REVISTA INTERDISCIPLINAR DE PESQUISA EM ENGENHARIA

CILAMCE 2016

XXXVII IBERIAN LATIN AMERICAN CONGRESS
ON COMPUTATIONAL METHODS IN ENGINEERING
BRASÍLIA - DF - BRAZIL

DEVELOPMENT OF LOW-COST WIRELESS ACCELEROMETER FOR STRUCTURAL DYNAMIC MONITORING

Emerson Galdino

Alexandre Cury

emerson.galdino@engenharia.ufjf.br

alexandre.cury@engenharia.ufjf.br

Federal University of Juiz de Fora

Rua José Lourenço Kelmer, 36036-330, Juiz de Fora, Minas Gerais, Brazil

Abstract. *Structural Health Monitoring (SHM) of civil infrastructures has great practical importance for engineers. Several researches have been carried out, such as the Rio-Niterói Bridge in Brazil, the former Z24 Bridge in Switzerland, the Millau Bridge in France, among others. In fact, some structures are monitored 24/7 to supply dynamic measurements that can be used for the identification of structural problems, such as the presence of cracks, excessive vibration, damage identification or even to perform life cycle analyses. SHM systems may provide automated assessments of structural health by processing data from sensors attached to the structure. SHM often uses wired systems, which are usually expensive due to the necessity of continuous maintenance and are not always suitable for sensing remote structures. On the other hand, commercial wireless systems often demand high implementation costs. In this sense, this paper proposes the development of a sensing system that uses an open-source prototyping platform (Arduino), which significantly reduces implementation costs while keeping data's integrity. The wireless communication is performed in real time through a local wireless network, responsible for sending and receiving data. The proposed system is validated by comparing its results with a commercial wired system through an experimental application performed in laboratory.*

Keywords: *Wireless accelerometer, Low-cost, SHM, Modal Analysis*

1 INTRODUCTION

The assessment of vibration tests performed on structural systems has a great practical importance for Civil Engineering. Several works have been published in the literature showing different types of structural instrumentation schemes and data acquisition systems. These systems are often used as a tool for dynamic monitoring in structures of significant value, such as the Rio-Niterói Bridge (Battista et al. 2000) in Brazil, the Z24 Bridge (Reynders et al. 2009) in Switzerland and the Millau Bridge (Gautier et al. 2005) in France.

Numerous researches have been carried out using long-term monitoring (Soyoz et al. 2009; Cardini et al. 2009). As a matter of fact, some structures are monitored 24/7 in order to supply dynamic measurements that can be used for the identification of structural problems, such as the presence of cracks (Lu et al. 2009), excessive vibration (Darus et al. 2005), damage identification (Cury et al. 2010), among others. Furthermore, through a structural dynamic analysis it is possible to perform a quite extensive structural evaluation concerning its reliability, vulnerability or even its life cycle (Torres et al. 2007).

Structural Health Monitoring (SHM) systems may provide automated assessments of structural health by processing data from sensors attached to the structure. SHM often uses wired systems, which are usually expensive due to the necessity of continuous maintenance and are not always suitable for sensing remote structures. Moreover, power and wiring constraints imposed by these systems can increase the cost of acquiring these data sets, impose significant setup delays, and limit the number and location of sensors. Thus, wireless sensor networks are a natural candidate for structural health monitoring systems, since they enable dense *in situ* sensing and simplify deployment of instrumentation (Sindhu et al., 2015, Pandey et al. 2016).

The number of studies seeking the development of new sensors for the acquisition of dynamic data is growing continuously. In parallel, one observes the innovation regarding the use of wireless networks, proving better results when it comes to decreasing the presence of noise in signals while reducing maintenance costs. Particularly, wireless sensor networks start being used as a way to facilitate data transmission. Wireless acquisition is advantageous for enabling instrumentation in inaccessible places, reducing installation and maintenance costs while expanding its use in situations where large wired systems are not feasible.

SHM makes use of different kinds of sensors to monitor structures: displacement sensors, strain-gage and accelerometers, to name a few. In this paper, we focus on an accelerometer based system. Accelerometers measure, as the name suggests, accelerations of the surface they are mounted on. From a structural engineering standpoint, accelerometers are characterized by several performance parameters: sensitivity, which denotes the smallest measurable acceleration and is expressed in g's (gravitational acceleration); dynamic range, which denotes the range of accelerations that the device is capable of measuring and is also expressed in g's; and noise, which is measured either as an RMS value, or is expressed as a function of the frequency of vibration (Xu et al. 2004).

