# High-g Shocking Testing of the *Martlet* Wireless Sensing System

Xi Liu, Xinjun Dong, Yang Wang*, Lauren Stewart, School of Civil and Environmental Engineering, Georgia Inst. of Technology, Atlanta, GA, USA
Jacob Dodson, Air Force Research Laboratory, Munitions Directorate, Eglin AFB, FL, USA
Bryan Joyce, Energy Technology and Materials Division, University of Dayton Research Inst., Eglin AFB, FL, USA

This article reports the latest development of a wireless sensing system, named *Martlet*, on high-g shock acceleration measurement. The *Martlet* sensing node design is based on a Texas Instruments Piccolo microcontroller, with clock frequency programmable up to 90 MHz. The high clock frequency of the microcontroller enables *Martlet* to support high-frequency data acquisition and high-speed onboard computation. In addition, the extensible design of the *Martlet* node conveniently allows incorporation of multiple sensor boards. In this study, a high-g accelerometer interface board is developed to allow *Martlet* to work with the selected microelectromechanical system (MEMS) high-g accelerometers. Besides low-pass and high-pass filters, amplification gains are also implemented on the high-g accelerometer interface board. Laboratory impact experiments are conducted to validate the performance of the *Martlet* wireless sensing system with the high-g accelerometer board. The results of this study show that the performance of the wireless sensing system is comparable to the cabled system.

**Keywords:** Shock test, wireless sensors, data acquisition system, hydraulic blast actuator, *Martlet* wireless sensing unit.

## 1 Introduction

In a shock/impact test, the test specimen is usually placed inside an enclosure to protect equipment and humans from potentially flying objects. Since the data acquisition (DAQ) unit usually sits outside the safety enclosure, relatively long cables are needed to connect the DAQ unit and the accelerometers mounted on the test specimen (subject to impact). Sudden movement of the object upon impact usually poses safety hazards to the cable connections, potentially damaging or breaking the connections. Eliminating cables, wireless sensors provide a great alternative in alleviating such risks.

Wireless sensing systems have experienced significant advances over the past decades, owing to their lower system cost and faster installation compared to traditional cabled sensing systems. For instance, the wireless system developed by Lynch et al. was instrumented on the Alamosa Canyon Bridge in New Mexico, installed in parallel with a commercial cabled sensing system[1]. Another wireless sensing system designed by Wang et al. was instrumented on the Geumdang bridge in South Korea, along with a cabled sensing system, measuring vertical acceleration response[2]. The wireless sensing system named Narada, developed by Swartz et al.[3], was tested on the Yeondae Bridge in South Korea. The Imote2 wireless sensing system was developed and tested by Rice et al. on the Jindo Bridge[4]. These previous studies have shown that the wireless sensing systems could provide comparable performance as the cabled system. However, despite past development, most of the wireless sensing systems either could not provide high-g and high-speed data acquisition required for shock/impact tests or were rarely tested in such applications.

In this study, we investigate the capability of a lately developed wireless system, named *Martlet*, for high-g shock tests. The performance of *Martlet* has been validated on various types of structures, including a wind turbine tower, a full-scale concrete frame, and a highway bridge[5-7]. Besides normal data acquisition, *Martlet* is also capable of high-speed data acquisition up to 3 MHz, suitable for ultrasonic non-destructive testing[8]. In this research, a new sensor interface board is developed to power the high-g accelerometer and apply onboard signal conditioning. At the same time, a high-speed data acquisition firmware is developed to sample the analog signal of the accelerometer with a programmable trigger level. Two groups of experiments are conducted to verify the performance of the wireless sensing system. The first group involves a guardrail post impact test using an ultra-fast hydraulic actuator, in which the maximum acceleration magnitude reaches around 300 g. The second group involves a Very High G (VHG) impact test, with different acceleration magnitudes up to 15,000 g. Most of the results in this article have been previously presented at the 36th International Modal Analysis Conference (IMAC XXXVI)[9].

The rest of the article is organized as follows. The *Martlet* wireless sensing system, the new sensor interface board and the high-speed DAQ firmware are introduced in Section 2. Section 3.1 describes the test setup and result comparison of the guardrail post impact test. Section 3.2 describes the test setup and result comparison of the VHG impact test. Finally, the article is summarized with conclusions and on-going research.

## 2 *Martlet* Wireless Sensing System

### *2.1 Hardware Development*

*Martlet* is a next-generation low-cost wireless sensing node developed for smart structures applications[6]. The *Martlet* wireless node adopts a Texas Instruments Piccolo microcontroller as the core processor (TMS320F28069), whose clock frequency can run up to 90 MHz. The *Martlet* node integrates a 2.4 GHz radio for low-power wireless communication through the IEEE 802.15.4 standard[10]. With an onboard analog-to-digital conversion (ADC) module, the *Martlet* node is able to sample analog signal of high-g accelerometers through a sensor interface board. The high clock frequency of the microcontroller enables the *Martlet* node to execute high-speed data acquisition and onboard computation. The direct memory access (DMA) module on the microcontroller allows the *Martlet* node to sample data at a frequency up to 3 MHz, which is sufficient for sampling acceleration signal from high-g accelerometers. A 32 k×16-bit random access memory (RAM) in the microcontroller can be accessed by the DMA module. To store a large quantity of data, a typical Micro SD card (like those used in digital cameras) can be plugged into the *Martlet* motherboard. The data stored in the Micro SD card can be either wirelessly transmitted or easily read offline by a personal computer.

