. During forced vibration testing, the wireless and cable-based monitoring systems are commanded to record the vertical bridge response. In addition to the collection of response data, the wireless sensing units are also commanded during testing to calculate the Fourier spectra of the measured acceleration response records.

During the field tests conducted in December 2004, the acceleration response of the bridge is recorded using sensor configuration #1. Sensor location #7 is located at the center of the span and will experience the maximum vertical acceleration during truck loading. When a 40 ton truck crosses the bridge at 60 km/hr, the response of the bridge is recorded by the wireless and cable-based monitoring systems. As shown in Fig. 4, the maximum acceleration witnessed at sensor location #7 is approximately 20 mg. During field testing in December 2004, the response of the bridge is recorded without using the amplifying signal condition circuit. As can be seen in Fig. 4, the wireless sensing unit is capable of accurately measuring the response of the bridge when the truck dynamically loads the bridge. For comparison, the same bridge response recorded by the cable-based monitoring system is presented in Fig. 4. When comparing the two identical time-history responses, it is clear that noise inherent in the ADC conversion process slightly degrades the time-history measurement record collected by the wireless system.

During field testing in July 2005, the same tests are carried out except that the wireless sensing units are installed using the amplification signal conditioning circuits with the accelerometers. Provided the low acceleration response (20 mg), the amplification factor is selected as 20. When repeating the bridge test with the same weight truck (40 ton) crossing the bridge at 60 km/hr, we see a dramatic improvement in the time-history response recorded by the wireless sensing unit. The acceleration response of the bridge is free of high-frequency noise (present in the previous time-history records) with the loading and free-vibration response phases well defined and free of measurement noise.

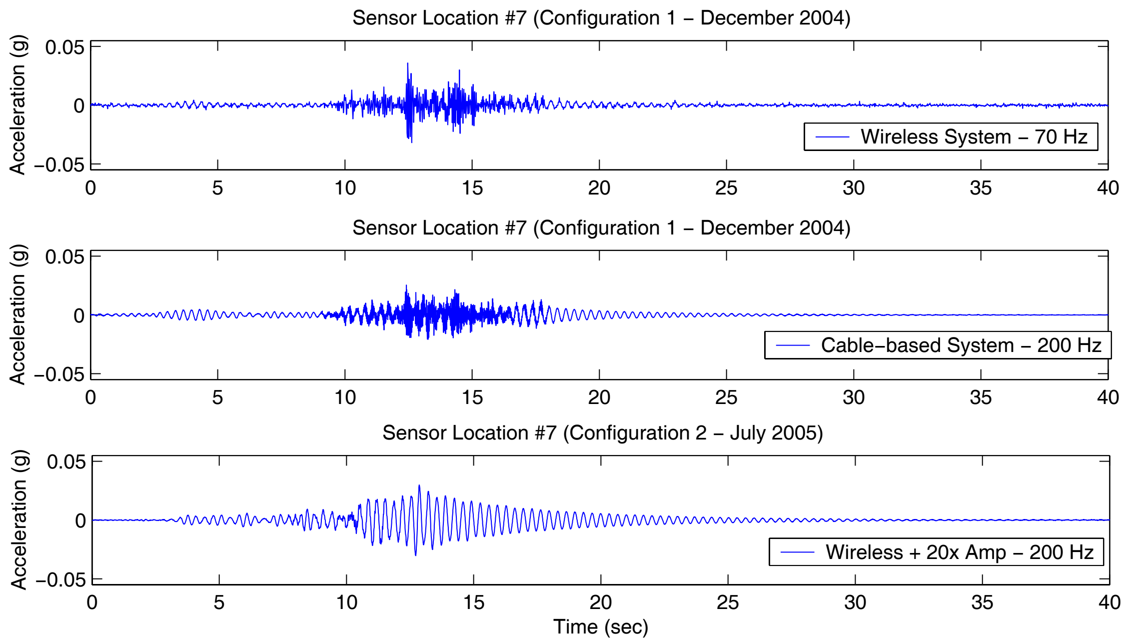


Figure 4. Measured vertical bridge acceleration response to a 40 ton truck crossing at 60 km/hr; acceleration response measured at sensor location #7.

