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Field validation of a wireless structural monitoring system on the Alamosa Canyon Bridge

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ABSTRACT

A state-of-art design of a wireless sensing unit, which serves as the fundamental building block of wireless modular monitoring systems (WiMMS), has been optimized for structural sensing applications. Employing wireless communications as a primary means of data transfer, the high-cost but fragile cables of traditional tethered monitoring systems is eradicated resulting in a low-cost and flexible monitoring infrastructure. An additional innovation is the inclusion of advanced embedded microcontrollers to accommodate the computational tasks of engineering and decision support analysis. To quantify the performance of the wireless sensing unit, field validation upon a full-scale benchmark structure is undertaken. The Alamosa Canyon Bridge in New Mexico is instrumented with wireless sensing units and a traditional cable-based monitoring system in parallel. Forced vibrations are applied to the bridge and monitored using both (wireless and tethered) data acquisition systems. Recorded time-history measurements are used to identify the modal properties of the structural system. The performance of the wireless sensing units is compared to that of the commercial wire-based monitoring system.

Keywords: Wireless sensors, structural monitoring, sensing networks, system identification.

1. INTRODUCTION

Monitoring systems designed for recording the response of structures to ambient and forced (wind, seismic, etc.) vibrations could play an important role in improving our fundamental knowledge of structural systems and their response to external disturbances. A need for low-cost monitoring systems is underscored by the vast number of highway bridges in the United States that can benefit from continuous performance monitoring. The Federal Highway Administration ensures the safety of the nation's 583,000 highway bridges by mandating regular visual inspections [1]. Damage can be difficult to visually detect unless it is severe with structural corrosion and fatigue often showing no visible indicators. Monitoring systems can augment the visual inspection process and provide quantitative performance measures that would be useful to bridge management officials.

The current cost of commercial monitoring systems has limited their widespread use, with only critical structures (suspension bridges, dams, hospitals, etc.) located in zones of seismic activity instrumented. As an example, consider the Tsing Ma Suspension Bridge constructed in 1997 in Hong Kong; a 600 channel structural monitoring system was installed at a cost of over $16 million [2]. In Europe, fiber optic monitoring systems used in concrete bridges can cost between $20 thousand to $100 thousand for bridges with spans of 650 feet or more [3]. The high cost of current structural monitoring systems results from labor intensive installation of system cables. Up to 25% of the total system cost and 75% of the installation time can be attributed solely to installation of systems cables [4].

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The advancement of technologies in related engineering fields, such as advanced integrated circuits, solid-state sensors, and wireless communications, can have an immediate impact in modernizing structural monitoring systems. The use of wireless communications in a structural monitoring system was first proposed by Straser and Kiremidjian in order to eradicate the need for extensive cabling [4]. Lynch *et al*. has extended this work to include powerful microcontrollers with wireless sensors to facilitate the interrogation of structural response measurements prior to communication on the wireless network [5]. The result of these research efforts have resulted in the design of a low cost wireless sensing unit whose hardware design has been optimized for structural monitoring. The wireless sensing unit is a fundamental building block of spatially distributed wireless sensing networks termed wireless modular monitoring systems (WiMMS). The inherent flexibility of WiMMS architectures render them suitable as an underlying infrastructure for future structural health monitoring systems that will identify and quantify damage in civil structures. The computational core of the wireless sensing units would be capable of executing embedded damage detection methods [6].

The performance of a prototype wireless sensing unit design has previously been validated in the laboratory with initial design goals attained [5]. The purpose of this study is to further validate the unit performance in the field using a full-scale highway bridge. The Alamosa Canyon Bridge, located in southern New Mexico, is chosen as a test structure because it is easily accessible to the authors and past studies have thoroughly documented the model properties of the bridge [7, 8, 9]. Two methods of bridge excitation are considered in this study: a modal hammer is used to deliver impulsive loads and a truck is driven over the bridge deck. A monitoring system comprised of wireless sensing units is installed in parallel with a cable-based commercial monitoring system. The commercial system will provide a baseline for judging the performance of the wireless sensing units. An additional focus of the study is to interface microelectromechanical system (MEMS) accelerometers with the wireless sensing units. MEMS accelerometers represent an accurate and inexpensive alternative to traditional force balance and piezoelectric accelerometers.

2. WIRELESS SENSING UNIT DESIGN FOR STRUCTURAL MONITORING

The combination of advanced microcontrollers, analog-to-digital converters and wireless radios for the creation of wireless sensors has been explored by both academia and industry. These development efforts have resulted in some commercial vendors offering wireless sensing platforms with diverse performance specifications. However, the unique demands of the structural engineering community such as the need for low-power consumption and long communication ranges warrants the design of a wireless sensing platform optimized for structural monitoring. A prototype wireless sensing unit is designed and fabricated for structural monitoring. A modular design with off-the-shelf components is chosen to keep fabrication efforts reasonable and total unit costs low. The architectural design of the wireless sensing unit, as shown in Fig. 1, is divided into three major subsystems: multi-channel sensor interface, computational core and wireless communications.

