Validation of wireless sensing technology densely instrumented on a full-scale concrete frame structure

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ABSTRACT The adoption of wireless sensing technologies in structural health monitoring (SHM) community has shown certain advantages over traditional cable-based system, such as simplified installation process and lower system cost. Recently, a new generation wireless sensing device, named *Martlet*, has been developed for SHM purpose. In order to obtain accurate high-resolution acceleration data and in the meantime reduce hardware cost, an accessory sensor board for *Martlet*, named integrated accelerometer *wing*, is developed. For performance validation, the *Martlet* wireless sensing system is installed on a full-scale two-story, two-bay concrete frame structure. Shakers from NEES@UCLA are used to provide dynamic excitations. In addition to *Martlet*, the performance of *Narada*, a precursor wireless sensing unit, is also validated in this test. The performance of the wireless sensing system is compared with a high-precision cabled sensing system through side-by-side comparison at critical locations of the frame. Results from this full-scale experiment demonstrate that the accuracy of the wireless sensor data is comparable to that of the counterpart cabled system. Furthermore, using the data collected by the densely deployed wireless and cabled sensors, detailed modal properties of the structure are identified for future model updating.

1 INTRODUCTION

In order to improve the safety assessment of engineering structures, structural health monitoring (SHM) technologies have been widely investigated for monitoring structural performance and identifying potential damage. In an SHM system, various types of data (such as acceleration, displacement, strain, and so on) are needed to evaluate the safety of a structure (Sohn, et al. 2003). In traditional SHM systems, coaxial cable is usually adopted for data acquisition because of its reliable performance. However, extensive cable lengths in a cabled SHM system may result in cost at a few thousand dollars per sensing channel (Çelebi 2002). Furthermore, in order to obtain more detailed structural information, it is required to install a large amount of sensors on the structure. Such dense instrumentation is usually not feasible due to the budget limit. In order to overcome the limitation of cabled SHM systems, significant efforts have been devoted to developing wireless SHM systems (Lynch & Loh 2006). Recently, a new generation wireless sensing unit, named *Martlet*, is developed for SHM purpose (Kane, et al. 2014). In order to obtain accurate high-resolution acceleration data and in the meantime reduce hardware cost, an accessory sensor board for *Martlet*, named integrated accelerometer *wing*, is developed (Dong, et al. 2014).

This paper evaluates the performance of *Martlet* with the integrated accelerometer *wing* through the experiments conducted on a full-scale two-story, two-bay concrete frame structure on Georgia Tech campus. In addition to *Martlet*, the performance of *Narada*, a precursor wireless unit, is also validated in this test (Swartz, et al. 2005, Zimmerman, et al. 2008). The frame is first installed with 42 cabled accelerometers (Kinemetrics models EpiSensor ES-T and ES-U) on columns and girders to capture the acceleration responses. To increase spatial resolution of the instrumentation, 23 *Narada* and 13 *Martlet* wireless units are interspersed between cabled accelerometers on the columns, girders and slabs. The performance of the wireless system is first validated by comparing to the high-precision cabled system. Furthermore, the wireless and cabled acceleration sensor data are utilized for extracting the modal properties of the frame structure.

The rest of the paper is organized as follows. The full-scale two-story, two-bay concrete frame structure is described first. Secondly, the wireless and cabled SHM systems are introduced, including the *Martlet* wireless sensing unit and the integrated accelerometer *wing*, followed by the instrumentation for both the wireless and cabled sensing systems on the test structure. In addition, measurement data from the wireless and cabled sensors are compared. Thirdly, structural modal properties, i.e. resonance frequencies and mode shapes, are extracted using both the wireless and cabled acceleration data. Finally, the paper is summarized with conclusions and future work.

2 DESCRIPTION OF THE TEST STRUCTURE

The concrete test frames were built at full scale in the Structural Engineering and Materials Laboratory on Georgia Tech campus (Figure 1). Four identical frames with the same design were constructed. For experimental safety, two strong collapse prevention frames were constructed, one outside Frame 1 and the other one outside Frame 4. Although it is difficult to see in the photo, the total of six individual frames are separate from each other, with a gap between every two neighboring frames. Figure 2 shows the main dimensions of the test frame. Each test frame consists of two bays and two stories, and was meant to be representative of low-rise reinforced concrete office buildings in the central and eastern United States built in the 1950s-1970s. The frame design was carried out using simplified analysis techniques that would have been employed during the era when non-ductile reinforced concrete frames were built before modern seismic code was used. Frame 1 is an as-built bare frame as the reference structure, while different seismic retrofit measures are applied to the other three frames for seismic research. This paper reports on results from Frame 1 only.