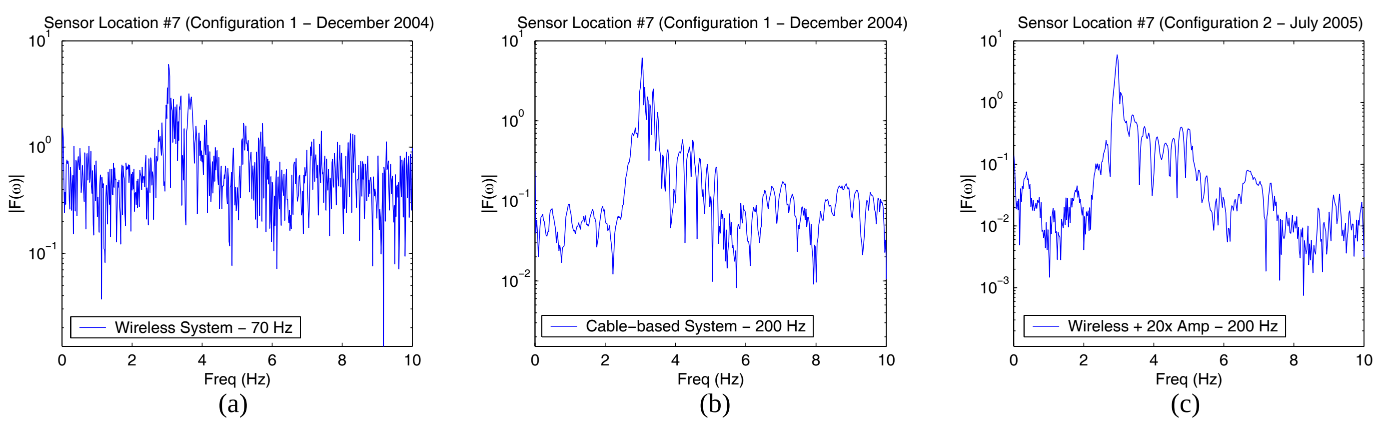


Figure 5. Fourier spectra corresponding to the acceleration response time-histories recorded at sensor location #7 during a 40 ton truck crossing at 60 km/hr. Wireless sensors calculate the complex Fourier spectra before communicating with the server.

To identify the primary modal frequencies of the instrumented bridge span, the acceleration response time histories are transformed to the frequency domain using an FFT algorithm. For the time-history data recorded by the wireless monitoring system, the Fourier spectra of the acceleration response is calculated using the FFT algorithm embedded in each wireless sensing unit. The Fourier spectra corresponding to the acceleration response measured by the cable-based monitoring system is calculated at the centralized data repository server. The absolute value of the Fourier spectra of the time-history records presented in Fig. 4 are shown in Fig. 5. The noise present in the wireless sensing unit when no amplification circuitry is utilized, is clearly shown in Fig. 5a. While the noise in the data acquisition process is evident at the low Fourier amplitudes, the primary modal frequency of the bridge is evident (~3 Hz). In contrast, when the amplification circuit is adopted, the absolute Fourier amplitude is greatly improved as shown in Fig. 5c. When comparing the absolute Fourier amplitude calculated by the wireless sensing unit when amplification is adopted and the absolute Fourier amplitude calculated by the cable-based monitoring system (Fig. 5b), they are nearly identical, as expected.

The response data collected at other sensor locations exhibit identical properties to the data presented for sensor location #7. However, for sensor locations situated in close proximity to the bridge piers (*i.e.* sensor locations #3 and #11), the bridge experiences low amplitude acceleration which become dominated by the noise floor of the PCB3801 accelerometer. In contrast, during field testing in July 2005, the amplification signal conditioning circuit reduces the noise floor of the accelerometer so that response measurements collected by the wireless sensors at these locations are of high fidelity.

4 BASE EXCITED STEEL STRUCTURE

In order to showcase the performance of the wireless monitoring system within a typical steel building, a three-story steel frame structure mounted to a large

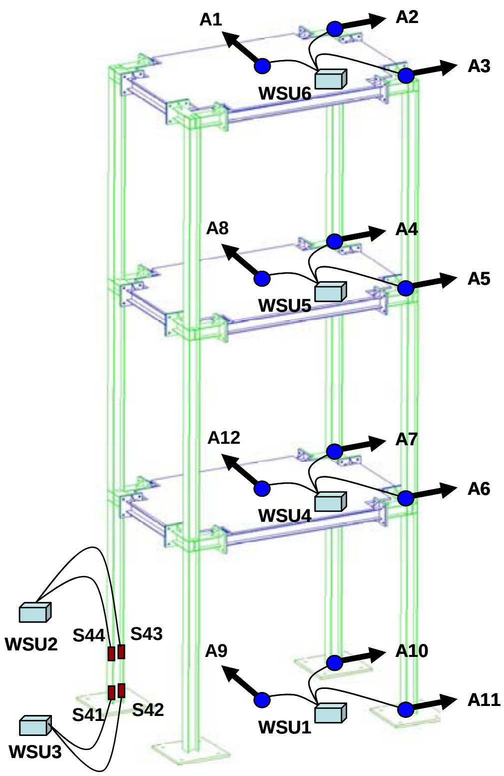


Figure 6. Three-story steel benchmark structure instrumented with 6 wireless sensing unit prototypes.