The first subsystem, the sensor interface, represents the unit's ability to collect measurements from a variety of sensing transducers that could provide measurement of structural responses and environmental loads. To accommodate multiple

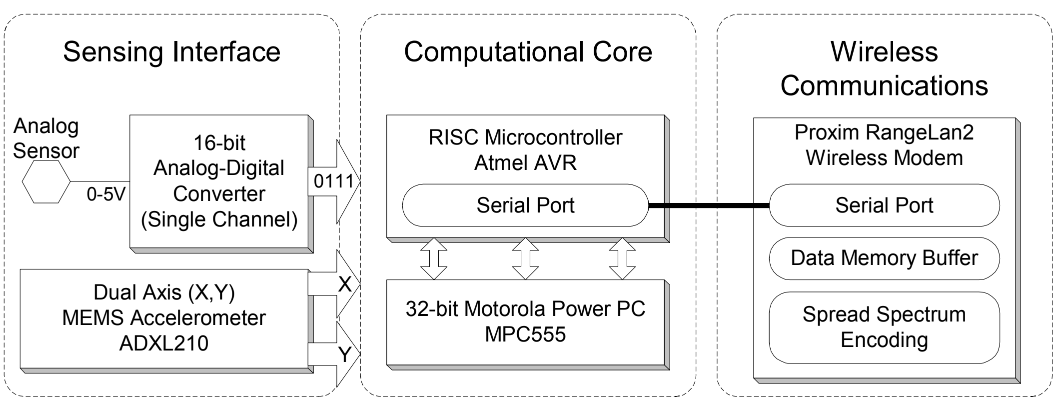

Figure 1: Architectural design of the proposed wireless sensing unit

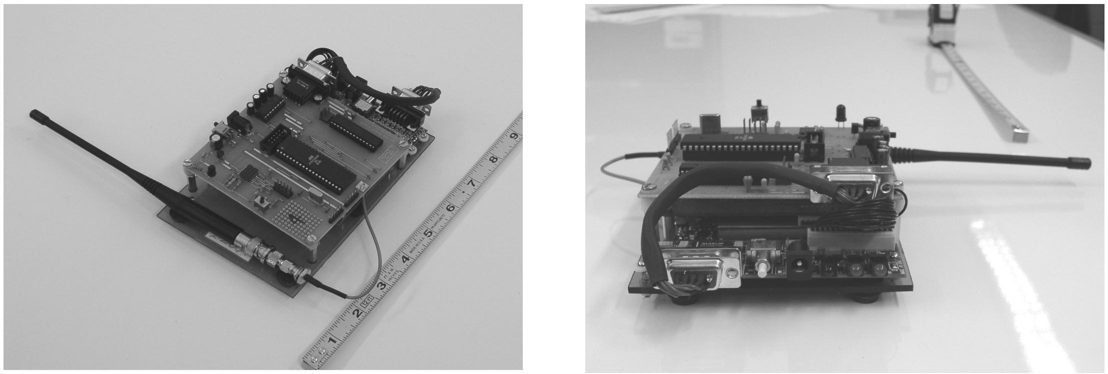

Figure 2: Prototype wireless sensing unit

sensors simultaneously, a multi-channel interface is designed. At the core of the sensing interface subsystem is a single-channel analog-to-digital (A/D) converter that can resolve the output of an analog sensor to a 16-bit digital representation. Most sensors used for structural monitoring including accelerometers, strain gages and anemometers employ analog voltages and can therefore be interfaced. Sampling rates as high as 100 kHz can be attained using the Texas Instruments ADS7821 16-bit A/D converter. Two additional sensing channels are provided that accept duty cycle modulated outputs from a wide class of digital sensors. Many commercial MEMS-based accelerometers provide duty cycle modulated outputs with resolutions of 14-bits [10].

The computational core is responsible for the overall operation of the wireless sensing unit. To collect data, the core will initialize the sensing interface and receive a stream of measurement data from the interface for storage in memory. Upon completion of acquiring raw time history data, the computational core can perform data interrogation tasks or transfer measurement data to the wireless sensor network using the wireless communication channel. In designing the sensing unit core, a balance between computational capabilities and low-power consumption is sought. To achieve a suitable balance, a two processor core design is created; a low power 8-bit microcontroller is chosen for simple unit operation and a powerful 32-bit microcontroller is added to carry out intensive data interrogation tasks. The 8-bit Atmel AT90S8515 AVR microcontroller is selected for its capability-rich hardware design, low cost and efficient power characteristics. For the execution of computationally demanding data interrogation algorithms, the 32-bit Motorola MPC555 PowerPC microcontroller is selected. With 448 Kbytes of flash ROM and 26 Kbytes of RAM, sufficient on-board memory is provided to serve as storage of measurement data. Special data registers are provided by the MPC555 to perform rapid floating-point calculations in hardware. The MPC555 microcontroller is kept off to conserve power and is turned on by the 8-bit microcontroller only when intensive computational tasks are required. After completion of those tasks, the MPC555 is turned off and no longer consumes power.

The Proxim RangeLAN2 radio modem is chosen to serve as a reliable wireless communication technology of the wireless sensing unit. Operating on the 2.4 GHz unregulated FCC industrial, scientific and medical (ISM) band, data rates of 1.6 Mbps can be attained with communication ranges of up to 1000 feet in unobstructed open space. Within structures constructed from heavy construction materials (e.g. concrete), the communication range reduces to about 450 feet [11]. To ensure reliable wireless communication, data packets are modulated using frequency-hopping spread spectrum (FHSS) techniques.