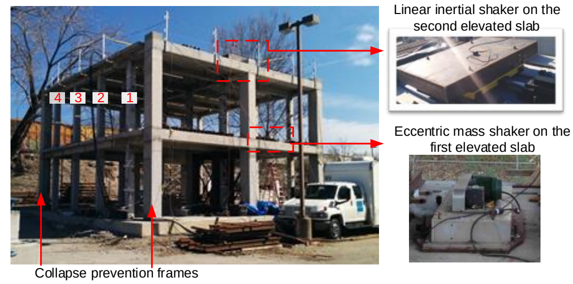


Figure 1 Photo of test frames and two shakers on Frame 1 under test (viewing from southwest corner)

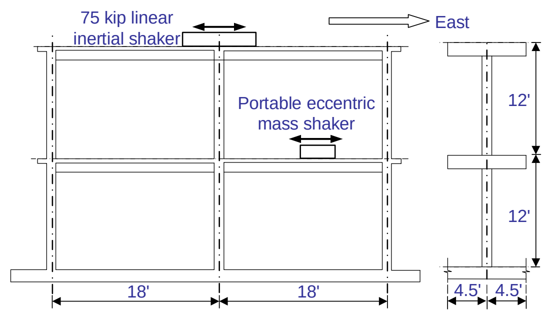


Figure 2 Elevation and side-view drawings

Also shown in Figure 2 are the locations of the two shakers provided by NEES@UCLA. A 75-kip hydraulic linear inertial shaker is mounted on the second elevated slab, and a portable 980-lb eccentric mass shaker is installed on the first elevated slab of the frame. Through tens of test runs for each frame, the excitation amplitude generated by the linear shaker increases as the experiment carries on, gradually causing damage to the concrete frame. The eccentric shaker is used occasionally for low-amplitude sine sweeping.

3 WIRELESS AND CABLED ACCELERATION SENSING SYSTEMS

Although the modal analysis in this paper only involves acceleration data, a large number of other types of sensors (including strain gages, string pots, and LVDTs) were also instrumented on the test structure. This section first describes the *Martlet* wireless sensing device and the integrated accelerometer *wing*, as well as the cable-based system. The field testing setups of the wireless and cabled systems are then described, followed by the comparison between the wireless and cabled sensor data.

3.1 Martlet wireless sensing system and the integrated accelerometer wing

Martlet is a next-generation low-cost wireless sensing node developed for SHM applications (Kane, et al. 2014). The development of *Martlet* is a joint effort among three academic research labs at the University of Michigan, the Georgia Institute of Technology, and Michigan Technological University, respectively. The *Martlet* wireless node adopts a Texas Instruments Piccolo microcontroller as the core processor to execute onboard computation and data acquisition. The clock frequency of an earlier version (TMX320F28069) of the microcontroller can be programmed up to 80 MHz, and a more recent version (TMS320F28069) can support up to 90 MHz. The dimension of the *Martlet* node is 2.5 in by 2.25 in.

One distinct feature of the microcontroller on *Martlet* is the capability of high-speed data acquisition. The high-speed onboard microcontroller and the direct memory access (DMA) module on the microcontroller allows the *Martlet* node to collect sensor data at a sampling rate up to 3 MHz. The *Martlet* node adopts a 2.4 GHz radio for low-power wireless communication through IEEE 802.15.4 standard (Cooklev 2004). The extensible hardware design of the *Martlet* node enables various sensor boards to conveniently stack up through four wing connectors and work with the motherboard. The combination of the extensible design feature with onboard 9-channel 12-bit analog-to-digital conversion (ADC) allows the *Martlet* node to simultaneously sample analog signals from multiple sensors through different accessory sensor boards (termed "*wing*" boards). In addition to *Martlet*, the performance of *Narada*, a precursor wireless unit, is also validated in this test (Swartz, et al. 2005, Zimmerman, et al. 2008).

In order to obtain accurate acceleration measurement, and in the meantime reduce sensor cost, one solution is to integrate a low-cost microelectromechanical (MEMS) accelerometer and specialized signal conditioning circuit into a single *wing* board. The integrated accelerometer *wing* adopts a tri-axial MEMS accelerometer, the STMicroelectronics LIS344ALH model. A jumper on the board selects between ±2g and ±6g measurement scales. The noise density of the measurement is 25 $\mu g/\sqrt{HZ}$ along the x-axis and y-axis, and 50 $\mu g/\sqrt{HZ}$ along the z-axis.