In this sense, this work proposes the design, programming, implementation and evaluation of a low-cost wireless accelerometer based on an open-source prototyping platform named Arduino. This platform significantly reduces implementation costs while keeping data's integrity. The wireless communication is performed in real time through a local wireless network, responsible for sending and receiving data. The proposed system is validated by comparing its results with a commercial wired system through an experimental application performed in laboratory.

2 DESIGN AND IMPLEMENTATION OF THE SYSTEM

In order to design a reliable and robust wireless accelerometer, it is necessary that certain minimum prerequisites are met to fulfil an adequate sensing performance. The most important requirements can be summarized as:

- **Sensor's autonomy:** the choice of proper physical components is of great importance to define the sensor's autonomy. Using modules with low-power consumption and a platform that supports the implementation of an external battery and sustainable energy systems are essential.
- **Real-time data acquisition and transmission:** real-time data acquisition at the instant a request is sent by the data acquisition module may be necessary in several cases. For a SHM system, the device must be able to receive orders from the data acquisition module and send real-time data acquisition according to a given command.
- **Low Cost:** the main purpose of this work is to propose an inexpensive wireless system. Thus, the physical components should be easy to buy, affordable as well as the controlling software should be preferably free.
- **Data reliability:** the data reliability covers several factors such as noise, data loss, sensitivity, frequency range and duration of data acquisition. Noise can vary according to the accelerometer's resolution and to its way of acquiring data. However, it can also be influenced by how devices are connected to each other, especially the wiring. Data loss happens especially in wireless communication if the wireless accelerometers and the data acquisition module are not well synchronized or if there is an incompatibility between the devices. Sensitivity, frequency range and duration must be provided for each application so that the accelerometer is arranged to receive values in a frequency band. Thus, sampling frequency and time of acquisition are defined according to the sampling Nyquist-Shannon theorem.

The proposed wireless system can be schematically represented as Fig. 1 shows.

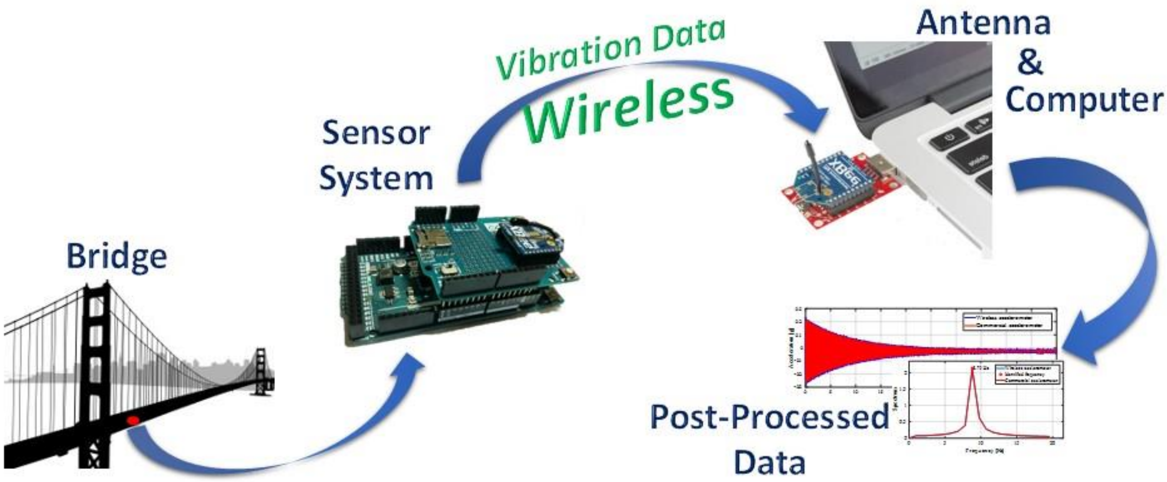

Figure 1. Wireless system schematic

2.1 Hardware

The physical components are chosen in order to meet the aforementioned prerequisites. Their specifications should meet the design specifications and must be compatible with each other. In order to assemble the wireless system proposed in this work, several components are used, such as:

- **Arduino Due Board:** it is the system's core and is used to synchronize data wirelessly, supply power to the system, store all data read by the accelerometer before sending them to the data acquisition module.
- **Wireless SD Shield:** used to adapt and plug the antenna to the Arduino Board.
- **XBee 2mW Wire Antennas:** used to communicate wirelessly to each other. One is attached to the accelerometer and the other to the data acquisition module.
- **MPU-6050**: the actual accelerometer.

