Field testing of *Martlet* wireless sensing system on an in-service pre-stressed concrete highway bridge

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ABSTRACT

In structural sensing applications, wireless sensing systems have drawn great interest owing to faster installation process and lower system cost compared to the traditional cabled systems. As a new-generation wireless sensing system, *Martlet* features high-speed data acquisition and extensible layout, which allows easy interfacing with various types of sensors. This paper presents a field test of the *Martlet* sensing system installed at an in-service pre-stressed concrete highway bridge on SR113 over Dry Creek in Bartow County, Georgia. Four types of sensors are interfaced with *Martlet* in this test, including accelerometers, strain gages, strain transducers and magnetostrictive displacement sensors. In addition, thermocouples are used to monitor the temperature change of the bridge through the day. The acceleration, strain and displacement response of the bridge due to traffic and ambient excitations are measured. To obtain the modal properties of the bridge, hammer impact tests are also performed. The results from the field test demonstrate the reliability of the *Martlet* wireless sensing system. In addition, detailed modal properties of the bridge are extracted from the acceleration data collected in the test.

Keywords: Structural sensing, wireless sensing system, modal analysis, highway bridge

1. INTRODUCTION

As an important part of modern structural engineering practice, various sensing technologies have been widely used to measure structural responses under various excitations. In a traditional cabled structural sensing system, extensive lengths of coaxial cables are required. The cable installation can be expensive, labor-intensive and time-consuming for large structures. As an alternative to traditional cabled systems, wireless sensing systems have drawn great interest owing to faster installation process and lower system cost [1].

To date, various academic and commercial wireless sensing unit (WSU) prototypes have been developed and tested with laboratory and field structures. For example, a prototypical WSU designed by Lynch *et al.* is validated on the Alamosa Canyon Bridge in New Mexico by installing 7 WSUs interfaced with accelerometers [2]. The WSU designed by Wang *et al.* [3] are compared with a cabled sensing system on the Geumdang bridge in South Korea, including 14 units to measure the vertical acceleration of the bridge during ambient and forced excitations [4]. A WSU named Narada is developed by Swartz *et al.* [5, 6] and its field performance is validated by installing 19 units on a highway bridge in Wayne, New Jersey [7]. Rice *et al.* tested the Imote2 units on Jindo Bridge, South Korea with a dense instrumentation involving 70 WSUs connected with accelerometers and one anemometer [8]. Those tests show that the wireless sensing system could provide acceptable performance and is able to reduce installation time and overall cost. However, in order to further explore possible applications of the wireless sensing technology, field studies of the wireless units interfaced with various types of sensors are needed.

As a newly developed wireless sensing system by Kane *et al.* [9], *Martlet* features versatile functionalities such as heterogeneous sensing, high-speed data acquisition, extensible storage with on-board microSD card, and capacity for real-time feedback control. The *Martlet* wireless sensing system has been tested in the structural vibration monitoring of a wind turbine tower at Los Alamos National Laboratory in New Mexico, USA. In total, six *Martlet* units with accelerometers are deployed and the operational deflection shapes of the tower are extracted. As new sensor boards and embedded code are developed, *Martlet* has been used in several other applications in the laboratory, such as strain measurement and ultrasonic nondestructive evaluation (NDE) [10]. This paper presents a latest field testing of the *Martlet* wireless sensing system, installed on an in-service pre-stressed concrete highway bridge. In this test, 29 *Martlet* units are deployed. The units are interfaced with various types of sensors, including accelerometers, strain gages, strain transducers, and magnetostrictive displacement sensors, to measure the bridge vibration responses due to traffic and

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ambient excitations. In addition, acceleration data are collected during hammer impact tests and analyzed to obtain the bridge modal properties.

The rest of the paper starts with the introduction of the testbed highway bridge and the *Martlet* wireless sensing system, together with the various sensor boards used in this test. The instrumentation plan of the wireless system is then described. The bridge vibration responses due to different traffic excitations are measured and analyzed, including acceleration, strain and displacement. Using the acceleration response from a modal hammer impact, the resonance frequencies and detailed mode shapes of the bridge are extracted. Finally, the paper is summarized with conclusions and future work.

