COVER SHEET

Title: *A Novel Wireless Acceleration Evaluator used for Health Monitoring of Aging Structures and Bridges.*

Proceedings of the **10th International Workshop on Structural Health Monitoring (IWSHM) 2015**

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ABSTRACT

Control aging structures and infrastructures is of importance as these systems may have economic and strategic relevance. Develop reliable and accurate instruments for monitoring the structural dynamic behavior plays a key role in predicting the onset of possible crisis scenarios. Recent advances in technology have made wireless Micro Electro-Mechanical System (MEMS) accelerometers an attractive tool for Structural Health Monitoring (SHM). In this paper, the Acceleration Evaluator (ALE) - a low cost, high sensitivity, wireless prototype sensor board installing a MEMS-based accelerometer - is used as a stand-alone sensor for the vibration monitoring of large-sized civil structures. In particular, two cases of study are reported. The first one consists of the earthquake induced vibration measurements on a real-size lab model. It is a 2,500 Kg, 3 meter high stone pinnacle of the Saint Peter and Saint Paul Cathedral Church (Washington National Cathedral) in Washington, D.C. Data collected using ALE are used for a back to back comparison with those recorded with wire-based, high-sensitivity devices. The evaluations carried out in time and frequency domains (e.g. peak ground acceleration, Arias' intensity, and excited frequencies) are used to determine the measurements accuracy in comparison with standardized and well-known devices. The second analysis is performed on a 104 meter pedestrian deck-stiffened arch bridge, located on the Princeton University campus in Princeton, NJ. The study aims to validate ALE performances in a real-world scenario. Recorded data are analyzed and compared with those reported in literature studies for the bridge. The results from both tests are examined to prove that ALE can be used as vibration monitoring devices to detect accelerations having amplitude in the order of 10^{-2} $m \cdot s^{-2}$ (ambient vibrations) as well as accelerations having amplitude in the order of 10^{0} $m \cdot s^{-2}$ (strong earthquakes). To conclude, the future works on the sensor board are described.

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INTRODUCTION

The process of controlling changes to the behavior of a structural system is referred to as structural health monitoring (SHM) [1, 2]. Complex structures, which are of valuable importance both economically and strategically, require cost effective inspection and preservation. Monitoring may prevent the structure from being jeopardized. Furthermore, detecting damages at an early stage can reduce the maintenance costs and repairs down time.

Several methods for controlling structures have been developed. They range from visual inspections to sensor arrays for nearly real-time damage detection. Despite its low-cost, visual inspection may be subjective and depends on the experience of the professional performing the survey [3]. On the other hand, wired sensor-based monitoring is relatively expensive and sometimes difficult to install. Micro Electro-Mechanical System (MEMS) and wireless communication have improved the possibility of controlling structures. Wireless transmission, compared to its wire-based counterpart, allows for an easier management of the monitoring systems [4]. It prevents from triboelectric noise, from installing signal amplifiers, as well facilitating the monitoring system's installation. MEMS-based sensors, due to their small dimension and low cost, allow employing non-invasive and widely diffused sensor-arrays on the structure [5]. Wireless and MEMS technologies are not entirely new and many uses have already been successfully tested [6, 8]. Nevertheless, SHM and vibration monitoring applications require the MEMS-based sensors to be accurate on a wide range of low frequency accelerations: from ambient to severe earthquake-induced vibrations [9]. Furthermore, civil engineering applications, requires high duty-cycle and large recorded data volume [4]. It increases difficulties of using wireless MEMS-based devices for SHM.

In this study, a novel wireless sensor board, embedding a MEMS-based accelerometer, is used for performing vibration monitoring analyses. The prototype is tested to prove if it can achieve the same measurement accuracy obtained when traditional sensors (e.g. piezoelectric accelerometers, laser transducers, etc.) are employed. The Acceleration Evaluator (ALE) is tested both with high-amplitude (10^0 $m \cdot s^{-2}$) and small-amplitude (10^{-2} $m \cdot s^{-2}$) vibrations. In particular, ALE is used in two experiments. The first one is a back-to-back comparison with wire-based sensors in measuring the earthquake-induced vibration on a stone pinnacle of the Washington National Cathedral. The second test is a vibration measurement performed on a bridge. Results show that ALE detects vibrations with a maximum error of 1% in time domain and less than 2% in frequency domain when comparisons with wire-based devices are performed. The rest of this paper is organized as follows. A first section compares ALE main features with those of other MEMS-based sensor boards. Then, a description of the tests performed, together with a discussion of results, is given. To conclude, ALE future developments are anticipated.

