Pedestrian bridge vibration monitoring using a wireless MEMS accelerometer board

Alessandro Sabato
Laboratorio di Tecnica del Controllo Ambientale
Dipartimento di Ingegneria Meccanica, Energetica e Gestionale (DIMEG) – University of Calabria
87036 Rende (CS), Italy
sabatoale@gmail.com

Abstract— **In recent years, growing interest has been aroused by the possibility of monitoring wirelessly the dynamic response and the state of aging infrastructures. Micro Electro-Mechanical System (MEMS) based equipment has revealed to be an emerging technology for vibration monitoring of large-sized civil structures such as bridges and buildings. Once problems related to the MEMS-based sensors resolution at very low-frequency and low-amplitude vibrations were solved, they have provided a low-cost and small alternative to the traditionally used wire-based devices. In this study, a newly designed wireless, MEMS-based, accelerometer board (Acceleration Evaluator, ALE) is used as stand-alone sensor for carrying out a vibration analysis on a pedestrian deck-stiffened arch bridge. Through an extensive series of quasi-static and dynamic tests, it is proved that the developed sensor board can be used as reliable devices to obtain measurements comparable with those obtained when equivalent-accuracy devices (i.e. Integral Electronics PiezoElectric (IEPE) accelerometers) are used for modal frequencies and dynamic parameters change analyses and damage detection.**

Keywords—Acceleration measurement, MEMS sensor, prototype validation, structural health monitoring, vibration measurement, wireless accelerometer.

I. INTRODUCTION

The monitoring process of structures state to detect damages, which can characterize the arising of crisis scenarios, is defined Structural Health Monitoring (SHM). Several methods for controlling aging structures have been developed. Nevertheless, with reference to bridges one of the mainly used still consists of visual inspection. It is clear that this technique may be subjective, depending on the experience of the technician that carries out the survey. Furthermore, it lacks of quantifiable parameters to decide weather or not the structure is close to its designed lifetime [1]. On the other hand, currently employed non-visual methodologies use wire-based sensors, which are relatively expensive [2]. Nevertheless, the poor state of several bridges worldwide (e.g. [3]), address the importance of reliable monitoring systems for preventing crisis scenarios and collapses similar to that happened in 2007 to Bridge 9340 in Minnesota, MN.

Nowadays, because of technological advancement in Micro Electro-Mechanical System (MEMS) technologies, it is possible employing small and inexpensive sensors for detecting the state of civil structures. In addition, the possibility of transmit data wirelessly through a Wireless Sensor Network (WSN), frees technicians from limitations due to cable connections. This for at least three reasons: a) wires impedance and quality of the signal, b) noise produced and c) mounting facility. The first of these reasons is connected to a technological limitation due to cables length. Connection wires between a sensor and the acquisition system require being well isolated and with low-noise. In addition, their length cannot exceed a few meters of extension, because of signal impedance [4], which requires the system to install amplifiers. The second reason is connected to the noise introduced in signals due to the wire itself (triboelectric noise). It can create problems when signals having low-amplitude - such as those characterizing the vibration of large civil structures - are analyzed. Triboelectric noise is produced because of mechanical movements of the wire itself and it is characterized by the generation of local currents which can interfere with transmitted signals. Fixing the cable on a stable support can significantly reduce the noise, but such an operation is not always feasible or easy to achieve. This last consideration introduces the third problem, which is connected to wire deployment. Often, it is extremely difficult to manage several cables. This operation is challenging because of the geometry of the monitored structure or because wires can interfere with the structure's functionality. Furthermore, in-situ wires can easily be damaged during the different phases of work. For these reasons particular care must be taken during cables positioning. Installation time and efforts are significantly reduced when a wireless system is used compared to its wire-based counterpart. It is easy to understand why signals retrieval using wireless transmissions have their advantages, especially where wiring connections are difficult or impossible.

The idea of controlling dynamic parameters through vibration monitoring analyses is effective for preventing from crisis scenarios. Indeed, deterioration or damage of a structure leads to changes in its structural characteristics such as mass

---

This research is part of a Ph.D. program funded at University of Calabria, Italy by European Union social founds (FSE – Fondo Sociale Europeo) within the POR Calabria FSE 2007 – 2013 project.