An accelerometer interface board is developed to allow *Martlet* to work with MEMS high-g accelerometers. The interface board powers the sensor at 3.3 V and incorporates onboard signal conditioning circuit, performing high-pass filtering, amplification, and low-pass filtering.

Figure 1 shows the functional diagram of the interface board. The differential output from the MEMS shock accelerometers is fed into the interface board. A second-order high-pass Bessel filter is first applied to minimize the zero-g offset before amplification. The filtered signals are then fed into an instrumentation amplifier to convert the differential signal to a single-ended signal with an amplification gain ranging from 1 to 1000. A second-order low-pass Bessel filter is applied to the amplified signal to reduce undesired noise. Lastly, the signal is sampled by the ADC module on the *Martlet* motherboard with a programmable acceleration trigger level.

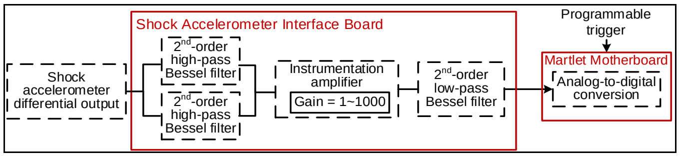



*Figure 1. Functional diagram of the shock accelerometer interface board.*

Figure 2 shows the *Martlet* wireless sensing unit, including the battery board, the motherboard and the interface board connected with a MEMS shock accelerometer. The dimension of the *Martlet* node is 2.5 in by 2.25 in. The accelerometer interface board can collect acceleration data from two MEMS high-g accelerometers simultaneously.

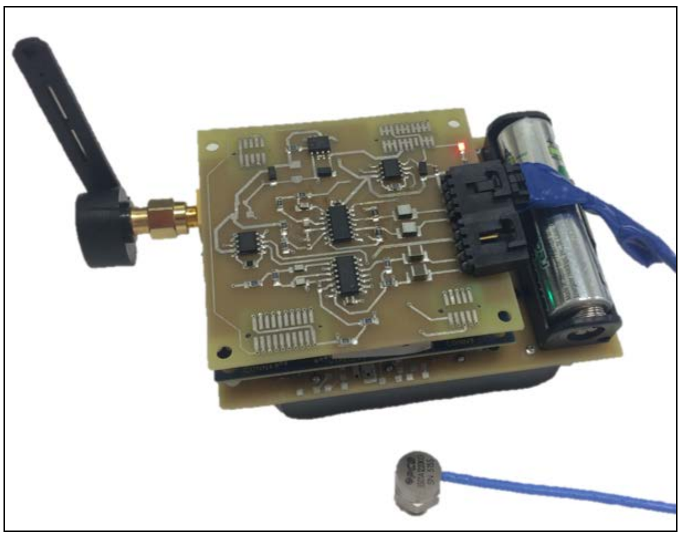


*Figure 2. A Martlet wireless sensing unit connected with a high-g shock accelerometer.*

### *2.2 Firmware Design*

To allow the *Martlet* unit to collect data from the high-g accelerometer during an impact test, a firmware program is developed (Figure 3). Initially, the RAM accessible by DMA module (32 k×16-bit) is subdivided into 100 memory blocks, 320×16-bit each. In an impact experiment, the sampling frequency can be set from 100 kHz to 1 MHz, which can be changed wirelessly on-the-fly. At the beginning of data acquisition, variable BlockNum is set as 0. Upon the start of data acquisition, the DMA module will store the data to the accessible RAM until filling up one memory block (320 data points). Afterwards, the DMA pointer will be moved to next memory block for data storage. Since the objective of this firmware programming is to collect acceleration response from an impact test, it is assumed that the response signal will have one peak followed by a decay. Therefore, during data acquisition, the *Martlet* node can have two possible statuses, PeakOccur=True or False.

When PeakOccur=False, it means that the impact has not taken place yet. In this case, the program constantly checks the data in the memory block with recently collected data. If a signal amplitude over certain trigger level is captured in the data block, the *Martlet* status will be changed to PeakOccur=True, and BlockNum will be set to 1. Otherwise, the *Martlet* node remains at PeakOccur=False and BlockNum stays at 0. In Figure 3, it should be noted that when detecting peak signal in the memory block, the data collection occurs in parallel, at the specified sampling frequency. As a result, the entire data acquisition process is continuous and not interrupted by peak detection process. When PeakOccur=True, it means that the impact has taken place, and the peak acceleration signal has been captured. As a result, the data in the recently collected memory block contains the impact. In this case, the data acquisition will continue until all of the 100 memory blocks are filled, i.e. BlockNum=100 (32 k data points in total). For example, if the sampling frequency is set to 100 kHz, 320 ms data will be collected by *Martlet* node. At the end of data acquisition, the collected data is saved to the onboard MicroSD card by default. In addition, same data can also be wirelessly transmitted to a computer server.