The analog signals from the LIS344ALH accelerometer are directly fed into an onboard signal conditioner that performs mean shifting, low-pass filtering, and amplification (Dong, et al. 2014). A distinct feature of the integrated accelerometer *wing* is that the cutoff frequencies of low-pass filters and amplification gains are remotely programmable. This feature is achieved by adopting digital potentiometers (Digipots), whose resistance value can be programed on-the-fly by the *Martlet* microcontroller through an Inter-Integrated Circuit (I^2C) interface. In addition to the integrated accelerometer *wing*, another two types of commercial accelerometers (Silicon Designs 2012-002 and Crossbow CXL01LF1) are adopted in this experiment. In order to allow those two accelerometers work with *Martlet*, a smart ADC/DAC *wing* is stacked on top of the *Martlet* node (Kane, et al. 2014). During the experiment on Frame 1, two Silicon Designs accelerometers, two Crossbow accelerometers and fourteen integrated accelerometer *wing*s are connected with *Martlet* nodes. Meanwhile, twelve Silicon Designs accelerometers, four Crossbow accelerometers, and twenty-four integrated accelerometer *wing*s are connected with *Narada* nodes.

3.2 Cabled sensing system

Two accelerometer models from Kinemetrics (EpiSensor ES-T and ES-U) are adopted in the cable-based system. A 6-channel 24-bit Quanterra Q330 data logger is used to collect the cabled accelerometer data.

Table 1 provides the performance comparison of the Kinemetrics cabled accelerometers and the STMicroelectronics LIS344ALH accelerometer used in the integrated accelerometer *wing*. Available at a relatively low price, the STMicroelectronics accelerometer has a higher noise floor, yet is more convenient for wireless deployment due to the low requirement on power supply. During the experiment on Frame 1, nine EpiSensor ES-T and thirty-three EpiSensor ES-U accelerometers are deployed on the structure.

Table 1 Parameter of accelerometers used by the cabled and wireless systems

Specification	EpiSensor ES-T	EpiSensor ES-U	LIS344ALH
# of axis	3	1	3
Range	±4g	±4g	±2g / ±6g
Bandwidth	DC~200Hz	DC~200Hz	DC~1.8kHz
Noise floor	3.5 $\mathrm{ng}/\sqrt{\mathrm{HZ}}$	3.5 $\mathrm{ng}/\sqrt{\mathrm{HZ}}$	25 or 50 $\mu\mathrm{g}/\sqrt{\mathrm{HZ}}$
Power supply	20V	20V	2.4 ~ 3.6V

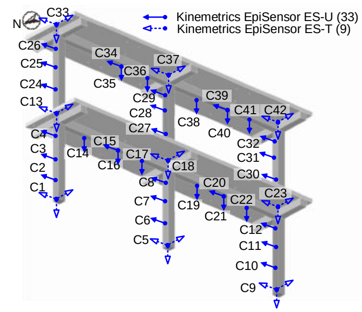
3.3 *Experimental setup of the first frame*

As shown in Figure 3 (a), the frame is first installed with 42 Kinematrics cabled accelerometers (EpiSensor ES-T and ES-U) on columns and girders (60 data acquisition channels in total) to capture the acceleration responses. To increase spatial resolution of the instrumentation, 23 *Narada* and 13 *Martlet* wireless units with overall 66 acceleration channels are interspersed between cabled accelerometers on the columns, girders and slabs (Figure 3 (b)). As a result, there are a total of 126 acceleration channels installed on the structure, including both cabled and wireless channels.

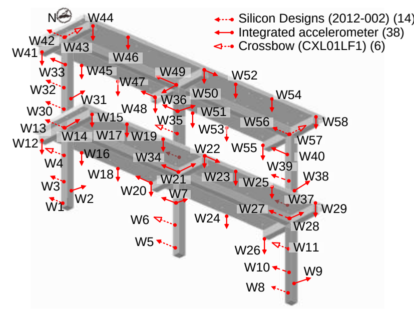
As seen in Figure 3, some cabled and wireless accelerometers are deployed side-by-side at the same location, i.e. W43 and C33 (Figure 4), so that the data collected by the cabled and wireless data acquisition systems can be synchronized. In the meantime, the cabled and wireless data can be compared at the side-by-side locations. Most of the wireless units use a smaller-size 2 dBi omni-directional whip antenna. At locations with thicker concrete blocking between the wireless unit and wireless server, a directional antenna (6 dBi Intellinet 525138) is used by the unit.