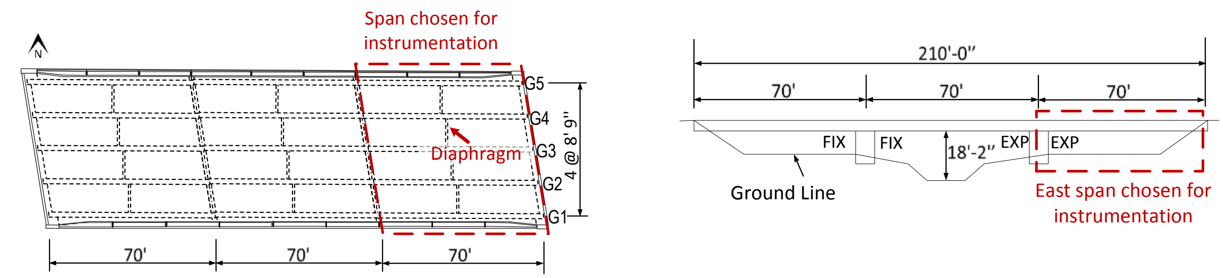
2. DESCRIPTION OF THE HIGHWAY BRIDGE

The testbed bridge was built in 2006, located on the highway SR113 over Dry Creek in Bartow County, Georgia, USA. The bridge has two lanes carrying the eastbound traffic. Figure 1 shows the plan and elevation view of the entire bridge. The bridge consists of three skewed spans, 70 feet long each. The continuous reinforced concrete bridge deck is supported by five I-shaped pre-stressed concrete girders, denoted as G1 ~ G5 in Figure 1(a). The girders are spaced 8 feet and 9 inches away from one another, connected by lateral diaphragms and simply supported at the two ends of every span. Detailed support condition is shown in Figure 1(b), where EXP stands for expansion and FIX stands for fixed. The east span here is chosen for instrumentation due to its accessibility. Figure 2 shows the top and bottom view of the bridge. Overall, the bridge is in very good condition, and can be a good testbed bridge for bridge-weigh-in-motion (BWIM) studies.

3. WIRELESS SENSING SYSTEM AND INSTRUMENTATION PLAN

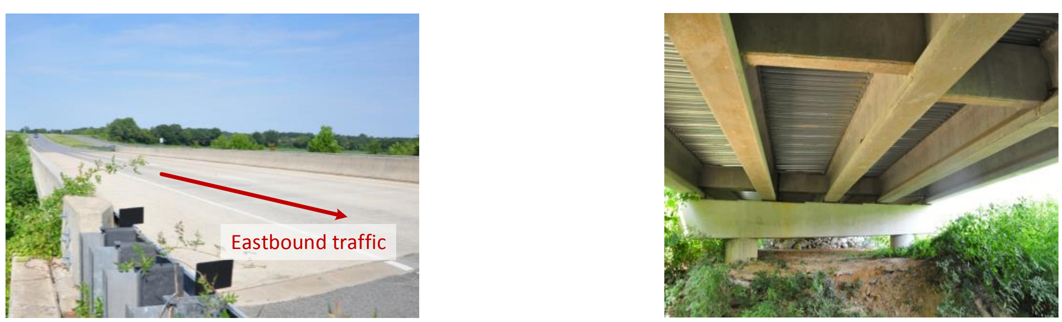
3.1 *Martlet* wireless sensing system

The wireless sensing system used in this test is named *Martlet*, developed by three academic research labs at the University of Michigan, the Georgia Institute of Technology, and Michigan Technological University [9]. The *Martlet*



(a) (b)

Figure 1. SR113 bridge over Dry Creek: (a) plan view, (b) elevation view



(a) (b)

Figure 2. Bridge photos: (a) top view, (b) bottom view

wireless node utilizes a dual-core microcontroller (TMS320F28069) as the processer, featuring up to 90MHz programmable clock frequency. The 9-channel 12-bit analog-to-digital converter (ADC) allows *Martlet* to sample analog signal at a rate up to 3MHz. For wireless communication, *Martlet* utilizes a 2.4GHz low-power radio conforming to IEEE 802.15.4 standard [11]. In addition, the extensible hardware design of *Martlet* allows easy interfacing with various kinds of sensors by conveniently stacking the sensor boards on top of *Martlet* motherboard. Furthermore, a microSD card up to 32GB memory can be inserted to *Martlet* for long-term data acquisition.