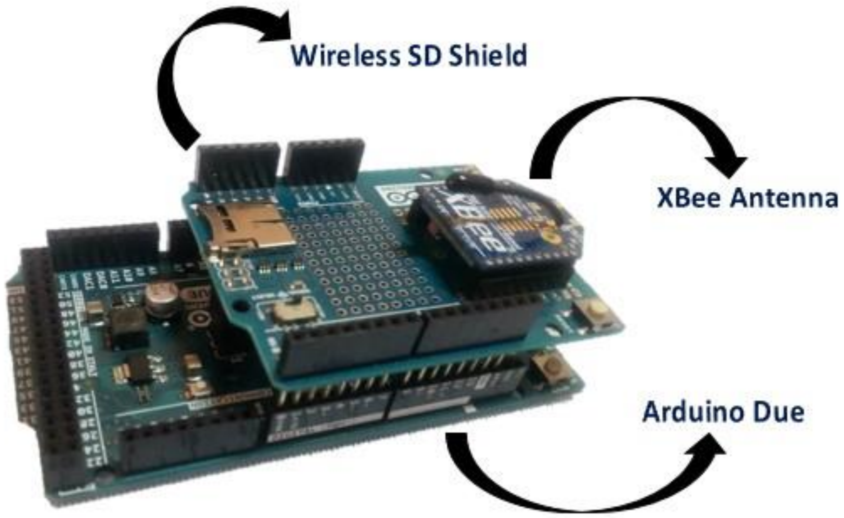

Figure 2. Arduino Due + Wireless SD Shield + Antenna

The total cost to assemble this system (Fig. 2) is approximately US$ 90,00. In the following sections, each one of these components is described with more details.

2.1.1 Arduino Due

The Arduino Due is a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. It is the first Arduino board based on a 32-bit ARM core microcontroller. It has 54 digital input/output pins, 12 analog inputs, 4 UARTs (hardware serial ports), an 84 MHz clock, an USB OTG capable connection, 2 DAC (digital-to-analog), 2 TWI, a power jack, an SPI header, a JTAG header, a reset button and an erase button.

The board contains everything needed to support the microcontroller. To get started, simply connect it to a computer with a micro-USB cable or power it with a AC-to-DC adapter or a battery unit.

The microcontroller specifications are very important to understand its limits and performance. The Arduino Due has an operating voltage of 3.3V, a 512 KB of internal flash memory and measures 101x53 mm, weighting only 36g. For more details, the reference (Arduino, 2016a) is advised.

2.1.2 Wireless SD Shield

The Wireless SD shield allows the Arduino board to communicate wirelessly using a wireless module. The module can communicate up to 30m indoors or 100m outdoors (with line-of-sight). It can be used as a serial/USB replacement or be put into a command mode and configured for a variety of broadcast and mesh networking options. The shield connects each of the Xbee's pins to a through-hole solder pad. For more details, the reference (Arduino, 2016b) is recommended.

2.1.3 XBee 2mW Wire Antenna - Series 2 (ZigBee Mesh)

The XBee XB24-Z7WIT-004 Series 2 module improves the power output and data protocol. Series 2 modules allow creating complex mesh networks based on the XBee ZB ZigBee mesh firmware. These modules allow a very reliable and simple communication between microcontrollers, computers and systems with a serial port.

Its specifications may vary according to the desired range of the project. In this work, the antenna used is the XBee 2mW Wire Antenna - Series 2 (ZigBee Mesh) with a range of 120 meters. The range will vary according to the strength of the antenna signal. If necessary, an antenna with higher power can be replaced without major difficulties.

The antenna specifications are very important for the best use of its power and energy savings. The antenna used in this work has a transmission data rate of 250 Kbps, a 2.4 GHz frequency band, 128-bit AES encryption system, 40m (indoor) and 120m (outdoor/line-of-sight) ranges and uses a 2.1-3.6V supply voltage (DC). For more details, please refer to (Digi International Inc., 2016a).