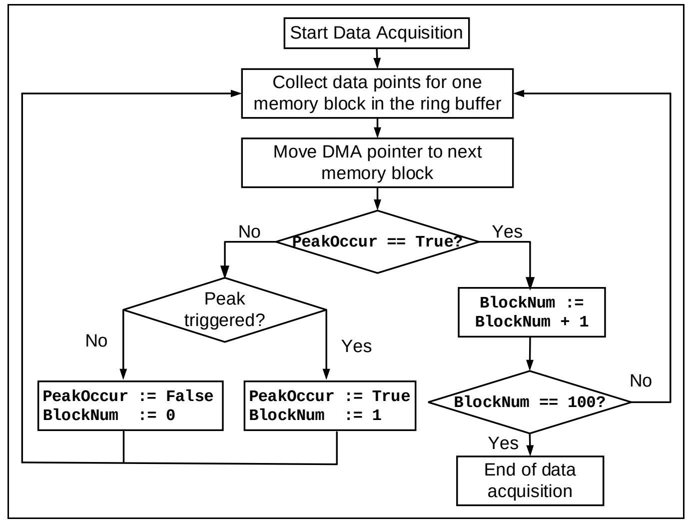



*Figure 3. Functional diagram of firmware programming.*

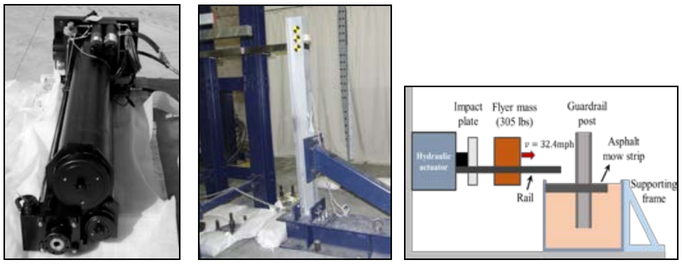
## 3 Experimental Validation

This section describes two experimental validations of the *Martlet* wireless sensing system used in high-g impact tests. Two different models of piezoresistive MEMS shock accelerometers are interfaced with *Martlet*, respectively. The measurement results obtained from the *Martlet* wireless sensing system are compared with the corresponding cabled sensing system.

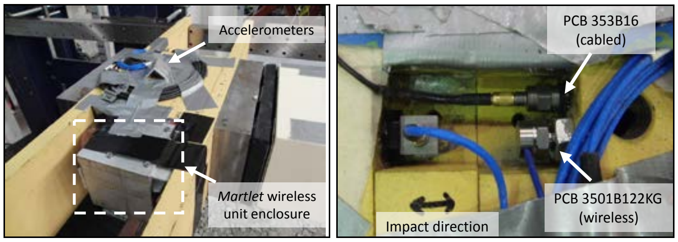
### *3.1 Guardrail Post Test*

*3.1.1 Test Setup*

The *Martlet* wireless sensing system is first validated in a guardrail post impact test using an ultra-fast hydraulic actuator at Georgia Institute of Technology. The actuator, shown in Figure 4(a) with combined control valves, accumulators and transducers, was designed to produce an impulsive load by impacting a test specimen with a mass in a controlled manner. The actuator is used in conjunction with appropriate loading media, which is attached to the variable masses and assists in the appropriate loading conditions for creating various shock-load environments on specimen[11]. In this test, a steel flyer mass, weighed 305 lbs and painted yellow, is accelerated by the actuator and impacts a steel guardrail post (Figure 4(b)) at a velocity of around 32.4 miles per hour (mph), as shown in Figure 4(c)[12]. After the initial impact, the mass flies freely and shortly afterwards hits onto the guardrail post, which is buried in compacted soil with an asphalt mow strip on top. Figure 4(d) and Figure 4(e) show the flyer mass and the close-up view of the accelerometers installed on the flyer mass. In this test, a cabled piezoelectric accelerometers (PCB 353B16) and a wireless accelerometer (PCB 3501B122 KG) are installed side by side on the flyer mass, measuring acceleration along the impact direction, indicated by the black arrow in Figure 4(e). The measurement results from these two accelerometers are compared.




(a) Ultra-fast hydraulic actuator; (b) Steel guardrail post; (c) Test setup illustration




(d) Flyer mass; (e) Wireless and cabled accelerometers

*Figure 4. Guardrail post test.*

The onboard signal conditioning of the wireless sensing system includes a 5 Hz 2nd-order high-pass Bessel filter, a 15 kHz 2nd-order low-pass Bessel filter and an amplification gain of 155. Table 1 shows the comparison of the wireless and cabled accelerometers used for the measurement comparison.