In this field test, four types of sensors are interfaced with *Martlet* through corresponding sensor boards (termed "*wing*" boards). As shown in Figure 3(a), the integrated accelerometer *wing* board includes a low-cost microelectromechanical (MEMS) accelerometer and an on-board signal conditioning circuit that performs mean shifting, low-pass filtering and amplification [12]. The use of digital potentiometers in the design makes the low-pass cutoff frequency and amplification gain of the integrated accelerometer *wing* remotely programmable. Figure 3(b) shows the strain gage *wing* connected with a 90mm strain gage for installation on the bridge girders. The strain gage *wing* can be connected with 120Ω or 350Ω strain gages, providing selectable amplification gains at ×96 and ×477 and low-pass filtering at 50Hz. Figure 3(c) is the strain transducer *wing* board developed to work together with a Bridge Diagnostics Inc. strain transducer, providing 3.3V power and on-board signal conditioning. Figure 3(d) shows the smart ADC/DAC *wing* board [9] connected with a MTS magnetostrictive (CS194AV) linear-position displacement sensor, which is used to measure the end displacement of the girder. The ADC/DAC *wing* powers the displacement sensor at 5V and provides programmable amplification gain from ×1.9 to ×190 and on-board low-pass filtering from 15Hz to a few hundred Hz.

3.2 Instrumentation plan

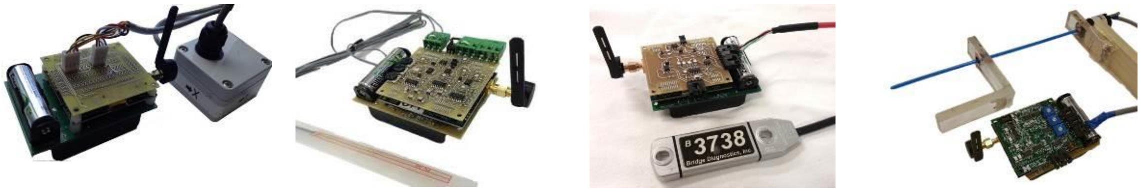
Because of its low-lost and versatility, the *Martlet* sensing system are able to incorporate various kinds of sensors to be installed on the bridge. In order to capture the bridge vibration and deformation under traffic excitations and to obtain bridge modal properties, a total of 15 integrated accelerometers, 20 strain gages, 2 strain transducers and 4 magnetostrictive displacement sensors are instrumented in this preliminary study.

As shown in Figure 4(a), the accelerometers are instrumented at the bottom of every girder at quarter span and mid-span locations to measure vertical accelerations. The strain gages are installed at the top and bottom of the girders at quarter spans to measure the longitudinal deformation. The two strain transducers are installed at the bottom of the two south girders, G1 and G2, at mid-spans. The four magnetostrictive displacement sensors are installed at the two ends of the central girder G3 to measure girder end displacement relative to the pier cap (Figure 4(b)). The east direction here is used as the positive direction. Furthermore, the corresponding *Martlet* wireless nodes are protected by weatherproof boxes and attached to the girders. Compact 2dBi omnidirectional whip antennas are connected with the *Martlet* wireless units located at the quarter and mid-spans, while 6dBi directional antennas are connected with the units located at each end of the girders. Figure 4(c)-(f) shows the close-up views of different types of sensors at several locations. In addition, 21 thermocouples are installed on the girders to monitor the temperature changes through the day.