The components chosen for inclusion with the wireless sensing unit design are packaged into a compact module. Integrated circuit chips and peripheral electric circuits are mounted upon a two-layer printed circuit board. Allowing the electrical components to share the same two-layer circuit board preserves space but special care is taken in the board design to prevent the injection of electrical noise typical of a poor circuit board layout [12]. The wireless modem comes packaged on its own printed circuit boards. The serial ports of the Atmel microcontroller and the Proxim wireless modem are used to establish communication between the two. When fully assemble, the completed wireless sensing unit is only 15 cubic inches in volume as shown in Fig. 2. The prototype is powered by a high density lithium-based battery that delivers 9V DC for over 15 continuous hours. More aggressive power sources can be considered that can potentially expand the operational life of the sensing unit to the order of years.

3. OVERVIEW OF THE ALAMOSA CANYON BRIDGE

The Alamosa Canyon Bridge, located in Truth or Consequences, New Mexico, is chosen to validate the performance of the wireless sensing units. The bridge is a suitable benchmark structure because its modal properties are well documented from previous system identification studies [7, 8, 9]. In addition, the two-lane bridge is located in a remote area of New Mexico and is seldom used by traffic. Constructed in 1937, the Alamosa Canyon Bridge is comprised of seven independent spans, each 50 ft. long and 24 ft. wide. A 7 in. concrete deck is supported by six W30x116 steel girders whose centerline separation is 58 in. apart. To provide additional lateral strength to the bridge, single channel braces are installed between adjacent girders at four locations along the length of each span. The deck loads of the interior spans are transferred from the girders to shared concrete piers situated at the girder ends with a standard roller at the girder-concrete pier interface. The two spans at the northern and southern ends of the bridge are supported by a concrete pier on one end and an abutment structure on the other. At the girder-abutment interface, the girder is bolted to a half-roller that acts like an ideal pin support. Fig. 3 illustrates the structural details of an interior span of the Alamosa Canyon Bridge and Fig. 4 presents top and side view pictures of the bridge.

Previous system identification studies have instrumented the northernmost span of the Alamosa Canyon Bridge. The northernmost span is supported by a concrete pier on one end and the bridge abutment at the other. Doebling *et al.* determined the modal properties of the span from forced and ambient vibration measurements [8]. Forced vibrations were induced in the structure using modal hammer blows to the bridge deck. Ambient vibrations of the Alamosa Canyon Bridge originated from heavy truck traffic carried on the I25 highway bridge immediately adjacent. Both sources provided modal frequencies within 3% of each other indicating strong agreement. The first four modal frequencies as

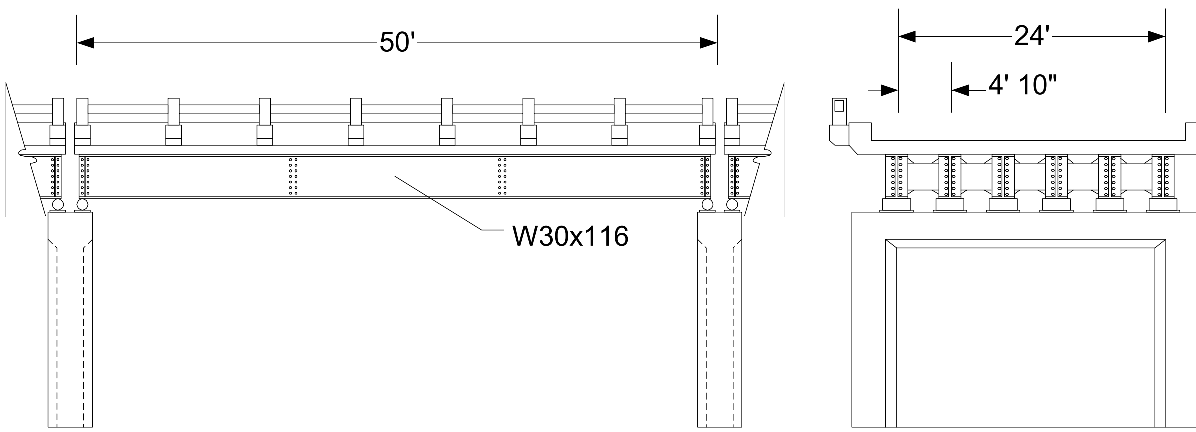

Figure 3: Structural details of an interior span of the Alamosa Canyon Bridge

Figure 4: Views of the Alamosa Canyon Bridge: (left) top roadway looking south and (right) side view

calculated using the eigensystem realization algorithm (ERA) were documented as 7.4, 8.0, 11.5 and 19.6 Hz. Additional studies of the Alamosa Canyon Bridge have explored changes in the modal properties of the bridge that result from the bridge's temperature. Farrer *et al*. has shown a 0.3 Hz rise in the bridge's first modal frequency as a result of a 20º F temperature drop that exists between the bridge's night and midday temperature [7].

4. SETUP OF THE ALAMOSA CANYON BRIDGE FOR MODAL TESTING

Given its easy access, the third northernmost span (an interior span) of the Alamosa Canyon Bridge is chosen for instrumentation. The goal of this study is to demonstrate the feasibility and performance of the prototype wireless sensing units in a full-scale civil structure. To achieve these goals, wireless sensing units are installed upon the span's girders to measure the span response to forced vibrations. A commercial monitoring system is installed in parallel to the wireless system to permit a baseline for performance comparison. The accuracy of the wireless sensing units will be assessed by comparing time-histories, frequency response functions and modal frequencies to those derived using the commercial system. An additional goal of the study is to document the difference in the modal frequencies of an interior span compared to those of the northernmost exterior span of the bridge. Differences in the modal properties result from the use of a fixed pin connection at the abutment support of the exterior span compared to roller supports for the interior spans. The mode shapes of the bridge are not calculated in this study because of the limited number of prototype sensing units available for installation. In addition, the internal clocks of the units have not been setup to synchronize with each other.