Alessandro Sabato received a Ph.D. in Mechanical Engineering from University of Calabria, 87036 Rende (CS), Italy. He was visiting Ph.D. student and Staff Associate at Columbia University in the City of New York, NY 10025 USA from March 2103 through June 2014. (e-mail: sabatoale@gmail.com).

and stiffness. They are reflected thorough changes in dynamic parameters such as the natural frequency of the structure itself [5]. Therefore, in the last years - once problems connected to sensors low-accuracy [6], [7] at the important low-frequency and low-amplitude vibrations have been solved - the wireless MEMS-based systems have proved their reliability for being used as SHM sensor [8], [9] and for bridge monitoring purposes in particular [10], [11].

In this study, a vibration monitoring application performed on a pedestrian bridge is reported. It is carried out using a newly designed wireless system (Acceleration Evaluator, ALE), which embeds a MEMS-based accelerometer. The study aims to prove whether or not ALE can achieve traditional SHM analyses for ambient vibration detection and modal identification. Performed tests aim to verify if ALE can be used as a low-cost alternative to currently used wire-based Integral Electronics PiezoElectric (IEPE) accelerometers. The rest of this paper is organized as follows. After a section II, which describes the accelerometer board features together with the related systems state-of-the-art; the results of the pedestrian bridge experiments are evaluated and discussed in section III. In the conclusions, a quantitative description of ALE enhancements compared to other vibration detection wireless sensor boards are presented and future work is anticipated.

II. SHM Boards State-Of-The-Art And ALE Features

A. *Related works*

ALE joins several sensor board prototypes for vibration detection. Among the others, those of Kurata el al. [7], Ruiz Sandoval et al. [12], Pakzad et al. [8], and Jo et al. [9] are the most interesting ones. For a detailed discussion on developed boards for SHM purposes, the interested reader can consult the review article by Lynch at al. [13]. In their research Kurata et al. [7] used a low-cost, high noise-floor level sensor (i.e. ADXL202) and a 10-bit Analog to Digital Converter (ADC) embedded on a commercial mote board platform. The board could detect only high-amplitude vibrations, a resolution not SHM-suited. Ruiz-Sandoval et al. [12] modified the accelerometer with a more sensitive one (i.e. SD-1221L) maintaining the same 10-bit ADC. The decision to use a low-accuracy ADC limited the board resolution to $23.94 \cdot 10^{-3}$ $m \cdot s^{-2}$. On the contrary, Pakzad et al. [8] proposed to use the SD-1221L accelerometer implementing the board with a 16-bit ADC. In this case, the limiting factor to the measurement resolution was the sensor, which had a resolution of $1.24 \cdot 10^{-3}$ $m \cdot s^{-2}$. Thus, sensor bandwidth and measurement range were decreased to improve accelerometer resolution. This operation allowed matching sensor resolution with that of embedded ADC ($0.37 \cdot 10^{-3}$ $m \cdot s^{-2}$), improving measurements quality. Analogously, Jo et al. [9] in their study with a customized design 16-bit ADC, artificially reduced the sensing range and the bandwidth for achieving a resolution of $0.43 \cdot 10^{-3}$ $m \cdot s^{-2}$ and a lower frequency limit of nearly 1 Hz.

B. *ALE Characteristics*

ALE is made of two components: a transmitter and a receiver unit as show in the block diagrams of Figure 1.