WIRELESS SENSOR BOARDS FOR VIBRATION MONITORING

ALE joins several other sensor boards for vibration monitoring. Besides the sensing element (i.e. accelerometer), the sensor system measurement performances also depend on the used data conversion technique. In this section, an overview of some sensor boards developed for vibration control is provided. Then, ALE features and laboratory-evaluated performances are described.

Sensor Boards Evolution and State-of-the-art

Over the last decade, several academia-built and commercial MEMS-based wireless sensor boards have been built [10]. One of the first one was the Mica-series mote [11], which embedded a low-cost, high noise-floor level sensor (i.e. ADXL202 by Analog Devices, Inc.) and a 10-bit Analog to Digital Converter (ADC). Achievable resolution ($92.08\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$) was too coarse for micro-vibration monitoring [4, 12]. Furthermore, this system operated on unregulated battery voltage, a characteristic that limited sensor readings and radio transmission [13, 14]. Improvements consisted in changing the accelerometer with a more sensitive one (i.e. SD-1221L by Silicon Design, Inc.), an operation which allowed to achieve a nominal resolution of $1.24\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$. Nevertheless, maintaining the 10-bit ADC, the effective resolution of the whole system was $23.94\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$ [15]. Thus, the board's next generation was designed using higher resolution converters (i.e. commercial and customized 16-bit ADCs), which allowed achieving a resolution of $0.37\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$. As can be observed, the limiting factor to the measurement accuracy became the accelerometer itself (resolution of $1.24\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$). For this reason, sensors bandwidth and measurement range were decreased to improve accelerometer's resolution (i.e. $0.31\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$ [16] and $0.37\cdot 10^{-3}\ \mathrm{m\cdot s^{-2}}$ [17]) matching it to that of the installed ADC.

ALE Features

The ALE prototype consists of a transmitter board and a receiver board. The transmitter embeds an accelerometer SiFlex 1600SN.A by Colibrys Ltd. (SF1600), a voltage stabilizer, an offset trimmer, a Voltage-To-Frequency (V/F) converter, a voltage buffer amplifier, a 2.4 GHz Industrial Scientific and Medical (ISM) antenna, and it is powered using a ± 12V battery. The receiver consists of a 2.4 GHz ISM antenna, tuned on the same frequency of the transmitter, a Frequency-to-Voltage (F/V) converter, a signal amplifier, and a voltage stabilizer as shown in Figure 1. The receiver output is connected to an external 24-bit Data Acquisition (DAQ) board. The DAQ is connected to a computer, which is used both for downloading data and powering the receiver through the Universal Serial Bus (USB) port.

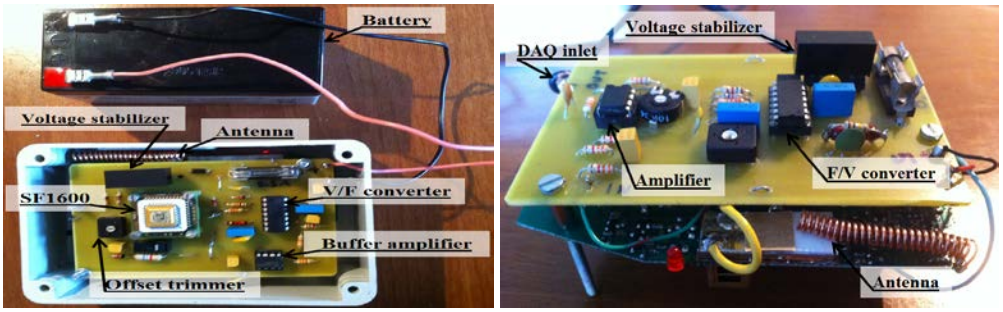


Figure 1. ALE transmitter (left) and receiver (right) prototype boards with main features highlighted.