shaking table is instrumented. Located at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan, the single-bay frame structure is constructed using steel I-beam sections. H150x150x7x10 steel sections are selected for the four columns as well as for the beams used to support each floor. The floor area dimension of the structure is 3 m by 2 m with each story having a height of 3m. To simulate dead load mass, 6 tons are added to each story. When fully constructed, the three-story test structure is mounted to a 6 degree-of-freedom shaking table whose table-top area is 5 m by 5m. The shaking table is used to apply bi-directional base excitations including ambient white noise and seismic excitations (El Centro (1940) and Chi-Chi (1999) seismic ground records).

As presented in Fig. 6, the three-story benchmark structure is instrumented with a wireless monitoring system consisting of 6 wireless sensing unit prototypes. The prototypes described in Section 2.1 integrate Maxstram 9XCite wireless modems communicating on the 900 MHz carrier frequency; in Taiwan, this frequency is unavailable for public use. To address this issue, an alternative radio operating on the publicly available 2.4 GHz frequency spectrum is adopted. The Maxstream XStream radio is selected and integrated into the design of the wireless sensing unit prototype prior to testing.

The instrumentation strategy of the wireless monitoring system is governed by an interest in both the acceleration response of the structure as well as the strain behavior of one of the structure's base columns. For each floor of the structure, including the structural base, one wireless sensing unit is used to record the acceleration response in two directions. For example, wireless sensing unit WSU6 is used to record the acceleration of the structure at locations A1, A2 and A3. This configuration of accelerometers is intended to capture both the longitudinal and lateral response of each floor, as well as any torsion behavior. The accelerometer selected for integration with the wireless sensing units are the Crossbow microelectromechanical systems (MEMS) CXL01 and CXL02 accelerometers. The CXL01 and CXL02 have linear ranges of $\pm$ 1g and $\pm$ 2g, respectively. In addition to accelerometers, 4 metal foil strain gages are mounted to the outer flange surface of one of the columns. The four strain gages, with nominal resistances of 120 Ω and gage factor of 2, are mounted at the base of the structure to capture the column flexural response during base excitation. To record the strain response, the strain gage interface circuit is used to convert the change in gage resistance into an amplified voltage signal. Two wireless sensing units (WSU2 and WSU3) are dedicated to recording the strain response with two gages interface to each wireless sensing unit.

A traditional laboratory-based data acquisition system is used to record the response of the structure at the same locations identified in Fig. 6. The laboratory data acquisition system used in this study has a resolution of 16-bits. To measure the acceleration response of the test structure, Setra 141 capacitive accelerometers are installed alongside the Crossbow accelerometers that have been interfaced to the wireless monitoring system. In addition, 120 Ω metal foil strain gages are mounted adjacent to the strain gages interfaced to the wireless monitoring system; these strain gages are then interfaced to the cable-based data acquisition system.

During the first set of tests, a 90 sec white noise excitation is applied at the structure base using the shaking table. In the X- (oriented parallel to accelerometer A2) and Y-directions (oriented parallel to accelerometer A1), the standard deviation velocity of the white noise record is 1 and 0.5 m/sec respectively. As can be seen in Fig. 7, the time history response measured by the wireless monitoring system at 100 Hz is identical to that measured independently by the cable-based monitoring system (also at 100 Hz). Fig. 7 presents the acceleration response of the structure at sensor location A1 and A2. In addition, the figure also presents the measured strain of the structure at strain gage location S44 which is roughly 0.5 m above the column-table connection. The results obtained at strain gage S44 by the wireless monitoring system underscores the precision offered by the strain gage interface circuit described in Section 2.3.