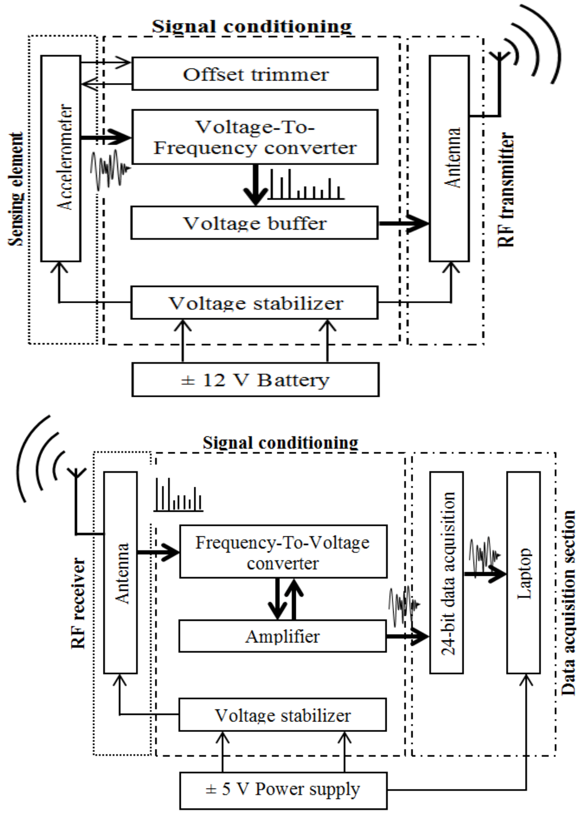

Fig. 1. ALE transmitter (up) and receiver (down) functional diagrams

The transmitter is equipped with the sensing element (a SiFlex 1600SN.A accelerometer manufactured by Colibrys Ltd.), a signal conditioning section (voltage stabilizer, offset trimmer, Voltage-To-Frequency (V/F) converter, and voltage buffer amplifier), and a 2.4 GHz Industrial Scientific and Medical (ISM) wireless antenna for radiofrequency (RF) transmission. The transmitter is powered using a ± 12 V battery.

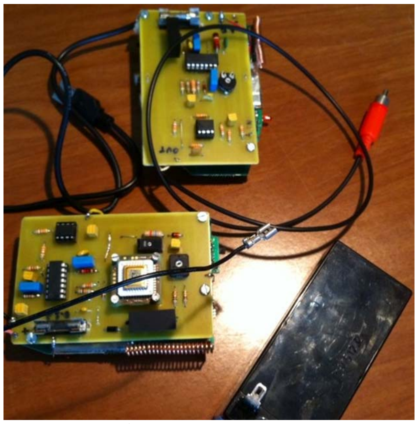

Fig. 2. ALE prototype

On the other hand, the receiver unit is made of a 2.4 GHz ISM receiver, a signal conditioning section (Frequency-to-Voltage (F/V) converter, signal amplifier, and voltage stabilizer), and a commercially available external 24-bit Data Acquisition (DAQ) board connected to a computer which is used both for downloading data and powering the receiver through its Universal Serial Bus (USB) port. A complete description of ALE electrical circuits, installed elements, and their functions can be found in [14], while Figure 2 shows the prototype used in this study.

It should be observed that, on the contrary of what happens in other MEMS-based sensor boards, no microcontrollers neither ADCs are embedded on-board [15], [16]. Therefore, accelerometer analog output is converted to a proportional frequency value by means of the V/F converter before being RF transmitted. In the receiver unit, the signal is demodulated with the F/V converter before being downloaded in an external computer for being post-processed off-board. The ALE key feature, compared to other wireless SHM sensor boards, is the frequency modulated (FM) analog transmission. It allows for more accurate and immune to noise data at the important low-frequency and low-amplitude vibrations despite the bigger amount of raw data transmitted via RF [17]. The V/F – F/V conversion accuracy in measuring low-amplitude and low-frequncy vibration has been provided in other studies carried out on ALE [14]. They have shown that the prososed system can detect vibration having frequency as low as 0.2 Hz and amplitude in the order of 10^{-2} $m \cdot s^{-2}$. The committed error is below 2% when the same records are taken with equal-resolution IEPE accelerometers. The same studies have shown that ALE experiences some problems when transmitter and receiver are deployed more than 30 meter away. It depends on the installed RF systems (not able to prevent interferences in the transmitted signal) rather than on the selected conversion system. It is reasonable to think that a more effective RF transmitter – receiver apparatus may solve the problems related to signal deterioration over distance. Further developments of the prototype will involve the selection of a RF system more suitable for FM analog signal transmission over a wider area.

III. VIBRATION MONITORING TESTS

A. *Streicker Bridge features and ALE deployment*

The structure tested was the Streicker Bridge, a 104 meter deck-stiffened arch bridge, located on the Princeton University campus in Princeton, NJ. It has a main span and four approach ramps (legs). The legs, whose cross-section are constant and measures nearly 3 meter, are horizontally curved and supported by steel columns. The main span has varying cross-section. All bridge decks are reinforced post-tensioned concrete [18], [19]. The picture of the bridge and the dimension of the southeast ramp (where ALE transmitter was deployed) are shown in Figure 3 and 4.

The Streicker Bridge was equipped with many SHM systems during the years. They aimed to transform the structure into an on-site laboratory [18]. Several studies and Finite Element Model (FEM) analyses were carried out on the bridge; therefore, literature data are available for comparison. In particular, the natural frequencies of the structure resulted from the experimental analyses were 3.11, 3.17 and 3.72 Hz with an expected error σ of 0.06 Hz. On the other hand, the natural frequencies evaluated using the FEM model were equal to 3.22 and 3.92 Hz [20].