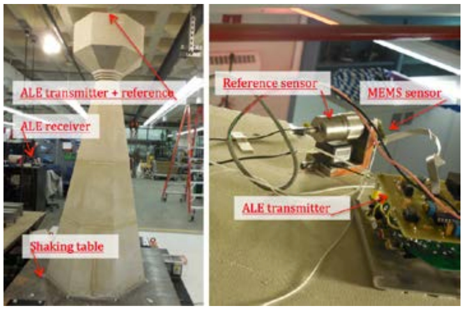
The use a V/F converter depends on the SF1600 features, which would be nullified if an ADC having resolution lower than 24-bit would be used. Furthermore, this converter permits a signal more immune to noise [18]. ALE laboratory tests proved it detects vibration with frequency as low as 0.2 Hz and Root Mean Square (RMS) amplitude of $1.60 \cdot 10^{-2}$ $m \cdot s^{-2}$. Error committed is below 2% when a comparison with equal-resolution Integral Electronic PiezoElectric (IEPE) accelerometers is performed [19, 20]. Furthermore, using the V/F converter is possible to maintain the sensor's whole bandwidth (0.2 - 1500 Hz) and sensing interval (± 29.42 $m \cdot s^{-2}$).

COMPARATIVE TESTS ON AGING AND LARGE-SIZED STRUCTURES

To verify ALE efficacy in measuring vibration, several tests on civil structures were carried out. In particular, vibration measurements on aging structures (stone pinnacle) and large-sized structures (pedestrian bridge) were performed.

Stone Pinnacle Vibration Monitoring

In this experiment, ALE was used to measure the earthquake-induced vibrations on a special lab-scale model stone pinnacle of the Washington National Cathedral. ALE records were compared with those of a wire-based IEPE accelerometer (i.e.: PCB 39B04 by PCB Piezotronic, Inc.) as the pinnacle, deployed on a shaking table, was subjected to an uniaxial acceleration Time History (TH) input. It corresponds to the 60% of the record taken from the Reston, VA seismograph station on August 23rd, 2011.



PGA	$(m \cdot s^{-2})$	2.281
I_A	$(m \cdot s^{-1})$	0.474
f_1	*(Hz)*	0.763
f_2	*(Hz)*	1.367
f_3	*(Hz)*	3.910

Figure 2. Pinnacle model (left), sensors deployment (center), and earthquake main features (right).

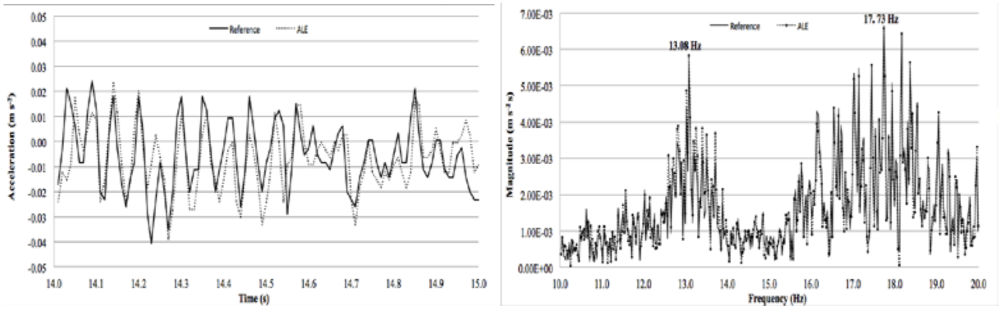


Figure 3. Comparison of measurements by the two sensors in time (left) and frequency (right) domains - low-amplitude vibration.

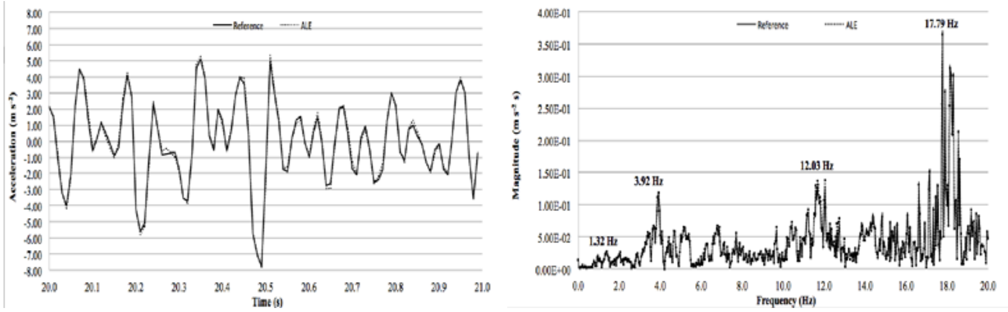


Figure 4. Comparison of measurements by the two sensors in time (left) and frequency (right) domains - high-amplitude vibration.