The commercially available data acquisition system selected is the Dactron SpectraBook dynamic signal analyzer. The SpectraBook accommodates 8 simultaneous input channels with sampling rates as high as 21 kHz. The internal sensing interface of the Dactron system employs a 24-bit analog-to-digital converter providing a range of 120 dB. Accelerometers mounted upon the structure are interfaced directly to the data acquisition system through one of the channels of the SpectraBook. A Windows-based laptop with RT Pro Signal Analysis software installed is interfaced to the SpectraBook in order to control the system and to easily obtain data. Once data is acquired, modal analysis tools provided by RT Pro can be used for modal identification of the test structure. A wireless modular monitoring system is also installed on the Alamosa Canyon Bridge. Multiple prototype wireless sensing units are installed within the structure with accelerometers directly interfaced. The wireless communication channel of the wireless sensing units is used to transfer data from the sensing units to a centralized data server. A Linux-based laptop running a custom designed data acquisition system is employed for controlling the wireless sensing units and to transfer data from the units to the laptop.

To measure the dynamic response of the bridge to forced vibrations, two different accelerometers were installed with each system. Used exclusively with the cable-based monitoring system is the Piezotronics PCB336C accelerometer. The PCB336 is part of the piezoelectric accelerometer family and is capable of recording vibrations within a 1 to 2000 Hz dynamic range. As the internal transduction mechanism of the accelerometer depends upon piezoelectric materials, measurement of low frequency (frequencies less than 1 Hz) and steady state (DC) accelerations are not possible. The PCB336 accelerometer has a large sensitivity of 1 V/g and a broad amplitude range of $\pm$ 4 g. Combined with the accelerometer noise level of 60 μg, the accelerometer has a broad dynamic range of 97 dB.

Interfaced to the wireless sensing units for bridge vibration measurements are Crossbow CXL01LF1 MEMS accelerometers. MEMS sensors are comprised of mechanical sensing transducers fabricated upon silicon dies adjacent to digital circuits, resulting in accurate sensors with small form factors and low unit costs. For this study, MEMS sensors are considered for integration because they represent relatively inexpensive sensors that complement the low cost nature of the proposed wireless sensing unit. The internal architecture of the CXL01LF1 is comprised of a silicon proof-mass with capacitive plates fabricated along its perimeter. Along the perimeter of the silicon substrate that houses the proof-mass are capacitive plates situated precisely between the differential plates of the proof-mass. As the proof-mass displaces relative to the silicon substrate, the equilibrium of the differential capacitor is disrupted with voltage changing proportionally with acceleration of the sensor [13]. The CXL01LF1 is a high sensitivity MEMS accelerometer with low-noise and high-stability characteristics. The CXL01LF1 sensitivity is 2 V/g and can sense accelerations in a range of $\pm$ 1 g. The 0.5 mg noise floor of the accelerometer combined with its maximum measurable acceleration provides a dynamic range of 67 dB. The accelerometer is capable of measuring vibrations from DC to its bandwidth of

50 Hz. An additional feature of the accelerometer is an internal anti-alias filter. Table 1 summarizes the performance attributes of the two accelerometers selected for installation in the Alamosa Canyon Bridge.

Locations for mounting the accelerometers to the span's steel girders are determined. The locations are distributed throughout the structure to provide good spatial separation for identification of the lower modes of response of the structure. To make identification of the sensor locations easy, the girders of the span are numbered 1 through 6. In total, seven locations are selected with each location denoted by a unique location number such as S1, S2, etc. Except for location S4, all accelerometers are mounted at the midpoint of the girder's web. The accelerometers installed at location S4 are situated 4 in. above the bottom flange surface of the girder. Fig. 5 shows the locations of the seven accelerometers installed including a picture of the accelerometers mounted at sensor location 5. As shown in Fig. 5, the PCB336 accelerometer is installed at the girder midpoint on the left and the CXL01LF1 on the right with wireless sensing units placed upon the girder flange. A 30 feet cable is used to connect the PCB336 to the Dactron SpectraBook that is situated beneath the bridge span.

Table 1: Performance characteristics of accelerometers used for modal testing of the Alamosa Canyon Bridge

Sensor Property	Crossbow CXL01LF1 [14]	Piezotronics PCB336 [15]
Maximum Range	1 g	4 g
Sensitivity	2 V/g	1 V/g
Bandwidth	50 Hz	2000 Hz
RMS Resolution (Noise Floor)	0.5 mg	60 µg
Dynamic Range	67 dB	97 dB