4. FIELD TESTING RESULTS

4.1 Bridge vibration measurement

Bridge vibration responses are measured under different traffic excitations. Two cases are compared here when a small truck and an 18-wheeler drive through the south lane of the bridge. The amplification gain and the low-pass cutoff



(a) (b) (c) (d)

Figure 3. Wireless sensing boards interfaced with *Martlet*: (a) integrated accelerometer, (b) strain gage board, (c) strain transducer board, (d) smart ADC/DAC sensor board with a magnetostrictive displacement sensor

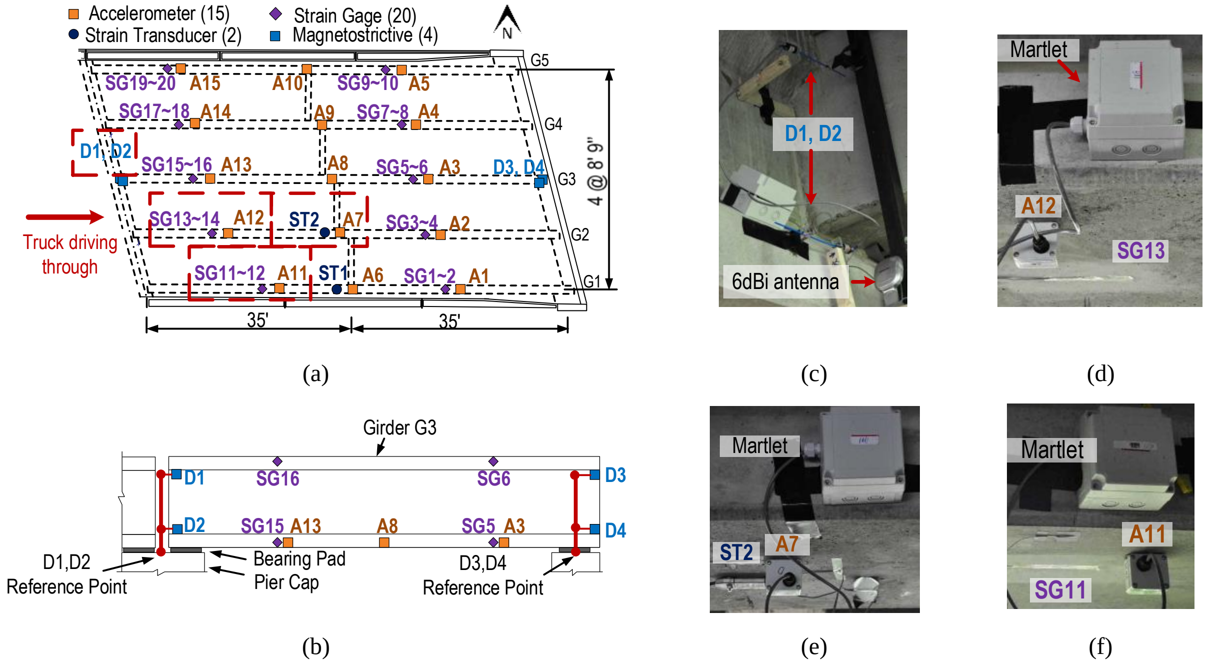


Figure 4. Instrumentation: (a) instrumentation plan, (b) elevation view of girder G3, (c) displacement sensor D1 and D2, (d) accelerometer A12 and strain gage SG13, (e) accelerometer A7 and strain transducer ST2, (f) accelerometer A11 and strain gage SG11

frequency are respectively set as ×20 and 25Hz for the integrated accelerometer *wing*, ×477 and 50Hz for the strain gage *wing*, ×101 and 50Hz for the strain transducer *wing*, and ×20 and 25Hz for the ADC/DAC *wing*. The sampling frequency is set as 100Hz for all sensing channels.

Figure 5 shows the comparison of the vibration responses between two truck excitations, including the bridge acceleration responses from sensor A11 and A12, the strain responses from SG11 and SG13, and the displacement responses from D1 and D2. In addition, strain responses measured by the strain transducer ST2 are also included. In both cases, larger vertical accelerations occur at A12 and A13 located at the bottom mid-span of girder G2 and G3 respectively, compared with other girders. The same trend is observed in the tensile strain measurements at the bottom of the girders. The displacement responses measured by sensors D1 and D2 located at the end of girder G3 also correspond to a convex bending curvature of the girder under traffic excitation. Compared to the small truck case, the magnitudes of the bridge responses for the 18-wheeler clearly increase as shown in all the acceleration, strain and displacement measurements. Overall, the vibration measurements of the bridge under traffic excitation demonstrate the reliability and versatility of the *Martlet* wireless sensing system and its potential ability to detect truck weight.