TABLE I. SUMMARY OF THE STONE PINNACLE VIBRATION MONITORING TEST

Quantity		Reference	ALE	ε (%)
PGA	$(m \cdot s^{-2})$	7.802	7.793	-0.10
I_A	$(m \cdot s^{-1})$	7.463	7.445	-0.25
f_1	(Hz)	1.319	1.319	
PSD_1	$(m \cdot s^{-2} \cdot s)$	$2.270 \cdot 10^{-2}$	$2.312 \cdot 10^{-2}$	1.85
f_2	(Hz)	3.916	3.916	
PSD_2	$(m \cdot s^{-2} \cdot s)$	$1.176 \cdot 10^{-2}$	$1.191 \cdot 10^{-2}$	1.28
f_3	(Hz)	13.078	13.078	
PSD_3	$(m \cdot s^{-2} \cdot s)$	$5.788 \cdot 10^{-3}$	$5.822 \cdot 10^{-3}$	0.67
f_4	(Hz)	17.732	17.732	
PSD_4	$(m \cdot s^{-2} \cdot s)$	$6.638 \cdot 10^{-3}$	$6.591 \cdot 10^{-3}$	-0.71

Figure 2 shows the 2,500 Kg, 3-meter high lab-scale model used in the test, the sensors deployment (compliant to [21]), and the earthquake TH main features (e.g. Peak Ground Acceleration PGA, Arias Intensity I_A, fundamental frequencies f_i). Figure 3 and 4 plot the THs recorded with the two sensors at two different times, together with their correspondent frequency response by Power Spectral Density (PSD). Figure 3 refers to the low-amplitude vibrations (RMS $2.08 \cdot 10^{-2}$ $m \cdot s^{-2}$) produced by the shaking table supporting machineries such us pumps and oil circuits. Figure 4 refers to the earthquake-induced vibration (RMS $2.56 \cdot 10^{0}$ $m \cdot s^{-2}$). Obtained results are compared in Table I, where an excellent match is observed. The relative error, ε committed on PGA and I_A values are equal to -0.10% and -0.25% respectively. Same conclusion can be draft for frequency domain analyses. The signal retrieved using ALE highlights the exact same frequencies of that detected using the reference sensor. Furthermore, the magnitude's relative error is on average equal to 1.13%. It proofs that ALE can detect the peak, the energy, and the spectral composition of a vibration acting on a system with the same accuracy of a high sensitivity, wire-based, IEPE accelerometer.

Pedestrian Bridge Vibration Monitoring

In the second experiment, ALE was used for monitoring the ambient vibration on the Streicker Bridge. It is a 104-meter long, reinforced post-tensioned concrete, deck-stiffened arch bridge, located on the Princeton University campus (Figure 5) [22]. Literature data are available for comparison as several studies and Finite Element Model (FEM) analyses were performed on the bridge. In particular, the bridge's natural frequencies resulted equal to 3.11 ± 0.06, 3.17 ± 0.06, 3.72 ± 0.06 Hz (from experimental analyses), and equal to 3.22 and 3.92 Hz (from FEM analyses) [23].

During the test, the ALE transmitter was deployed on the bridge's southeastern approach ramp; whereas the receiver on the road surface, nearly 15 meters away [21]. The wirelessly transmitted sensor output signals, caused by vibration induced by traffic on the bridge (e.g. people, bikes, and small karts), were acquired with a 30 Hz sampling rate using the external DAQ device connected to the receiver board. Recorded data were analyzed in time and frequency domains and compared with literature-available data.

Figures 6 plots a detail of the TH and the correspondent frequency response by PSD. Despite oscillations have extremely low amplitude (RMS $1.64 \cdot 10^{-2}$ $m \cdot s^{-2}$); the MEMS-based accelerometer sensor board can clearly identify them. Furthermore, analysis in frequency domain highlights the values of 3.08 and 3.73 Hz as the first two natural frequencies of the bridge. It can be observed that the frequencies are close to those evaluated in previous studies performed on the bridge. As listed in Table II, correspondence is verified both for experimental records (3.11 ± 0.06 and 3.72 ± 0.06 Hz) and computational data obtained through FEM (3.22 and 3.92 Hz). The relative errors committed, equal on average to -0.61% and 4.60% respectively, are negligible in engineering practice.