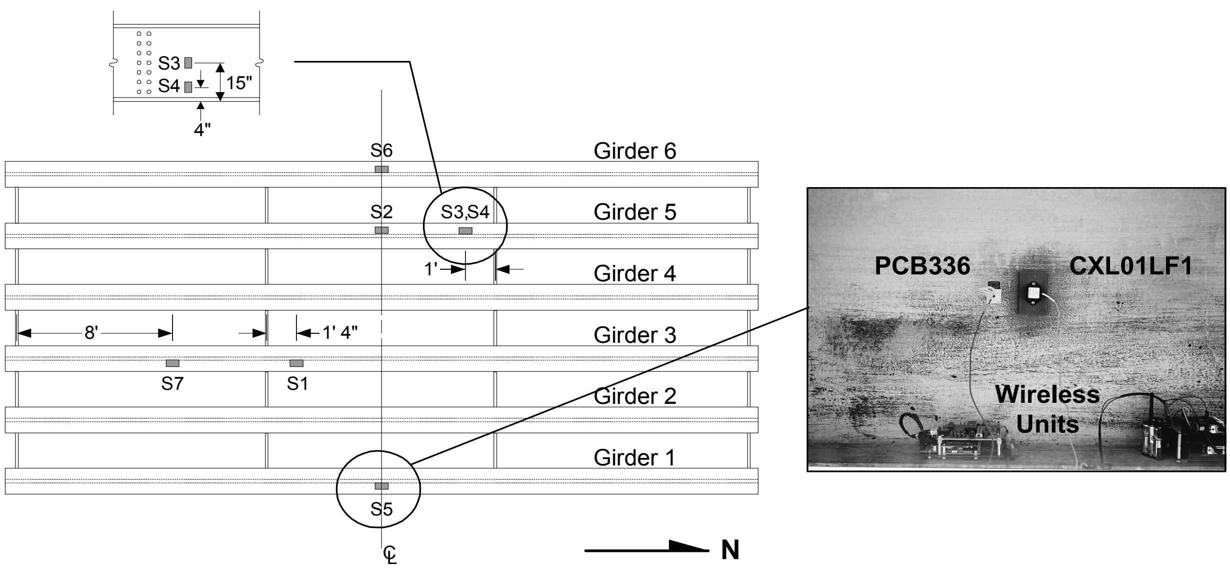

Figure 5: Accelerometer installation locations on the Alamosa Canyon Bridge

5. FORCED VIBRATION TESTING OF THE ALAMOSA CANYON BRIDGE

To produce a sizable vibration response of the selected span of the Alamosa Canyon Bridge, two excitation inputs are considered. The first excitation source selected is an impact blow to the span from a modal hammer. As a second excitation source, a large flatbed truck is used to drive over a wood plank placed in the center of the span as shown in Fig 6. Both excitation levels yield reasonably high structural responses that are measured and logged. These recorded time-histories yield frequency response functions that are used to identify the primary modes of response of the bridge span.

A nearly perfect low level impulse force can be exerted to a structure through the use of a modal hammer. The visual appearances of a modal hammer are similar to that of a large sledge hammer. The head of the modal hammer can be customized to deliver impacts of various magnitudes and frequency ranges. The tip of the hammer head is instrumented with a load cell to directly measure the force imparted to the structure. The point of impact of the modal hammer is selected to be the center of the deck (with respect to both the length and width directions). One valuable feature of the excitation delivered by the modal hammer is that it is a nearly perfect impulse with a flat frequency response function.

The modal impact test is repeated numerous times to measure acceleration at all sensor locations; a total of 7 tests are performed resulting in 14 time-history recordings (7 from the wireless sensing units and 7 generated by the Dactron system). The Dacton system measures the response at a sampling rate of 320 Hz while the wireless sensing unit is configured to record the response at 976 Hz. The response as measured by the accelerometers mounted at sensor location S3 recorded by the Dacton system and the wireless sensing unit are shown in Fig. 7. In comparing the measured acceleration response of the Alamosa Canyon Bridge to the same modal hammer impact force, strong agreement in both amplitude and time is evident. Minor discrepencies exist in the initial peak measured by the two systems, with the Dacton system measuring a peak of 0.17 g and the wireless sensing unit peak amplitude roughly 0.13 g. Subsequent peaks after the intial peak are in complete agreement with each other. For the other sensor locations, results similar to those for sensor location S3 are obtained with strong agreement in the response measured by the two systems. These time-history results indicate the reliability and accuracy of the prototype wireless sensing unit.

To assist in identifying the primary modal frequencies (modal analysis) of the bridge, the frequency response function of the system is determined from the hammer excitation time-history response measured at S3. The frequency response function is determined in two ways. First, the Dactron system employs RT Pro Signal Analysis, an analytical software package for modal analysis, to automatically calculate the frequency response function from the measured time-history. For the measurement data collected by the wireless sensing unit, the computational core of the unit is used to execute an embedded FFT algorithm (this implementation employs the Cooley-Tukey FFT algorithm) [16]. After locally executing the FFT algorithm, the calculated frequency response function is wirelessly transmitted to a laptop serving as a data repository. The FFT performed from the Dactron system measurements is an 8192 point analysis. With memory limited on the wireless sensing unit, only 5000 data points can be stored. As a result, the FFT performed by the wireless unit is a

Figure 6: Methods of forced excitation of the Alamosa Canyon Bridge; (left) modal hammer and (right) flatbed truck driving over a wood stud place in the center of the span