4.2 Modal property analysis

In order to obtain modal properties of the bridge, a 12.1-lb impact hammer (PCB Piezotronics 086D50) is used to generate an excitation on the bridge deck at the mid-span of girder G1. The response is sampled at 1000Hz for 15 seconds in total. Figure 6 shows the frequency spectra of all acceleration channels under hammer excitation. Four peaks are observed in the frequency spectra under 25Hz, which correspond to the approximate values of the first four captured resonance frequencies.

In order to get detailed modal properties, the acceleration responses are analyzed to extract the resonance frequencies, damping ratios and the corresponding mode shapes of the bridge. The commonly used eigensystem realization algorithm (ERA) [13] is adopted here and the first four modes are extracted (Figure 7). The resonance frequency of every mode matches well with the corresponding peak location in the frequency spectra. Specifically, Mode 1 shows all five girders

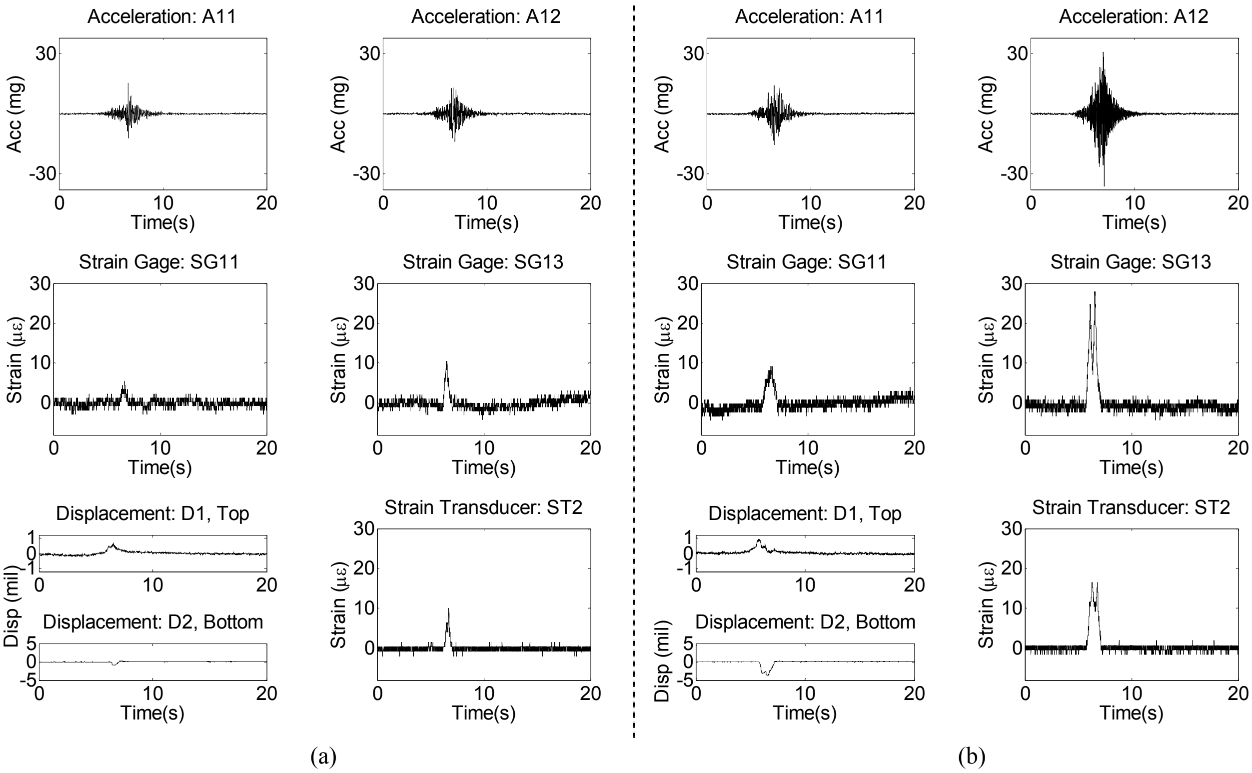


Figure 5. Bridge vibration measurement: (a) small truck, (b) 18-wheeler

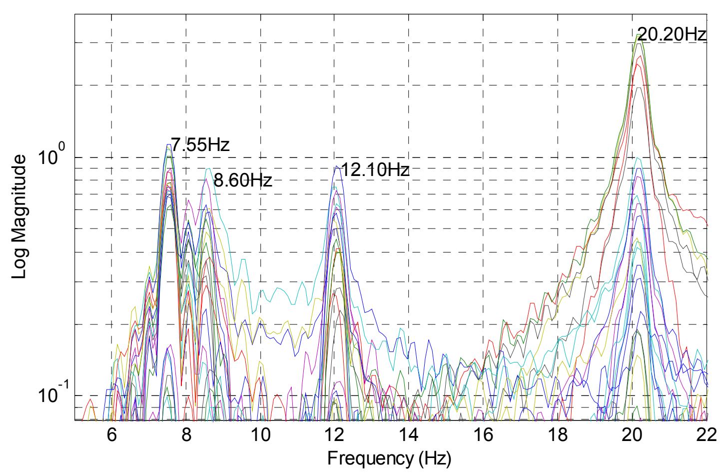


Figure 6. Frequency spectra of all acceleration channels in hammer test

bending in one direction, which is expected for this simply supported bridge span. Mode 2 shows opposite bending directions between girder G1, G2 and G4, G5, while girder G3 moves relatively little. Mode 3 shows the opposite bending directions between side girders G1, G5 and middle girders G2, G3, G4. Mode 4 shows the alternating bending directions among girder G1, G2, G4 and G5. All the modes agree well with the typical behavior of a simple supported bridge span.