Figure 5. Streicker Bridge down-view (left) and ALE deployment (right).

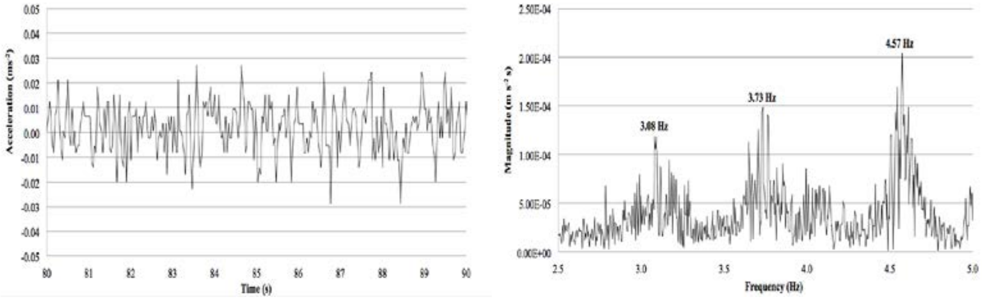


Figure 6. Detail of the TH (left) and frequency response by PSD (right) recorded on the bridge.

TABLE II. SUMMARY OF THE PEDESTRIAN BRIDGE VIBRATION MONITORING TEST

Test *(-)*	f_1 *(Hz)*	f_2 *(Hz)*	$\varepsilon_{,\,f1}$ (%)	$\varepsilon_{,\,f2}$ (%)
ALE	3.08	3.73		
Literature [23]	3.11	3.72	-0.96	0.26
FEM [23]	3.22	3.92	-4.35	-4.85

CONCLUSIONS

Wireless MEMS-based boards have proved to be an excellent alternative to wire-based accelerometers when a vibration monitoring has to be performed. In this paper, a novel system (ALE) is validated through extensive tests on large-sized civil structures. In particular, it was used for recording the earthquake-induce vibrations on a 2,500 Kg, 3-meter high stone pinnacle model of the Washington National Cathedral and for recording the ambient vibration on the Streicker Bridge, a pedestrian bridge located on the Princeton University campus.

In the first test, recorded data were compared with those obtained using wire-based IEPE accelerometers. Results have shown that no significant differences exist between the two data sets. Equivalence is proved for maximum acceleration detected (PGA), energy released (I_A), and excited frequencies. The maximum relative error committed in frequency domain analysis is equal to 1.85%, a value admissible in engineering practice. In the second test, recorded data were compared with those available in literature for the bridge. The results demonstrated ALE accuracy in measuring vibration relevant to civil engineering structures, including those of low-frequency (nearly 3 Hz) and low-amplitude ($1.64 \cdot 10^{-2}$ $m \cdot s^{-2}$), with a maximum committed error of -0.96%.

Both tests have proved ALE can be used as stand-alone alternative to currently used devices for vibration monitoring. Therefore, these results may conduce to develop a novel monitoring system, which can accurately detect vibration without interfering with functions and architectural features of aging and large-sized structures. An interesting and powerful development of ALE is the future possibility to use it as sensing node within a Wireless Sensor Network (WSN). That is: transforming the prototype from a stand-alone sensing device to a sensing node in a smart sensors network. It may include the construction of a star-type topology where more nodes (i.e. ALE sensor boards) interact with a common base station and the achievement of more complex topologies, where the node interacts with the base station as well with other nodes [24].

AKNOWLEDGMENT

The author would like to thank Carleton Laboratory’s staff at Department of Civil Engineering and Engineering Mechanics (CEEM) of the Columbia University - NY for assistance given in the stone pinnacle test. Furthermore, many thanks are own to Professor Branko Glisic, Doctor Dorotea Sigurdardottir and Doctor Hiba Abdel-Jabber from the SHMlab at Department of Civil and Environmental Engineering (CEE) of the Princeton University - NJ, for allowing the author to deploy ALE on the pedestrian bridge and sharing the results of their researches.

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