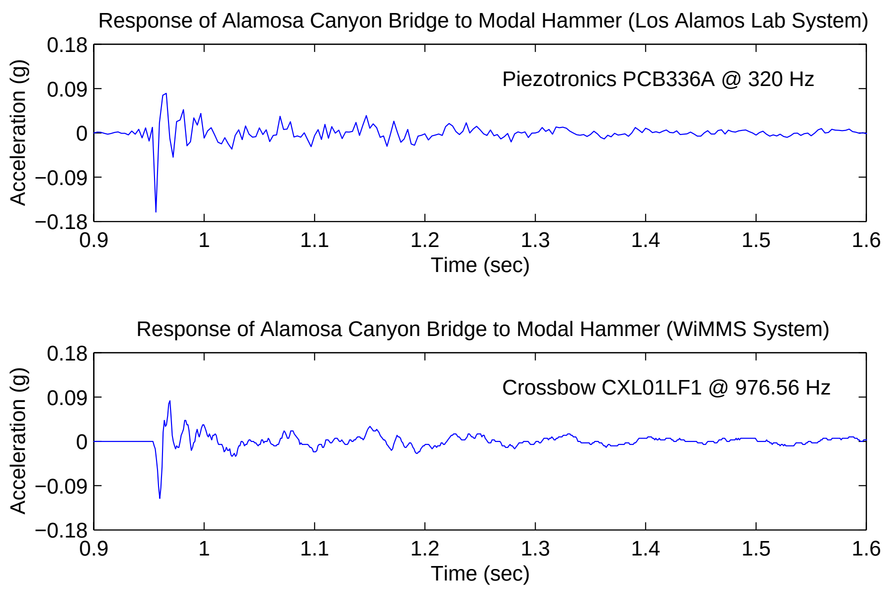

Figure 7: Magnified time-history response at sensor location S3 to modal hammer impact; (top) Dactron system and (bottom) prototype wireless sensor unit

4096 point analysis. The frequency response function calculated from the acceleration response of the bridge is nearly identical to the system transfer function because of the flat frequency response function of the modal hammer's impulse loading.

The frequency response function calculated by both systems from measurements obtained at sensor location S3 are presented in Fig. 8. Strong agreement exists in the two frequency response functions, particularly, with the peaks of the function in alignment. Some differences are present at the very low frequencies due to the DC limitations of the piezoelectric architecture of the PCB336C accelerometer. Three modes of response are immediately evident from the frequency response function at 6.7, 8.2 and 11.4 Hz. The frequency response function corresponding to data obtained by the Dactron system is smoother than that obtained from the wireless sensing unit. This is partly due to the resolution of the Dactron frequency response function being greater than that of the wireless system with six times more points defined in the frequency range (0 to 30 Hz) plotted. Second, the lower conversion resolution of the wireless sensing unit's A/D converter introduces more quantization noise in the lower magnitudes of the frequency response function.

The modal frequencies determined from the other sensor locations (S1 through S7) are tabulated in Table 2. The seven sensor locations yield similar modal frequencies for the span instrumented. The average first three modal frequencies are determined to be 6.83, 8.4 and 11.6 Hz. This is in contrast to the modal frequencies acquired for the northernmost span from past system identification studies: 7.4, 8.0, and 11.5 Hz. The percent difference between the identified mode frequencies of the two spans are 7% for the first mode, 5% for the second mode and 1% for the third mode. Subtle structural differences that exist between the two different spans instrumented (such as differences in the boundary conditions) can be the cause for variability.

An additional forced vibration test is performed on the Alamosa Canyon Bridge. A large truck is used to drive over a wood plank placed at the center of the span instrumented, as shown in Fig. 6. When the truck is driven at approximately 40 miles per hour, the force exerted by the truck is greater than that of the modal hammer, thereby inducing a greater acceleration response in the structure.

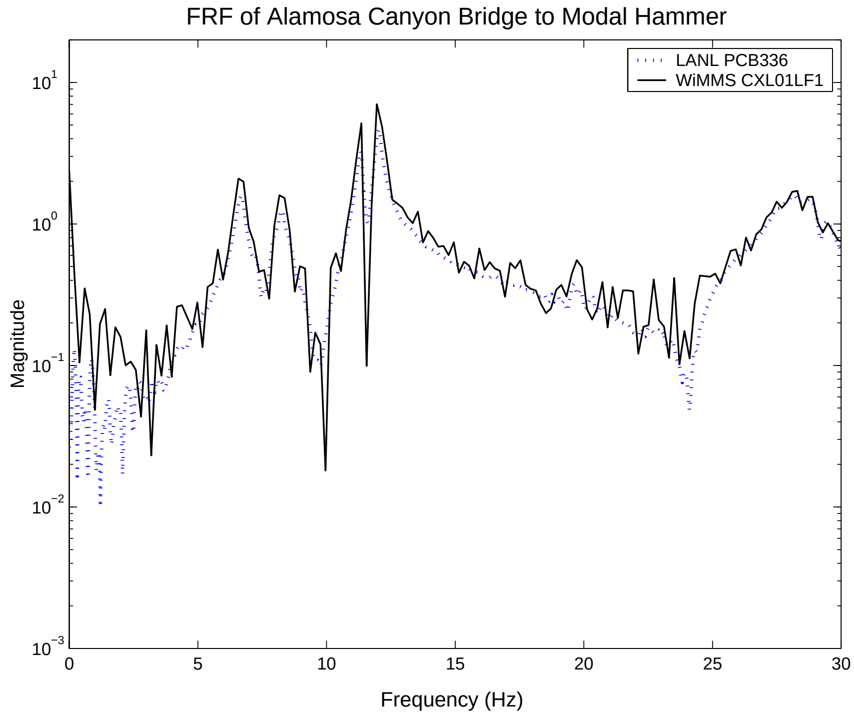

Figure 8: Frequency response functions derived from the acceleration response to the modal hammer at S3

Table 2: Modal frequencies of the Alamosa Canyon Bridge determined from modal hammer excitation records

Modal Frequency	First Span - Previous Results [8]	Sensor Location (WiMMS Acquired)						
		S1	S2	S3	S4	S5	S6	S7
1st Mode	7.4 Hz	6.7 Hz	6.8 Hz	6.7 Hz	6.7 Hz	6.9 Hz	7.0 Hz	7.0 Hz
2nd Mode	8.0 Hz	8.3 Hz	8.5 Hz	8.2 Hz	8.4 Hz	8.3 Hz	8.4 Hz	8.7 Hz
3rd Mode	11.5 Hz	11.6 Hz	11.3 Hz	11.4 Hz	11.7 Hz	11.5 Hz	11.8 Hz	11.9 Hz