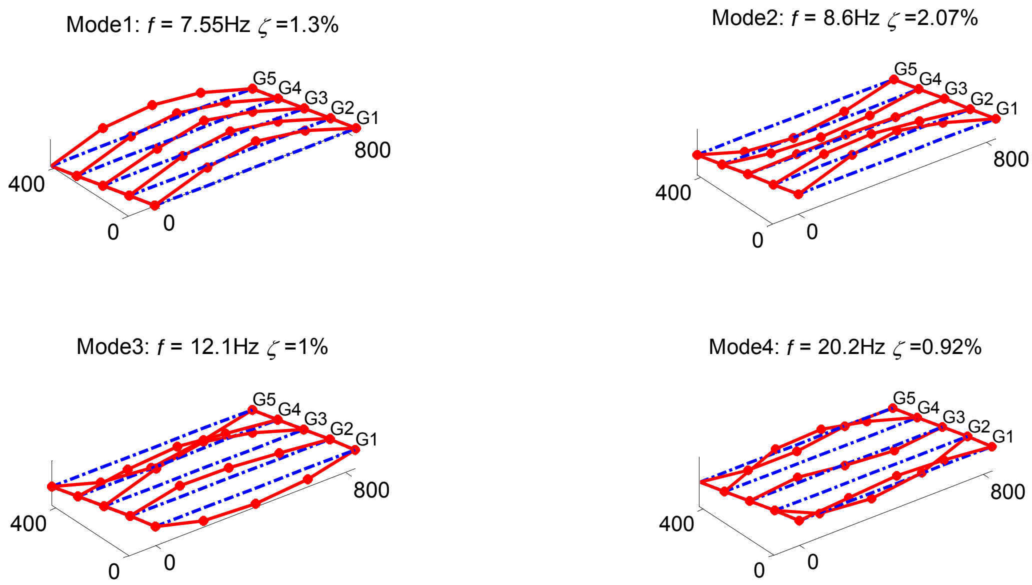


Figure 7. Bridge vibration modes

5. CONCLUSIONS AND FUTURE WORK

This research presents a latest field test of the *Martlet* wireless sensing system, interfaced with four types of sensors, including accelerometer, strain gage, strain transducer and magnetostrictive displacement sensor to capture the bridge responses under various traffic excitations. The vibration responses are measured and compared for a small truck and an 18-wheeler driving through the bridge. Clear differences in response magnitudes are shown in all four types of sensor measurements, which indicates the promising ability of the *Martlet* wireless sensing system to detect truck weight in future studies. In addition, the acceleration measurement during impact hammer tests are used to obtain bridge modal properties. Overall, the low-cost yet versatile *Martlet* wireless sensing system shows reliable performance during the field test and the potential to be used in various applications, such as bridge-weigh-in-motion systems. In addition, with the first four modes successfully extracted, bridge model updating will be performed to update the finite element model by minimizing the differences between the modeling and the experimental results.

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REFERENCES

[1] Lynch, J.P. and Loh, K.J., "A summary review of wireless sensors and sensor networks for structural health monitoring," Shock Vib. Dig., 38(2), 91-128 (2006).

[2] Lynch, J.P., Law, K.H., Kiremidjian, A.S., E., C., Farrar, C.R., Sohn, H., Allen, D.W., Nadler, B. and Wait, J.R., "Design and performance validation of a wireless sensing unit for structural health monitoring applications," Struct. Eng. Mech., 17, 393-408 (2004).

[3] Wang, Y., Lynch, J.P. and Law, K.H., "A wireless structural health monitoring system with multithreaded sensing devices: design and validation," Struct. and Infrastructure Eng., 3(2), 103-120 (2007).

[4] Lynch, J.P., Wang, Y., Loh, K.J., Yi, J.-H. and Yun, C.-B., "Performance monitoring of the Geumdang Bridge using a dense network of high-resolution wireless sensors," Smart Mater. Struct., 15(6), 1561-1575 (2006).