Fig. 3. Streicker Bridge at Princeton University campus (left: bottom view); (right: top view rendering – Source: www.princeton.edu)

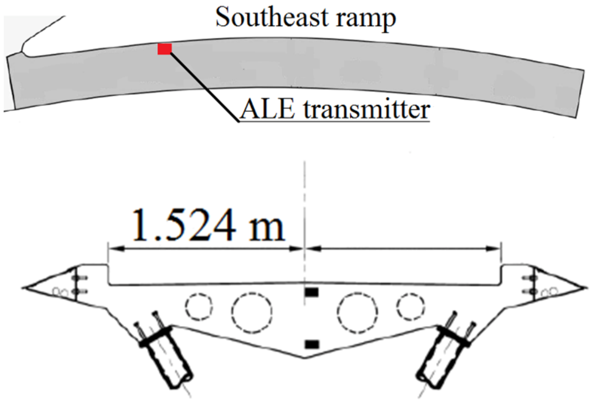

Fig. 4. Southeast approach ramp plan view (up) and cross-section (down) (Source: [21])

The ALE transmitter was deployed on the southeast leg, while the receiver was placed under the deck, at road level, nearly 10 meter away from the transmitter. Figure 5 shows the mutual position of the transmitter and receiver boards and a detail of the ALE transmiter deployment on the bridge deck.

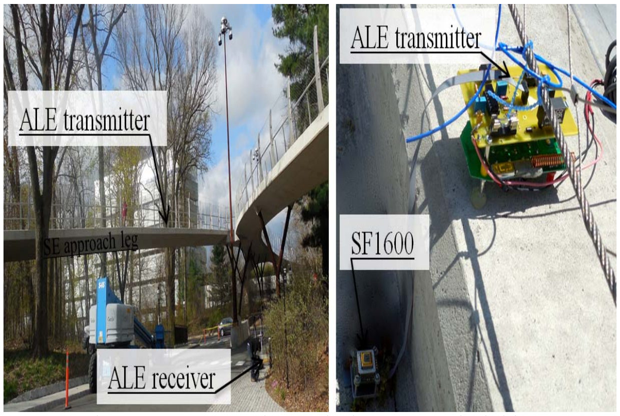

Fig. 5. Test setup and ALE deployment on the bridge

To allow an easier deployment, the MEMS-based accelerometer was removed from the transmitter board and connected to it by means of a 10-pin Insulation Displacement Contact (IDC). The sensor was then secured to the bridge using a thick layer of double-sided tape compliant with recommendations provided by the ISO Directive [22]. Three different experiments were carried out: the first consisted of a quasi-static test using the truck shown in Figure 6 as moving static load. The second test consisted of a group of eight people jumping at approximately 3 Hz for 30 seconds and then stopping in correspondence of one quarter of the bridge's southeast approach ramp total length. The last test consisted in the same group of eight people running at different random frequencies between the main span-ramp connection point and half of the leg total length. This study is based on the principle that the natural frequencies of a structure can be determined with tests such as a shaker test or an impact test that introduce free vibrations in the structure itself [23]. In particular, by exciting the structure with ambient vibrations, the frequencies found would be approximately equal to the natural frequency of the bridge with the advantage of tests simplicity. During the experiments, the wirelessly transmitted sensor output signals were acquired with a 30 Hz sampling rate using the external DAQ device connected to the receiver board.

B. *Quasi-static test*

As shown in Figure 6, a truck having a total load of nearly 40 kN, was positioned sequentially at different locations along the southeast approach ramp and measurements were taken continuously during the vehicle's moving phases and the stops.