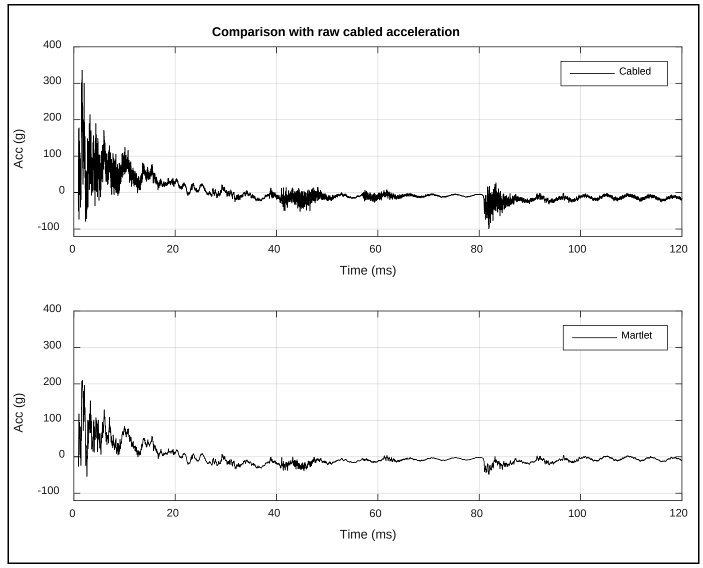
*3.1.2 Measurement Results*

The sampling frequency for both cabled and wireless measurements is set at 100 kHz. Before comparison, the two data sets are synchronized. The 120 ms of data after the initial impact are compared. Figure 5(a) shows the entire 120 ms raw acceleration measurement from the cabled and wireless (*Martlet*) sensors. Figure 5(b) shows the close-up comparison of two data sets during 0-15 ms, when the actuator hits the flyer mass. The peak acceleration on the flyer mass reaches over 300 g, and the shock duration estimated by 10%-peak crossings is about 0.86 ms. Figure 5(c) shows the close-up comparison in 80-95 ms, when the flyer mass hits the guardrail post.

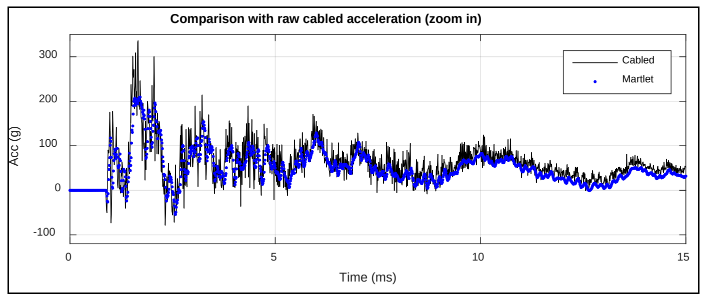
To obtain a better comparison, a numerical high-pass Butterworth filter of 1.2 Hz and low-pass Butterworth filter of 15 kHz are applied to the cabled acceleration measurements. Figure 6 shows the comparison after the filtering. Figure 6(b) and Figure 6(c) shows the close-up view of the signal from 0 ms to 15 ms and 80 ms to 95 ms. It can be seen that the signals from the cabled and *Martlet* wireless sensing systems match well, where the drift difference is possibly caused by the digital high-pass filter.

*Table 1. Accelerometer and DAQ comparison in the guardrail post test.*

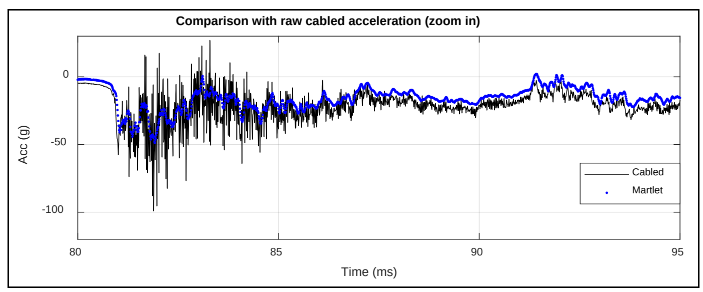
| | Wireless accelerometer with interface board | Cabled accelerometer |
|---|---|---|
| Model | PCB 3501B122 KG | PCB 353B16 |
| Range | ±210 g | ±500 g |
| Sensitivity | 8.0612 mV/g at 3.3 V | 10 mV/g |
| Frequency Bandwidth | 5 Hz~10 kHz | 1 Hz~10 kHz |
| RMS Noise | 0.1 g | 0.02 |