[5] Swartz, R.A., Jung, D., Lynch, J.P., Wang, Y., Shi, D. and Flynn, M.P., "Design of a wireless sensor for scalable distributed in-network computation in a structural health monitoring system," Proc. the 5th International Workshop on Structural Health Monitoring, (2005).

[6] Zimmerman, A.T., Shiraishi, M., Swartz, R.A. and Lynch, J.P., "Automated modal parameter estimation by parallel processing within wireless monitoring systems," J. Infrastruct. Syst., 14(1), 102-113 (2008).

[7] Zhu, D., Wang, Y. and Brownjohn, J., "Vibration testing of a steel girder bridge using cabled and wireless sensors," Frontiers of Architecture and Civil Engineering in China, 5(3), 249-258 (2011).

[8] Rice, J.A., Mechitov, K., Sim, S.-H., Nagayama, T., Jang, S., Kim, R., Spencer Jr, B.F., Agha, G. and Fujino, Y., "Flexible smart sensor framework for autonomous structural health monitoring," Smart Struct. Syst., 6(5-6), 423-438 (2010).

[9] Kane, M., Zhu, D., Hirose, M., Dong, X., Winter, B., Häckell, M., Lynch, J.P., Wang, Y. and Swartz, A., "Development of an extensible dual-core wireless sensing node for cyber-physical systems," Proc. SPIE, Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security, 9061, (2014).

[10] Dong, X., Chen, S., Zhu, D., Kane, M., Wang, Y. and Lynch, J.P., "High-speed heterogeneous data acquisition using Martlet - a next-generation wireless sensing device," Proc. the Sixth World Conference on Structural Control and Monitoring (6WCSCM), (2014).

[11] Cooklev, T., Wireless Communication Standards: A Study of IEEE 802.11, 802.15, and 802.16, Standards Information Network IEEE Press, New York, (2004).

[12] Dong, X., Zhu, D., Wang, Y., Lynch, J.P. and Swartz, R.A., "Design and validation of acceleration measurement using the Martlet wireless sensing system," Proc. ASME 2014 Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS), (2014).

[13] Juang, J.N. and Pappa, R.S., "An eigensystem realization algorithm for modal parameter identification and modal reduction," J. Guid. Control Dynam. , 8(5), 620-627 (1985).