For the dynamic truck load test, the accelerometers mounted at sensor location S7 are employed. The acceleration response of the Alamosa Canyon Bridge at S7 is recorded by both the Dactron and wireless data acquisition systems Similar to the modal hammer test, the wireless sensing unit is configured to first locally store the data and to then transmit the data upon demand after the completion of the test. Different from the modal hammer test, the wireless sensing unit is configured to sample at 244 Hz. Fig. 9 presents the acceleration response of the structure measured over a 10 second interval. The truck is loading the span between the first and second seconds of the recording. Again, good agreement exists in the two recorded time-histories. Fig. 10 plots the frequency response function of the recorded time-history at S7 as calculated by the wireless sensing unit. Similar to the frequency response function derived from the modal hammer, the first three modes of response are self-evident in the plot. Unfortunately, no sensors are equipped on the vehicle thereby limiting our knowledge of the input excitation. As a result, the frequency response function calculated by the vehicle excitation test is not immediately useful for more rigorous system identification.

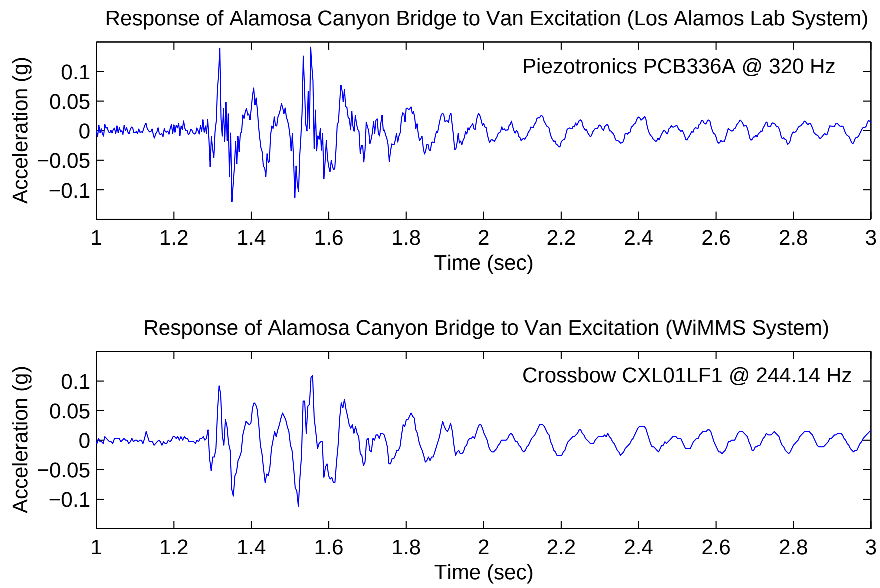

Figure 9: Magnified time-history response at sensor location S7 to the vehicle excitation; (top) Dactron system and (bottom) prototype wireless sensor unit

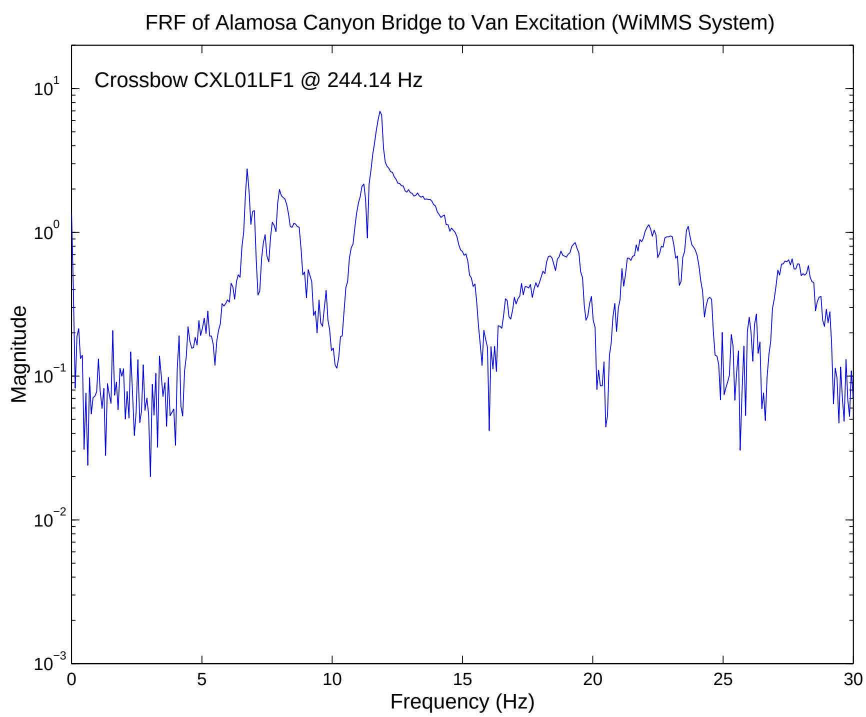

Figure 10: Frequency response functions derived from the acceleration response to the vehicle at S7

6. CONCLUSIONS

This paper has utilized a wireless sensing unit for monitoring the forced vibration response of the Alamosa Canyon Bridge. The Alamosa Canyon Bridge serves as a realistic deployment of the wireless sensing unit with a controllable environment well suited for testing. A commercial cable-based monitoring system is installed in parallel with the wireless sensor network to facilitate a fair assessment of the wireless sensing unit performance. From both excitation sources, time-history recordings of the third northernmost span are in strong agreement with only minor variation at the amplitude peaks. Translating the time-domain response to the frequency domain, the frequency response functions derived from both monitoring systems were nearly identical above 1 Hz. Disagreement in the frequency response function at low frequencies is attributed to the limitations of the piezoelectric accelerometer. The frequency response function calculated using data obtained by the wireless sensing unit can be improved by increasing the resolution of the A/D conversion and collecting longer time-histories. Identification of the primary modal frequencies is an easy task with frequency response function peaks well defined. The modal frequencies determined are within a few percentages of those determined from previous system identification studies of the bridge's northernmost span.