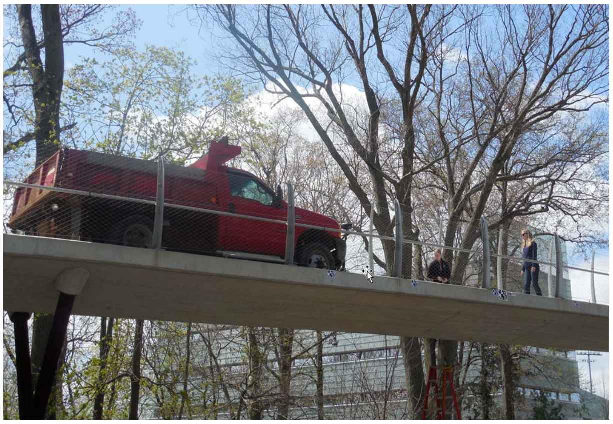

Fig. 6. Quasi-static test setup

Recorded data were analyzed in time and frequency domains and compared with literature-available data. Due to the length of the quasi-static test, only a short portion of the recorded signal is reported in this study, while frequency domain analyses were carried out on the whole signal. Figures 7 and 8 plot a detail of the time-history (TH) and the correspondent frequency response by Power Spectral Density (PSD) evaluated from the acceleration recorded during the quasi-static test. It is observed that the oscillation have extremely low-amplitude (Root Mean Square, RMS equal to $1.21 \cdot 10^{-2}$ m·s^{-2}). Despite the fact that these amplitudes are low, the MEMS-based accelerometer system can clearly identify them. Furthermore, the frequency domain analysis clearly highlights the value of 3.08 and 3.75 Hz as the first two natural frequencies of the bridge. These frequencies are close to those of 3.11 and 3.72 Hz found in previous studies [20].

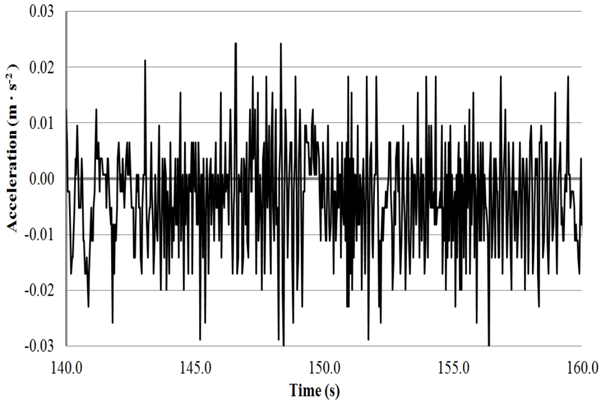

Fig. 7. Detail of the TH recorded during the quasi-static test

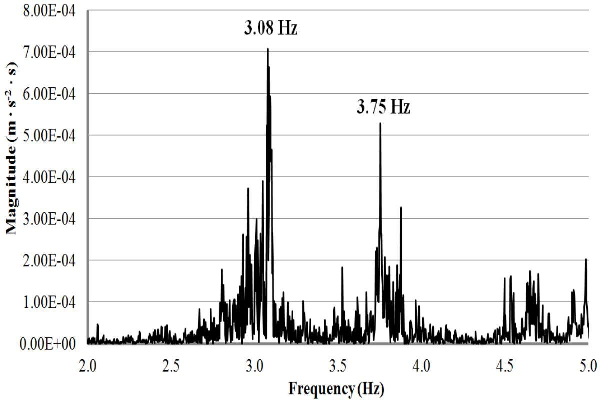

Fig. 8. Detail of the PSD evaluated from the quasi-static test recorded TH

C. *3 Hz-Input Solicitation Test*

In the second test, a group of eight people was left jumping, in correspondence of one quarter of the bridge's southeast approach ramp total length, with a frequency of approximately 3 Hz. The people jumped for nearly 30 second and then suddenly stopped. When the people stop moving, the input simulates a damped free vibration system, which oscillates at its natural frequency ω_n before motion dies out. Furthermore, this test could be used for evaluating the damping factor of the system.