(a) Raw acceleration comparison

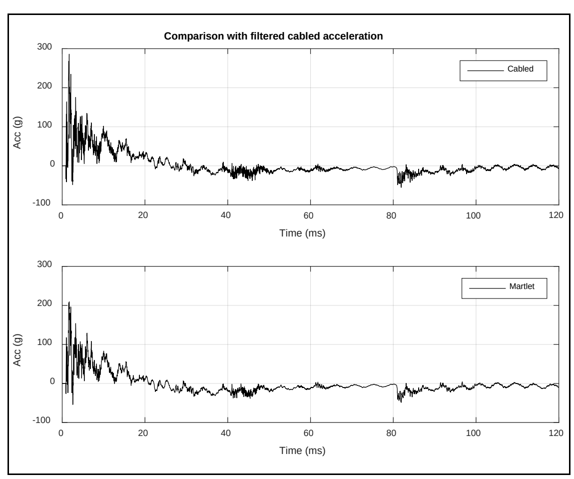



(b) Close-up view of raw accelerations: 0-15 ms

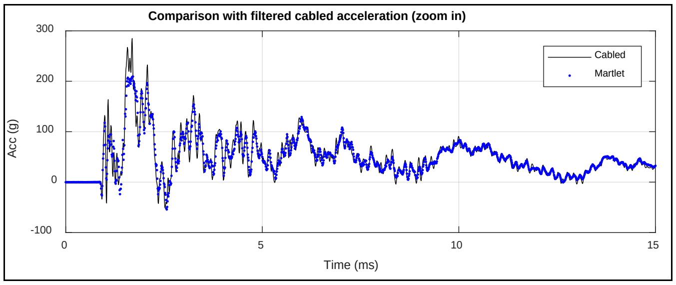



(c) Close-up view of raw accelerations: 80-95 ms

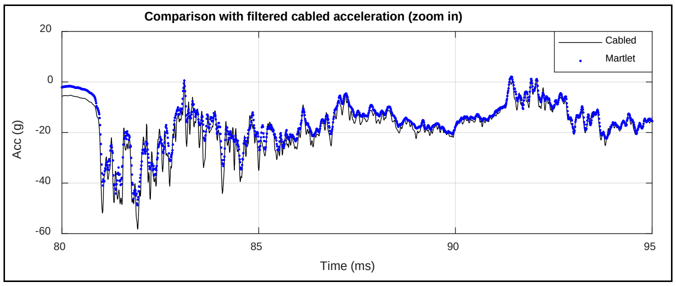
*Figure 5. Guardrail post test: Raw measurement comparison.*




(a) Filtered acceleration comparison




(b) Close-up view of filtered accelerations: 0-15 ms




(c) Close-up view of filtered accelerations: 80-95 ms

*Figure 6. Guardrail post test: Filtered measurement comparison.*

In addition, the root-mean-square difference $\Delta_T$ between the filtered cabled and wireless measurements in time domain is calculated as follows.

$$\Delta_T = \mathrm{RMS}(y - x) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} |y_n - x_n|^2} \tag{1}$$

where $x$ is the cabled measurement, $y$ is the wireless measurement, and $N$ is the number of data points for comparison.

Table 2 shows the values of $\Delta_T$ for 0-120 ms, 0-15 ms and 80-95 ms, respectively. The values of $\Delta_T$ are relatively small compared to the magnitudes of each time interval.

*Table 2. Time domain RMS difference between cabled and wireless measurements in the guardrail post test.*

| Time | 0-120 ms | 0-15 ms | 80-95 ms |
|---|---|---|---|
| $\Delta_T$ (g) | 6.55 | 12.85 | 3.46 |

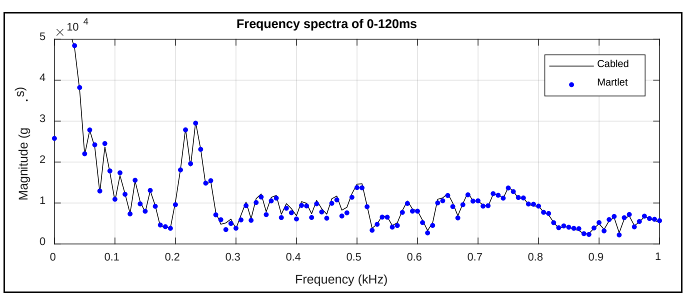



*Figure 7. Guardrail post test: Frequency spectra of filtered acceleration measurements.*

In order to further compare the performance of the two measurement systems, frequency spectra of the filtered signal are obtained using the entire data (0-120 ms), shown in Figure. It can be seen that the cabled and wireless sensing systems have comparable performance in frequency domain as well.

The root-mean-square difference between frequency spectra from 0-1 kHz is calculated as follows.

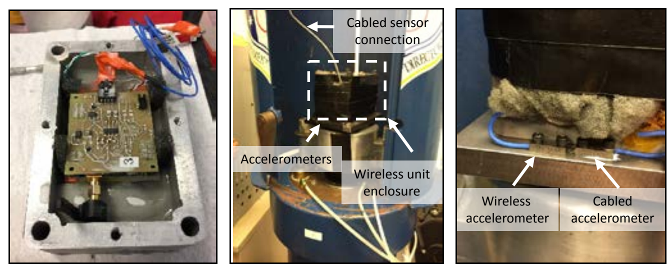
$$\Delta_F = \mathrm{RMS}(|Y - X|) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} |Y_n - X_n|^2} \tag{2}$$

where $X$ is the discrete Fourier transform of the cabled measurement, $Y$ is the discrete Fourier transform of the wireless measurement, and $|\cdot|$ is the magnitude of a complex number. In this test, $\Delta_F$ is found to be $0.114 \times 10^4$ g·s, which is relatively small compared to the magnitude of the frequency spectra.