2.1.4 MPU-6050

The InvenSense MPU-6050 sensor (Fig. 3) contains a MEMS accelerometer and a MEMS gyro in a single chip. It is very accurate, as it contains a 16-bit analog-to-digital conversion hardware for each channel. Therefore, it captures the *x*, *y*, and *z* accelerations at the same time. The sensor uses the I2C-bus to interface with the Arduino. The MPU-6050 is not expensive, especially given the fact that it combines both an accelerometer and a gyro.

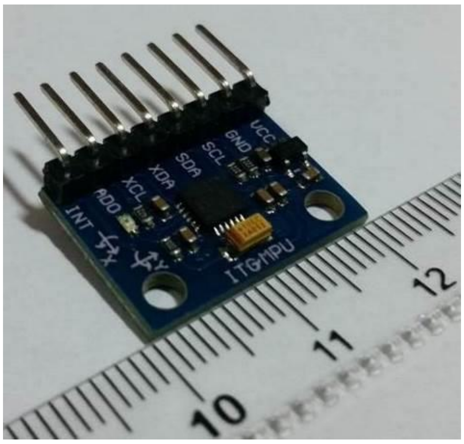

Figure 3. MPU-6050

For precision tracking of both fast and slow motions, the MPU-6050 features a user-programmable gyro full-scale range of ±250, ±500, ±1000, and ±2000°/sec and a user-programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g. The MPU-6050 has a 6-16V input voltage, a low-pass filter response between 5-260 Hz and has an output date rate between 4-1000 Hz. For more details, see reference (InvenSense Inc., 2013).

2.2 Software

The choice of a proper controlling software is of utmost importance, since it has to successfully communicate between the remote user and the accelerometer. Moreover, considering a low-cost system, the preference was given to free-to-use softwares. In this work, three softwares were used:

- **XCTU (free):** used to configure the antenna and the communication protocol.
- **Arduino Software (free):** used to compile and upload commands to be executed remotely in the Arduino board.
- **MATLAB:** used to receive raw data wirelessly and post-processing (signal processing and modal identification).

In the following sections, each one of these programs is briefly described.

2.2.1 XCTU

XCTU is a free multi-platform application designed to access and set parameters for the XBee Antenna.

The communication protocol used in this work was based on direct data streaming without cryptography. This choice was made for process simplification, considering that there were only one sender (antenna attached to the accelerometer) and one receiver (antenna connected to the computer). Thus, there is no need to allocate channels and addresses for communication. For more details, the reference (Digi International Inc., 2016b) is advised.

2.2.2 Arduino Software (IDE)

Arduino Software (IDE) is an open source Arduino software to facilitate code writing and subsequent uploading to the board. The environment is written in Java and has several functions ready to use that can be employed to ease the programming process.

On the board programming process is where the greatest amount of information is defined for the system operation. The code sets the sampling rate, sends read requests to the accelerometer, and stores all the raw data readings before sending for processing. Moreover, they are also set to wait for a start-byte from the data acquisition module before start sending data.

During data acquisition, the readings are made at the highest frequency allowed by the accelerometer, which according to the technical specifications is 1000 Hz. Due to Arduino Due’s storage limitation, the readings are saved during ten seconds and then, they are sent to the computer.

The wireless transmission is established through a "start-byte" and an "end-byte". This is necessary so that the communication may happen in a coordinated manner and to prevent any data loss. Upon receiving the "start-byte", the sender starts taking and saving readings without sending any data. Once this task is completed, it starts sending the data uninterruptedly until it reaches the "end-byte". Thus, one can ensure that no data was lost. For more details, see reference (Arduino, 2016c).

2.2.3 MATLAB

MATLAB is a well-known software and is widely used in various fields of science. The platform has a support package for the Arduino, so it can communicate simply and efficiently with the computer. Once all data are received, the post-processing algorithms are performed in MATLAB, such as the modal identification techniques (both time and frequency domain), plots, etc. In addition, through the GUI platform (Graphical User Interface) it is possible to create a simple, intuitive and dedicated interface to control both data acquisition and transmission. For more details, the reference (MathWorks, 2012) is recommended.

3 RESULTS

In order to assess the efficiency and robustness of the proposed wireless acquisition system, an experimental application is carried out. The main idea is to compare the signals obtained using the proposed low-cost wireless sensor with a commercial wired accelerometer.