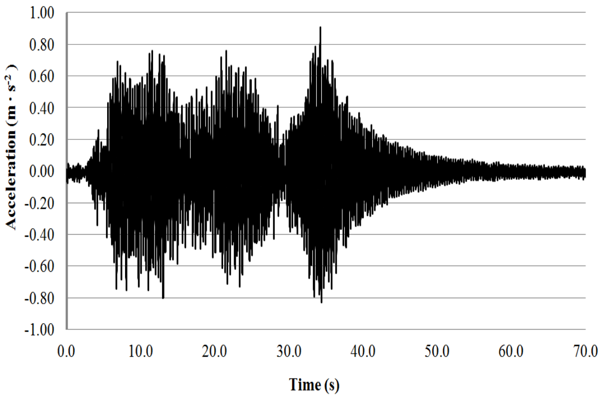

Fig. 9. TH recorded during the 3 Hz-input solicitation test

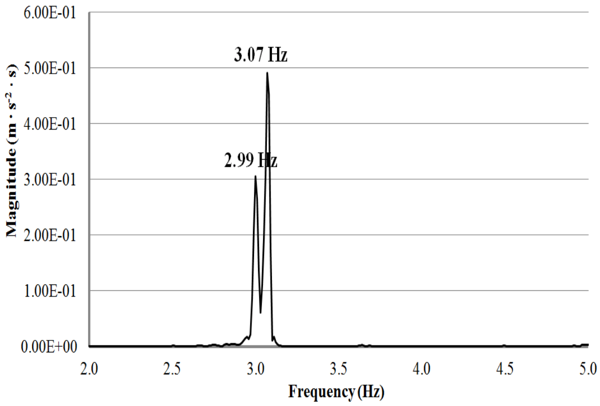

Fig. 10. Detail of the PSD evaluated for the 3 Hz-input solicitation test

Figures 9 and 10 plot the TH and the PSD recorded with ALE. In Figure 9, two parts are clearly intelligible. The first portion of the signal (5 through nearly 30 second) when people jump on the bridge and the second part (35 second on) when the motion starts to decrease until it dies out. When a frequency domain analyses is carried out (see Figure 10), two frequency values are observed. 2.99 Hz is the frequency of the input solicitations (jump), whereas 3.07 Hz is the bridge's excited frequency.

D. Random-Input Solicitation Test

To make sure that the measured frequencies are the natural frequencies of the bridge, and not imposed frequencies, random running was also performed. During this experiment, the same group of eight people of the previous test was left running between the main span-ramp connection point and half of the leg total length for nearly 2 minutes.

The results presented in Figures 11 and 12 show that the first two modes (3.08 Hz and 3. 75 Hz) are close to those detected in the other tests. Furthermore, a summary of bridge's first two natural frequencies, obtained through all tests performed in this study, is listed in Table I together with results coming from a literature review of other analyses performed on the Streicker Bridge. They include outcomes from both experimental and FEM studies. Of course, no evaluation on the magnitude of excited frequencies can be done and it is not reported. Magnitude mainly depends on the inputs used, which are different for each of the three tests described in this study.

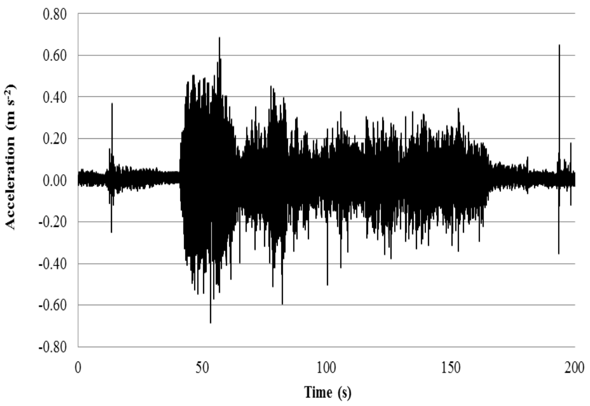

Fig. 11. TH recorded during the random-input solicitation test

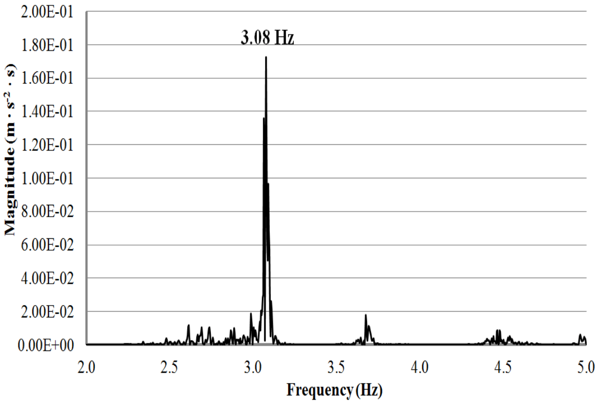

Fig. 12. Detail of the PSD evaluated for the random-input solicitation test

TABLE I

SUMMARY RESULTS FOR STREICKER BRIDGE NATURAL FREQUENCIES

Test *(-)*	f_1 *(Hz)*	f_2 *(Hz)*
Literature [21]	3.11	3.72
FEM [21]	3.22	3.92
Quasi-static	3.08	3.75
3 Hz-Input	3.07	-
Random-Input	3.08	3.75