### *3.2 VHG Shock Test*

*3.2.1 Test Setup*

Shock tests with varying magnitudes are later conducted with a Very High G (VHG) setup to validate the performance of the *Martlet* wireless sensing system. In these tests, the *Martlet* unit is protected by an aluminum enclosure filled with wax, as shown in Figure 8(a). The enclosure, together with the wireless and cabled shock accelerometers, is fixed on a steel plate and attached to the impact actuator. Figure 8(b) and Figure 8(c) show the test setup and a close-up view of the two accelerometers, which are placed side by side. The VHG machine uses a pneumatically fired piston to strike the steel plate from underneath and produce a large upward acceleration over a short duration. The amplitude and duration of the acceleration pulse can be adjusted through changing the air pressure used to fire the piston and using shock mitigating foam between the piston and the enclosure.



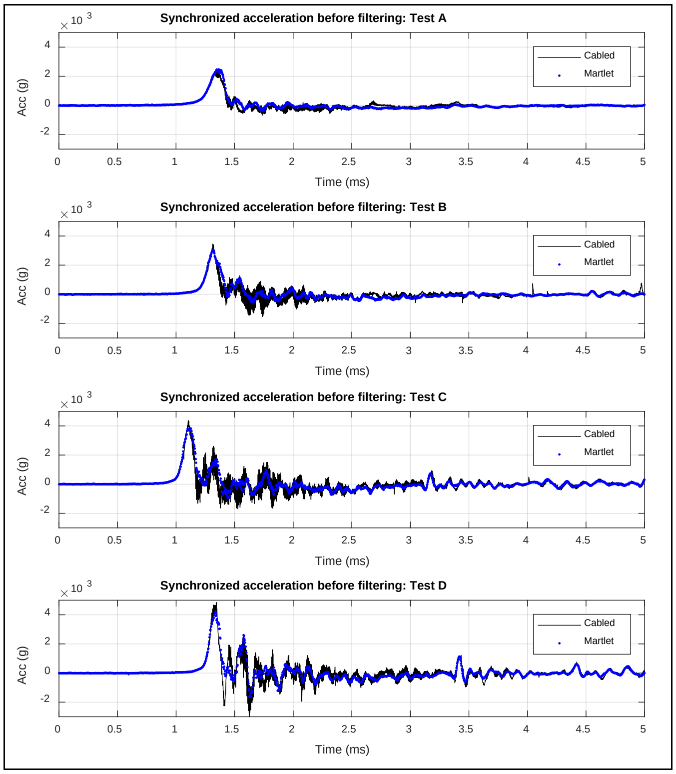

(a) *Martlet* enclosure; (b)Test setup; (c) Wireless and cabled sensors

*Figure 8. VHG test setup.*

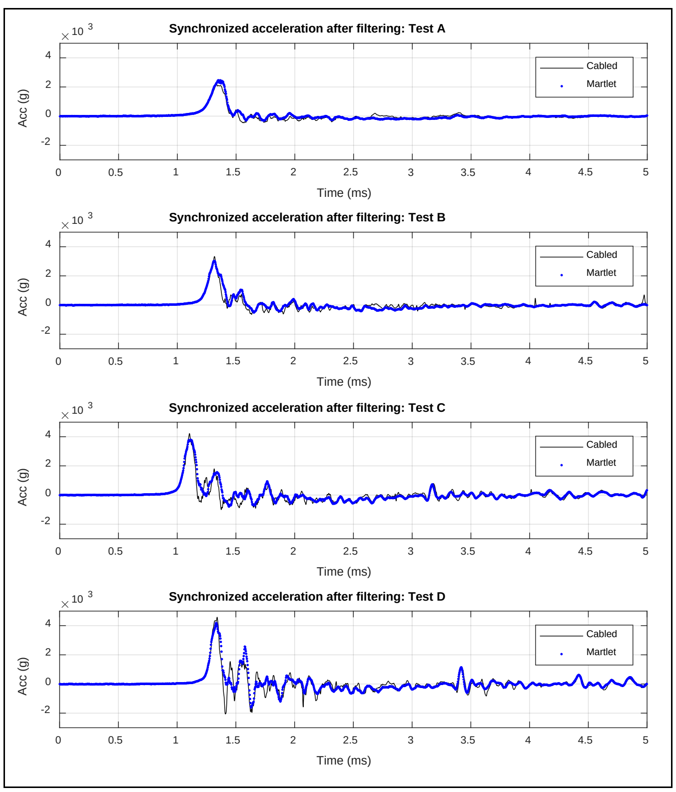
The accelerometers used in this test are both PCB 3991A1060 KG. Table 3 shows the detailed specification of the two accelerometers with wireless and cabled sensing system. Both sensors have been calibrated in house before testing. The wireless sensing system also performs on-board high-pass filtering at 0.28 Hz, low-pass filtering at 184 kHz and amplification gain of 64.