The installation times of the wireless and cable-based systems were not the same. The wireless sensing units were installed with ease and were completed in approximately half the time of the cable-based monitoring system. The cable-based monitoring system installation was more labor-intensive with special care required to ensure safe placement of cables on the bridge. In contrast, the wireless sensing units only had to be placed on the flange of the span's girders and turned on.

Future improvements can be made to the wireless sensing unit design. As previously mentioned, an improved A/D resolution would allow the wireless sensing unit to calculate more accurate frequency response functions. Furthermore, the limited memory available on the wireless sensing unit meant only short duration records could be acquired. With a maximum of 5000 data points possible for storage in memory, only a 4092 point fast Fourier transform could be calculated. While modal frequencies are easy to identify, calculation of the mode shapes of the span are not possible without an accurate method of synchronizing the internal clocks of the wireless sensing units. A cable-based monitoring system has the distinct advantage that all sensors log data with a centralized data server that has a single clock. Straser and Kiremidjian have been able to illustrate the ability to synchronize wireless sensing units to within 0.1 milliseconds using a frequency modulated (FM) beacon signal [4]. Research has begun to explore *a posteriori* techniques for synchronizing time-history records using time-series predictive modeling approaches [17].

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REFERENCES

1. S. B. Chase, "The role of smart structures in managing an aging highway infrastructure," Keynote Presentation, *SPIE Conference on Health Monitoring of Highway Transportation Infrastructure*, March 7, 2001.
2. C. R. Farrar, "Historical overview of structural health monitoring." *Lecture Notes on Structural Health Monitoring using Statistical Pattern Recognition,* Los Alamos Dynamics, 2001.
3. K. Bergmeister, "Maintenance and repairs: an expert opinion." *Freyssinet Magazine,* **10**(209), pp. 4-5, 2000.
4. E. G. Straser and A. S. Kiremidjian. *A modular, wireless damage monitoring system for structures*. Report No. 128, John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, 1998.

5. J. P. Lynch, K. H. Law, A. S. Kiremidjian, E. Carryer, T. W. Kenny, A. Partridge, and A. Sundararajan, "Validation of a wireless modular monitoring system for structures," *Proceedings of SPIE Conference on Smart Structures and Materials* pp. 124-135, 2002.
6. J. P. Lynch, A. Sundararajan, K. H. Law, A. S. Kiremidjian, T. W. Kenny, and E. Carryer, "Embedment of structural monitoring algorithms in a wireless sensing unit," *Structural Engineering and Mechanics*, in press, 2003.
7. C. R. Farrar, S. W. Doebling, P. J. Cornwell, and E. G. Straser, "Variability of modal parameters measured on the Alamosa Canyon Bridge," *Proceedings of the 15th International Modal Analysis Conference – IMAC*, pp. 257-263, 1997.
8. S. W. Doebling, C. R. Farrar, and P. J. Cornwell, "A statistical comparison of impact and ambient testing results from the Alamosa Canyon Bridge," *Proceedings of the 15th International Modal Analysis Conference – IMAC*, pp. 264-269, 1997.
9. S. W. Doebling, C. R. Farrar, and R. S. Goodman, "Effects of measurement statistics on the detection of damage in the Alamosa Canyon Bridge," *Proceedings of the 15th International Modal Analysis Conference – IMAC*, pp. 919-929, 1997.
10. Analog Devices, Inc., *ADXL202/ADXL210 Datasheet – Low Cost 2g/10g Dual Axis iMEMS Accelerometers with Digital Outputs*, Analog Devices, Inc., Norwood, MA 1999.
11. Proxim Corp., *Proxim RangeLAN2 Wireless Modem – Datasheet*, Proxim Corporation, Sunnyvale, CA, 2001.
12. G. L. Ginsberg, *Printed Circuit Design Featuring Computer-Aided Technologies*, McGraw-Hill Inc., New York, NY 1990.
13. H. Weinberg, "Dual axis low-g fully integrated accelerometers," *Analog Dialogues*, Analog Devices Inc., pp. 1-2, 1999.
14. Crossbow, Inc., *High Sensitivity, LF Series Accelerometers - CXL01LF1 Datasheet*, Crossbow, Inc., San Jose, CA 2002.
15. PCB Piezotronics, *Model PCB336 Accelerometer Datasheet*, PCB Piezotronics, Inc., Depew, NY 1995.
16. W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*, Cambridge University Press, Cambridge, U.K., 1992.
17. Y. Lei, A. S. Kiremidjian, K. K. Nair, J. P. Lynch and K. H. Law, "Time synchronization algorithms for wireless monitoring system," *Proceedings of SPIE Conference on Smart Structures and Materials*, in press, 2003.