It can be observed that the frequencies evaluated from the record obtained using ALE are close to those evaluated in previous studies performed on the bridge. Correspondence is verified both for experimental studies (3.11 ± 0.06 and 3.72 ± 0.06 Hz) and computational analyses obtained through a Finite Element Model (3.22 and 3.92 Hz) [20]. The relative errors committed, equal to -0.97% and 0.80% respectively, are negligible in traditional engineering practices. Indeed, they could be due to the fact tests were carried out in different periods (i.e.: seasons, years). Furthermore, slight changes in dynamic response may be due to different boundary conditions (e.g.: temperature, concrete assessment, concrete aging, etc.). Nevertheless, if the standard deviation ($\sigma = \pm 0.06$ Hz) associated to results obtained from the literature review was considered, the measurement interval of tolerance for the two frequencies would become [3.05 - 3.17 Hz] and [3.69 - 3.81 Hz] respectively. The results found with ALE are within those intervals. Therefore, a perfect match is found. Since data obtained with ALE are the same of those obtained in other studies when different typologies of sensor were used, it demonstrates that the proposed MEMS-based system can be used as wireless alternative to traditionally used sensors for carrying out vibration monitoring of large-sized structures without accuracy loss.

IV. CONCLUSIONS

Wireless MEMS-based accelerometers have proved to be an excellent alternative to traditionally used devices when structural health monitoring analyses have to be carried out. In this study a newly design Acceleration Evaluator (ALE) is used as stand-alone sensor for the vibration monitoring of a pedestrian deck-stiffened arch bridge. The proposed wireless system embeds a MEMS-based accelerometer and can wirelessly trasmitt the recorded data. As can be observed from the results presented in this research, ALE can achieve performances extremely accurate without modifying the accelerometer features. In particular, because of the use of the V/F converter it is possible to mantain a wide bandwidth (0.2 - 1500 Hz) and the full sensing interval (± 29.42 $m \cdot s^{-2}$) [24]. The best resolution ($0.21 \cdot 10^{-3}$ $m \cdot s^{-2}$) and the lower detectable frequency (0.2 Hz) among the current wireless sensor boards [8], [9] are achieved as demonstrated in [14]. Furthermore, since no bandwidth reduction is applied, ALE can be used as multi-purpose device for monitoring systems having higher natural frequencies as well.

In this study, ALE was widely tested through different experiments each of them having different characteristics (i.e.: amplitude of the input vibrations, different input frequencies). The test results demonstrated ALE accuracy in measuring vibration relevant to civil engineering structures, including those of low-frequency (nearly 3 Hz) and low-amplitude (in the order of 10^{-2} $m \cdot s^{-2}$) with accuracy comparable to that of traditionally used devices (i.e. IEPE accelerometers). The measurement errors were less than 1% when a comparison with literature studies carried out on the same bridge is performed.

Further developments of the prototype may consist of using the accelerometer board as a sensing node within a Wireless Sensor Network (WSN) [25], [26] for controlled maintenance of the state of aging large-sized structures without interfering with their functionalities.

ACKNOWLEDGMENT

This research is part of a Ph.D. program funded at University of Calabria, Italy by European Union social founds (FSE - Fondo Sociale Europeo) within the POR Calabria FSE 2007 - 2013 project. The author would also like to thank Professor Branko Glisic, Doctor Dorotea Sigurdardottir, Doctor Hiba Abdel-Jabber from the Civil and Environmental Engineering Department of the Princeton University, and the SHMlab at Princeton University. They have shared the results of their researches and allowed the author to deploy the prototype on the Streicker Bridge located on the Princeton University campus in Princeton, NJ.

REFERENCES

[1] A. Basharat , N. Catbas and M.A. Shah, “A framework for Intelligent sensor network with video camera for structural health monitoring,” in Proc. PerCom, 2005, pp. 385-89.

[2] Calebi, M., “Seismic instrumentation of buildings (with emphasis on federal buildings), United States geological survey, Technical report No. 0-7460-68170, Menlo Park, CA, 2002.

[3] American Society of Civil Engineering, “Report Card for America's Infrastructure,” ASCE, Technical report, USA, 2013.

[4] M. Alonso and E.J. Finn, Physics, Vol. 2, 7th ed. Prentice Hall, Boston, 2002.

[5] Y. Fujino and M. Abe, “Structural Health Monitoring in Civil infrastructures and Research on SHM of Bridges at the University of Tokyo,” in Proc. WCSC, 2002, Como, Italy, pp. 125-140.

[6] J. Mitrani, J. Goethals, and S. D. Glaser, “Field Testing of Wireless Interactive Sensor Nodes,” Port and Airport Research Institute, Technical report, Yokosuka, Japan, 2002.