3.4 *Vibration measurement on the first frame*

Figure 5(a) presents the example acceleration time histories recorded at beam and column joint at the first elevated slab (C13 and W13). The data is collected when the linear shaker operates on the second elevated slab with a scaled El Centro earthquake record. In this test, the acceleration record is scaled such that the corresponding maximum displacement is 4 inches. The amplification gain and cutoff frequency of the integrated accelerometer *wing* is set to be ×20 and 25 Hz,

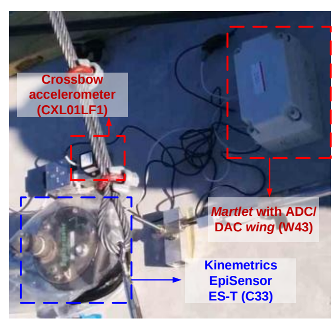


(a) Cabled sensing system



(b) Wireless sensing system

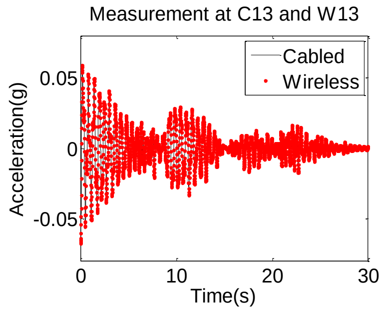
Figure 3 Accelerometer instrumentation on Frame 1



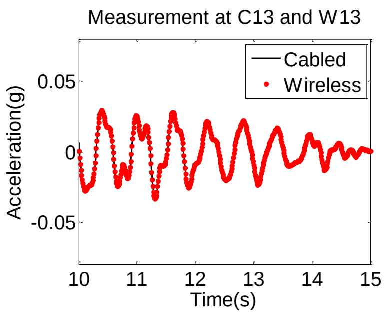
(a) Cabled and wireless accelerometer

Figure 4 Pictures of deployment on Frame 1

respectively. A 25 Hz low-pass digital filter has been applied to both the wireless and cabled data sets so that signal in the same frequency range is compared. Figure 5(b) shows the close-up comparison of acceleration time histories. Both plots demonstrate excellent agreement between the cabled and wireless system.



(a) Comparison for C13 and W13



(b) Close-up comparison of C13 and W13

Figure 5 Comparison of acceleration time history plots between cabled and wireless system

4 STRUCTURAL MODAL PROPERTY ANALYSIS USING WIRELESS AND CABLED SENSOR DATA

Among the large number of tests performed with Frame 1, this paper reports modal analysis results using data from two tests when the linear inertial shaker was used. Using an accelerometer mounted on the moving mass of the linear inertial shaker, time history of the shaker force can be estimated as dynamic input to the structural system. With known input to the system, frequency response functions (FRFs) can be calculated for all response DOFs instrumented with cabled and wireless accelerometers. The commonly used eigensystem realization algorithm (ERA) is applied to extract the structural modal properties (Juang & Pappa 1985). Because the unidirectional inertial shaker force is along the horizontal in-plane direction, this paper focuses on the extraction of in-plane mode shapes of the frame. Extraction of out-of-plane modes using other sets of acceleration data will be reported in future studies.

The first set of data analyzed herein is when the linear shaker operates on the second elevated slab with a scaled El Centro record (the corresponding maximum displacement scaled to 1”). Figure 6 shows the first three in-plane modes of Frame 1 extracted from ERA method. Those three mode shapes are obtained by using data from the cabled system only (52 channels in total). Recall that Figure 3 shows all cabled channels are instrumented on the frame, and no cabled accelerometer is installed on the edge of the concrete slabs. The first mode shape shows all nodes moving along one direction, which is expected for this frame structure. In addition, Figure 7 shows modal analysis results from the test data when the maximum displacement amplitude of the El Centro excitation is increased to 4”. Both cabled and wireless acceleration data, 95 channels in total, are used for modal analysis this time. The resonance frequencies of all identified modes show decrease, compared with the El Centro 1” results. With more sensor channels available for modal analysis, more detailed vibration modes are obtained with denser measurement nodes on the columns. The benefit of dense sensor nodes is particularly obvious for Mode 3 in Figure 7, where vertical vibration of the concrete slabs is captured by the wireless accelerometers.

From El Centro 1” test to the 4” test, the decrease in resonance frequencies is possibly due to structural damage caused by the shaker excitation. Difference observed between the two sets of mode shapes can be a promising indicator for locating and assessing the severity of structural damage.