In addition to recording the time history response of the test structure, an additional test objective is to execute an AR model fitting algorithm stored in the wireless sensing units. During a white noise excita-

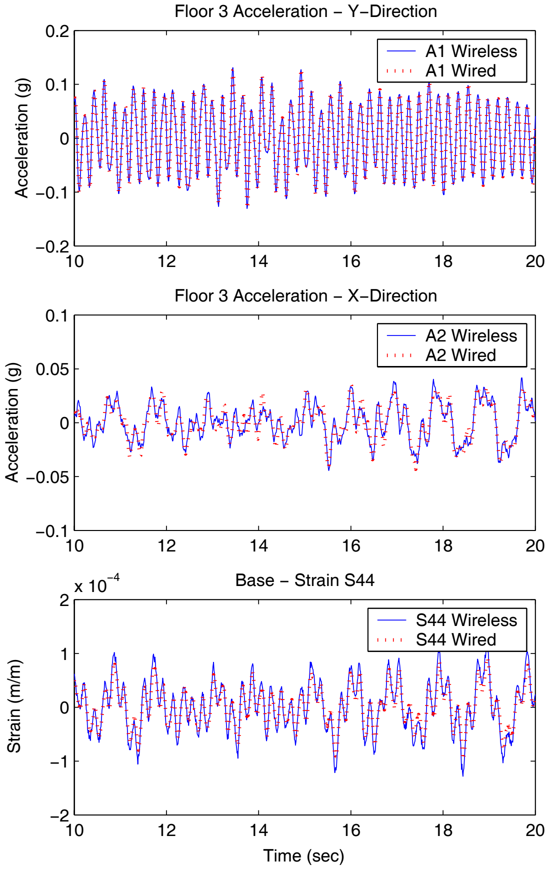


Figure 7. Steel structure time-history response including third story acceleration and column base strain.

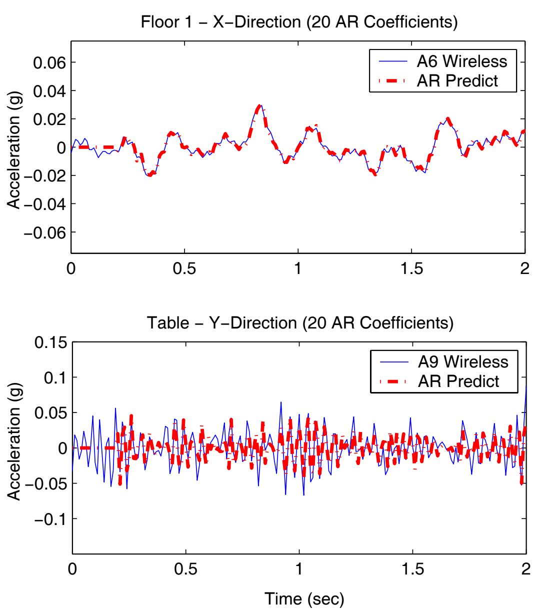


Figure 8. AR predicted response of the steel structure excited by white noise base excitation.

tion test, the wireless sensing units are commanded to determine the optimal AR model fit to acceleration and strain response data. Once the AR model is calculated, the wireless sensing units wirelessly transmit the original time history records and the AR model coefficients. The number of coefficients determined is specified by the system end user.

As presented in Fig. 8, the acceleration response of the test structure to the white noise base excitation described above is presented for sensor locations A6 and A9 (located on the first floor and table, respectively). In addition to recording these accelerations, the wireless sensing units are commanded to determine an AR model with 20 coefficients. At the central data repository where the raw time-history record and AR coefficients are received, the response of the structure and table predicted by the AR model are calculated. As shown in Fig. 8, if the predicted response is superimposed over the true response, we see that the AR models calculated by the wireless sensing units accurately predict the response of the structure. It should be noted that the first prediction offered by the AR model occurs at the 21st time sample; hence, the prediction shows a zero output for the first 20 samples.

5 CONCLUSIONS

The stated objective of this study was to validate the performance of a prototype wireless sensing unit in realistic civil structures. Towards that end, the Geumdang Bridge and a three-story steel structure were selected as benchmark structures. In addition to assessing the performance of the wireless sensing unit design, signal conditioning circuits for low-output sensors and strain gages were tested during field testing. The amplification signal conditioning circuit was shown to greatly enhance the measured acceleration response of the Geumdang Bridge. During base excitation of the steel frame structure, the strain gage interface circuit was shown to accurately measure the strain response of the column. The final objective of the two field studies was to illustrate the computing capabilities of the wireless sensing units. During testing on the Geumdang Bridge, the computational resources were utilized to determine the Fourier spectra of the bridge response. In a similar approach, AR time-series models were successfully fit to response data of the three-story steel structure excited by ambient bi-directional base motion.

Future work will be aimed at installing wireless monitoring systems in additional civil structures. In particular, installations defined by larger nodal densities will be considered. In this study, the wireless monitoring system is kept in the structure for a few days; future field deployments will focus on longer-term installations.

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