*Table 3. Accelerometer and DAQ comparison in the VHG test.*

| | Wireless accelerometer with interface board | Cabled accelerometer |
|---|---|---|
| Model | 3991A1060 KG SN3668 | 3991A1060 KG SN3678 |
| Range | ±29,000 g | ±60,000 g |
| Sensitivity | 0.0566 mV/g at 3.3 V | 0.00247 mV/g at 10 V |
| Frequency Bandwidth | 0.28~20 kHz | 0~20 kHz |
| Overload limit | ±100,000 g | ±100,000 g |
| Resonant frequency | >120 kHz | >120 kHz |
| Noise floor | 12.3 g | 12.3 g |




(a) Raw measurements

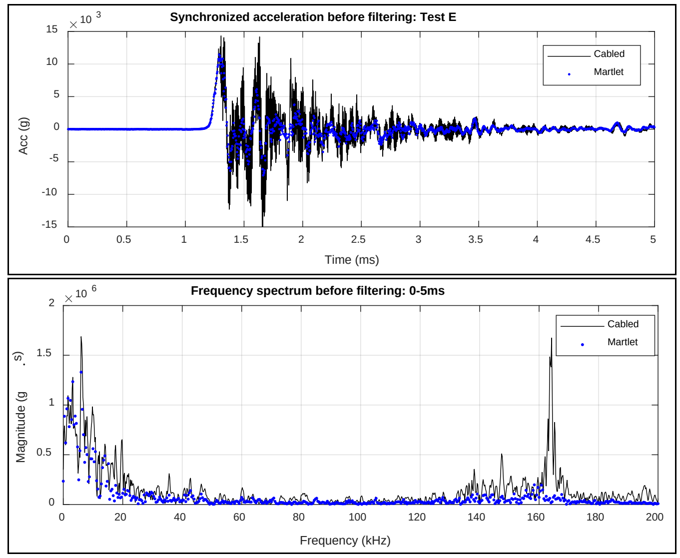



(b) Filtered measurements

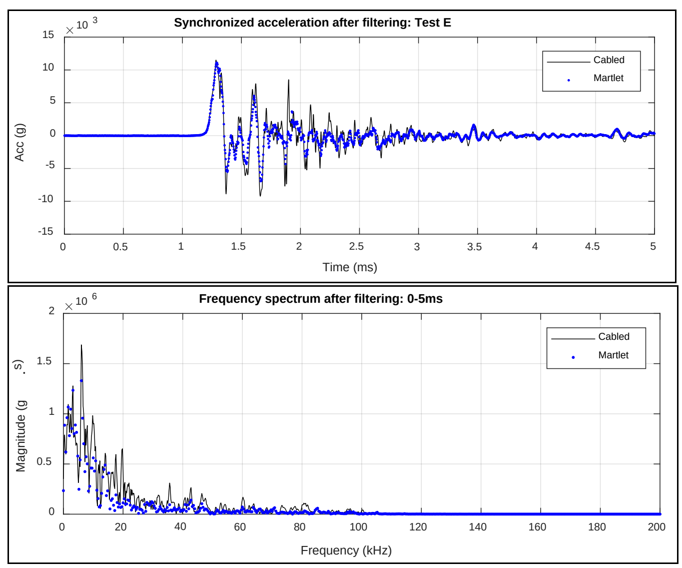
*Figure 9. VHG test: Raw and filtered measurement comparison (shocks below 5,000 g).*

*3.2.2 Measurement Results*

The following shows the acceleration measurement results of the cabled and wireless sensing system under different excitation magnitudes, ranging from 2,000 g up to 15,000 g. The sampling frequency is 1 MHz for the wireless system and 2 MHz for the cabled system. The cabled and wireless measurement results are first low-pass filtered at 100 kHz for synchronization. Because the wireless and cabled DAQ systems have different signal conditioning hardware, the synchronized data sets are then compared using both unfiltered and digitally filtered cabled measurements, respectively. Figure 9 shows four sets of result comparison, with peak accelerations gradually increasing from 2,500 g to 5,000 g. The shock duration estimated by 10%-peak crossings is about 0.275 ms in Test A, and gradually reduces to 0.162 ms in Test D. It can be seen that the wireless measurements generally match well with the cabled measurements, particularly after digital filtering.