[7] N. Kurata, B.F. Spencer, and M. Ruiz-Sandoval, “Risk monitoring of buildings with wireless sensor networks,” Structural control and health monitoirng, vol. 12, no.3-4, pp. 315-327, Jun, 2005.

[8] S. N. Pakzad, G.L. Fenves, S. Kim, and D. Culler, “Design and implementation of scalable wireless sensor network for structural monitoring,” J. Infrast. Sys., vol. 14, no.1, pp. 89-101, Mar, 2008.

[9] H. Jo, S. Sim, T. Nagayama, and B.F. Spencer, “Development and Application of High-Sensitivity Wireless Smart Sensors for Decentralized Stochastic Modal Identification,” J Eng. Mech., vol. 136, no.6, pp. 683-694, Jun, 2012.

[10] M.J. Whelan, M.V. Gangone, and K.D. Janoyan, "Highway bridge assessment using an adaptive real-time wireless sensor network," IEEE Sensors Journal, vol. 9, no. 11, pp. 1405-1413, Nov, 2009.

[11] S. Jang, H. Jo, S. Cho, K. Mechitov, J. A. Rice, S. H. Sim, and G. Agha, "Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation," *Smart Structures and Systems*, vol. 6, no. 5, 6, pp. 439-459, Jun, 2010.

[12] M. Ruiz-Sandoval, B.F. Spencer, N. Kurata, “Development of a high sensitivity accelerometer for the Mica platform,” in Proc. IWSHM, Stanford, CA, 2003, pp. 1027-1035.

[13] J.P. Lynch, and K.J. Loh, “A summary review of wireless sensors and sensor networks for structural health monitoring,” Shock and Vib. Dig., vol. 38, no.2, pp. 91-130, 2006.

[14] A. Sabato, and M.Q. Feng, “Feasibility of frequency-modulated wireless transmission for a multi-purpose MEMS-based accelerometer,” Sensors, vol. 14 no.9, pp. 16563-16585, Sep, 2014.

[15] J.P. Lynch, “An overview of wireless structural health monitoring for civil structures,” Phil. Trans. Royal Society, vol. 365, no.1851, pp. 345-372, Feb, 2007.

[16] S. Gajjar, N. Choksi, M. Sarkar, and K. Dasgupta, “Comparative analysis of wireless sensor network motes,” in IEEE - SPIN, Noida, India, 2014, pp. 426-431.

[17] D.H Wang, and W.H. Liao, “Wireless transmission for health monitoring of large structures,” Inst. and Meas., IEEE Trans. on, vol. 55, no.3, pp. 972-981, Jun, 2006.

[18] D.H Sigurdardottir, and B. Glisic, “Measures of structural art: A case study using Streicker Bridge,” in Khaled Mahmoud (Ed.) “Durability of Bridge Structures” – Proc. NYCBC, New York City, NY, 2013, pp. 275-284.

[19] D.H Sigurdardottir, and B. Glisic, “Neutral axis as damage sensitive feature,” Smart Mater. Struct., vol. 22, no. 7, pp. 075030, Jun, 2013.

[20] D.H. Sigurdardottir, B. Glisic, and J. P. S. Afonso, "Streicker Bridge in Its Early Years: Structural Identification and Damage Characterization," in TRB Annual Meeting, Washington, D.C., 2013.

[21] H. Abdel-Jaber, and B. Glisic, “A method for the on-site determination of prestressing forces using long-gauge fiber optic strain sensors,” Smart Mater. Struct., vol. 23, no. 7, pp. 075004, May, 2014.

[22] Mechanical vibration and shock - Mechanical mounting of accelerometers, ISO 5348:2007, 2007.

[23] A.G. Piersol, T. L. Paez, and C.M. Harris. Harris' Shock and Vibration Handbook. 6th ed. McGraw-Hill, New York, 2010.

[24] SF1600SN.A: Single axis best in class seismic accelerometer, Available online: http://www.colibrys.com (accessed on Apr. 2014).

[25] G. Fortino, A. Guerrieri, G.M.P. O'Hare, and A.G. Ruzzelli, “A flexible building management framework based on wireless sensor and actuator networks,” J. Network and Computer Applications, vol. 35, no. 6, pp. 1934-1952, Jun, 2012.

[26] G. Fortino, R. Giannantonio, R. Gravina, P. Kuryloski, and R. Jafari: “Enabling Effective Programming and flexible management of efficient body sensor network applications”. IEEE T. Human-Machine Systems, vol. 43, no.1, pp. 115-133, Jan, 2013.