5 CONCLUSIONS AND FUTURE WORK

This research evaluates the performance of a recently-developed wireless sensing unit, *Martlet*, with the integrated accelerometer *wing* during the experiment conducted on a full-scale two-story, two-bay concrete frame structure on Georgia Tech campus. In addition to *Martlet*, the performance of *Narada*, a precursor wireless unit, is also validated in this experiment. The acceleration time histories are compared between wireless and cabled systems, illustrating that the wireless data achieves comparable quality to the cabled

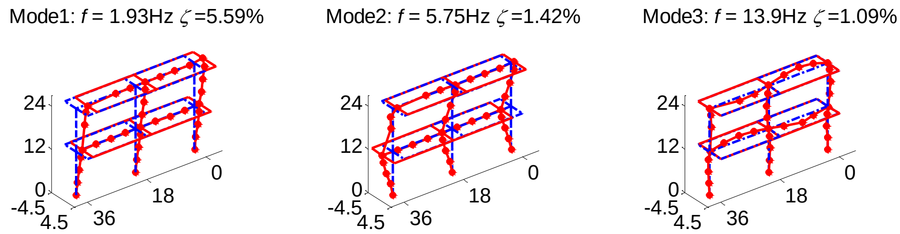


Figure 6 First three identified mode shapes of Frame 1 (El Centro 1”)

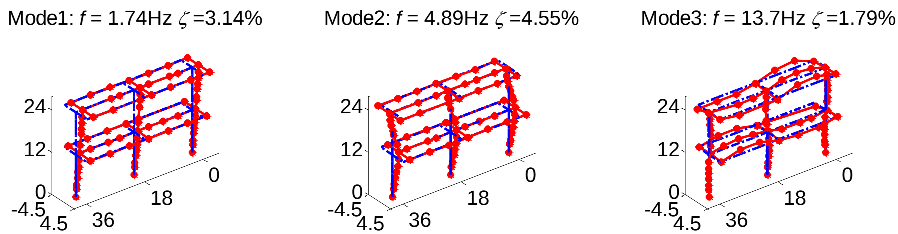


Figure 7 First three identified mode shapes of Frame 1 (El Centro 4”)

data. In addition, modal properties of the structure are successfully obtained by using both the wireless and cabled acceleration data. The decrease in the resonance frequencies of the frame structure may indicate the existence of structural damage. The difference in the mode shapes may help to localize and assess the severity of the damage. In the future, data collected from different stages of the experiment will be analyzed so as to assess the growth of structural damage through the course of the experiment. In addition, more vibration modes may be obtained by analyzing structural response data from other tests.

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REFERENCES

Sohn, H., C. R. Farrar, F. M. Hemez, *et al.* 2003. "*A Review of Structural Health Monitoring Literature: 1996-2001*," Los Alamos National Laboratory, Los Alamos, NM Report No. LA-13976-MS.

Çelebi, M. 2002. "*Seismic Instrumentation of Buildings (with Emphasis on Federal Buildings)*," United States Geological Survey, Menlo Park, CA Report No. 0-7460-68170.

Lynch, J. P. & K. J. Loh. 2006. "A summary review of wireless sensors and sensor networks for structural health monitoring," *The Shock and Vibration Digest*, vol. 38, pp. 91-128.

Kane, M., D. Zhu, M. Hirose, *et al.* 2014 "Development of an extensible dual-core wireless sensing node for cyber-physical systems," *Proceedings of SPIE, Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security*, San Diego, California, USA.

Dong, X., D. Zhu, Y. Wang, *et al.* 2014 "Design and validation of acceleration measurement using the Martlet wireless sensing system," *Proceedings of the ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS)*, Newport, RI, USA.

Swartz, R. A., D. Jung, J. P. Lynch, *et al.* 2005 "Design of a wireless sensor for scalable distributed in-network computation in a structural health monitoring system," *Proceedings of the 5th International Workshop on Structural Health Monitoring*, Stanford, CA.

Zimmerman, A. T., M. Shiraishi, R. A. Swartz, *et al.* 2008. "Automated modal parameter estimation by parallel processing within wireless monitoring systems," *Journal of Infrastructure Systems*, vol. 14, pp. 102-113.

Cooklev, T., 2004. *Wireless Communication Standards : a Study of IEEE 802.11, 802.15, and 802.16*. New York: Standards Information Network IEEE Press.

Juang, J. N. & R. S. Pappa. 1985. "An eigensystem realization algorithm for modal parameter identification and modal reduction," *Journal of Guidance Control and Dynamics*, vol. 8, pp. 620-627.