(a) Raw measurements




(b) Filtered measurements

*Figure 10. VHG test: Raw and filtered measurement comparison (15,000 g shock).*

In addition, Figure 10 shows the measurement comparison in both time domain and frequency domain as the peak acceleration reaches around 15,000 g. The shock duration estimated by 10%-peak crossings is about 0.142 ms. It can be seen that after low-pass digital filtering, the wireless measurement matches with the cabled measurement. Note that in the frequency spectrum of the unfiltered cabled measurement (Figure 10(a)), the accelerometer connected to the cabled sensing system has possibly reached its resonant frequency at around 165 kHz, which results in the high-frequency noise in the raw cabled measurement. As a result, the difference between the wireless and cabled measurements is larger than those of previous tests.

Using Equations (1) and (2), RMS differences $\Delta_T$ and $\Delta_F$ between the filtered cabled and wireless measurements are calculated for Test A-E, and shown in Table 4. Specifically, the time domain RMS difference, $\Delta_T$, is calculated for the first 5 ms. The frequency domain RMS difference, $\Delta_F$, is calculated up to 100 kHz. The values of $\Delta_T$ and $\Delta_F$ are relatively small compared to the magnitudes of the corresponding measurements.

*Table 4. RMS differences between cabled and wireless measurements in the VHG test.*

| Test Name | Test A | Test B | Test C | Test D | Test E |
|---|---|---|---|---|---|
| Time domain $\Delta_T$ ($\times 10^3$ g) | 0.118 | 0.166 | 0.234 | 0.287 | 1.015 |
| Frequency domain $\Delta_F$ ($\times 10^6$ g $\cdot$ s) | 0.017 | 0.025 | 0.036 | 0.045 | 0.160 |

**4 Conclusions**

In this study, the performance of the *Martlet* wireless sensing system in high-g shock tests is validated. The wireless data acquisition system design and the corresponding firmware development for high-g impact tests are described. Two different experiments have been carried out to demonstrate the promising performance of the *Martlet* sensing system. The wireless measurement results are compared with corresponding cabled measurements in both time domain and frequency domain. Overall, the *Martlet* system shows robust shock survivability and comparable performance as the cabled system. A second version of the shock accelerometer interface board is currently under development to enable programmable filter frequencies and amplification gain, which will make it possible to change signal conditioning settings on-the-fly for different tests.

**References**

1. Lynch, J. P., Law, K. H., Kiremidjian, A., Farrar, C. R., Sohn, H. et al., “Design and performance validation of a wireless sensing unit for structural health monitoring applications,” Structural Engineering and Mechanics, Vol. 17, pp. 393-408, 2004.
2. Wang, Y., Lynch, J. P., Law, K. H., “A wireless structural health monitoring system with multithreaded sensing devices: Design and validation,” Structure and Infrastructure Engineering, Vol. 3, No. 2, pp. 103-120, 2007.
3. Swartz, R. A., Jung, D., Lynch, J. P., Wang, Y., Shi, D. et al., “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, USA, 2005.
4. Rice, J. A., Mechitov, K., Sim, S. H., Nagayama, T., Jang, S. et al., “Flexible smart sensor framework for autonomous structural health monitoring,” Smart Structures and Systems, Vol. 6, pp. 423-438, 2010.
5. Dong, X., Liu, X., Wright, T., Wang, Y., DesRoches, R., “Validation of wireless sensing technology densely instrumented on a full-scale concrete frame structure,” Proceedings of International Conference on Smart Infrastructure and Construction (ICSIC), Cambridge, United Kingdom, 2016.
6. Kane, M., Zhu, D., Hirose, M., Dong, X., Winter, B. et al., “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, 90611U, San Diego, California, USA, 2014.
7. Liu, X., Dong, X., Wang, Y., “Field testing of *Martlet* wireless sensing system on an in-service pre-stressed concrete highway bridge,” Proceedings of SPIE 2016, Health Monitoring of Structural and Biological Systems, Las Vegas, NV, USA, 2016.
8. Chen, S., Dong, X., Kim, J. Y., Wu, S., Wang, Y., “Design and performance validation of a compact wireless ultrasonic device for localized damage detection,” Advances in Structural Engineering, Vol. 19, No. 2, pp. 270-282, 2016.
9. Liu, X., Dong, X., Wang, Y., Stewart, L., Dodson, J. et al., “High-g shock acceleration measurement using *Martlet* wireless sensing system,” Proceedings of the 36th International Modal Analysis Conference (IMAC XXXVI), Orlando, FL, USA, 2018.
10. Texas, Instruments, “CC2520 datasheet: 2.4 GHz IEEE 802.15. 4/Zigbee RF Transceiver,” Texas Instruments, Dallas, Texas, USA, 2007.
11. Stewart, L., Durant, B., Wolfson, J., Hegemier, G., “Experimentally generated high-g shock loads using Hydraulic Blast Simulator,” International Journal of Impact Engineering, Vol. 69, pp. 86-94, 2014.
12. Lee, S. H., “Static and dynamic assessment of the influence of asphalt layers on the structural response of steel guardrail posts,” Georgia Institute of Technology, 2017.

The author can be reached at: yang.wang@ce.gatech.edu.