The experimental application was performed using an aluminum-cantilevered beam shown in Figure 4. The beam's dimensions are 0,545m (L) x 0,016m (W) x 0,004m (H). Both accelerometers are instrumented at the free end of the beam. The commercial accelerometer is a Kyowa AS-1GA (±1G), 0,5mV/V, 0.1-1 kHz, with an estimate cost of US$ 600,00.

The beam was excited using an impact device placed at 0,10 m from the fixed end (see Fig. 4). This excitation point was chosen in order to excite at least the first two natural modes of the beam. The structural vibration was registered during 50s at a frequency rate of 1000 Hz.

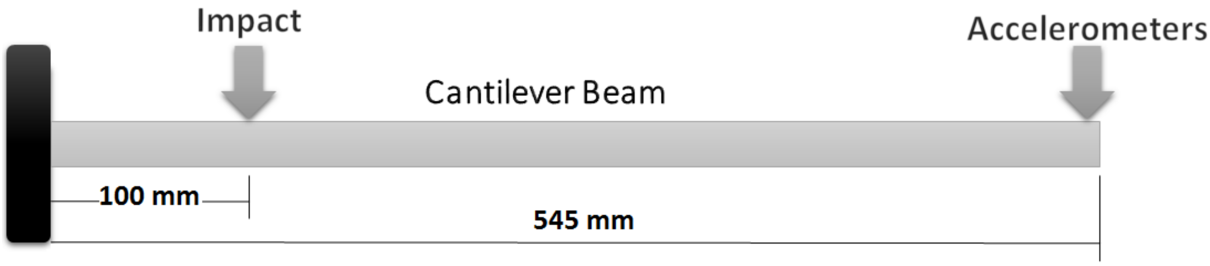

Figure 4. Cantilever beam.

Figures 5 and 6 show the results obtained by both accelerometers. The original signal was cut into 2 parts in order to highlight their differences. Figure 5 shows the first 3,5s of the acquired signal, whereas Fig. 6 shows its last 20s. In blue, one observes the signal registered by the low-cost wireless accelerometer, while in red, the signal acquired by the commercial wired accelerometer. From Fig. 5, it is nearly impossible to notice any difference in terms of acceleration amplitudes, especially when these amplitudes have higher values (occurring from 0 to 3,5s).

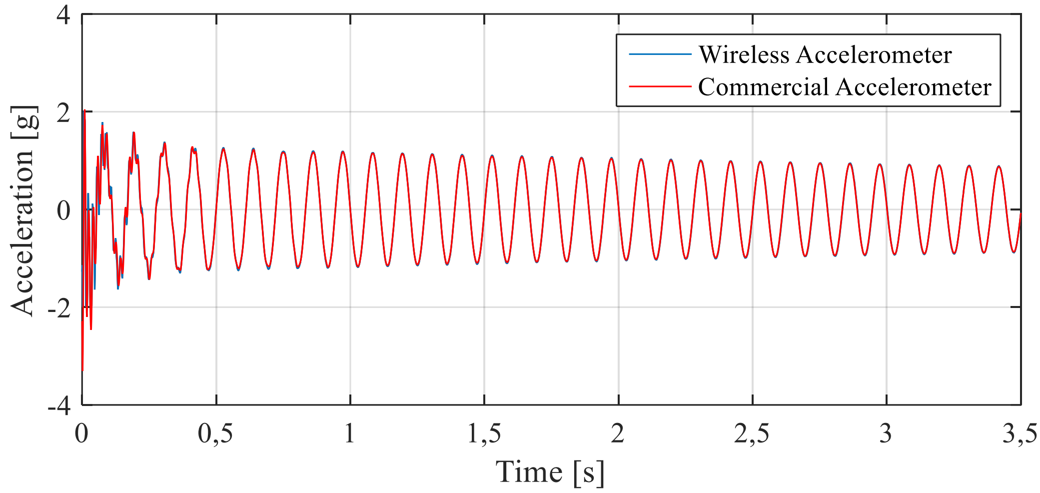

Figure 5. Signals acquired by both accelerometers (from 0 to 3,5s).

However, for lower acceleration magnitudes (occurring from 30 to 50s), it is clearly perceptible that the signal-to-noise ratio is sensibly higher for the wireless accelerometer (Fig. 6). This occurs since the commercial accelerometer is connected to a data acquisition module (Lynx ADS1800), which has built-in signal conditioning procedures. On the other hand, the wireless accelerometer is connected directly to the computer, without any type of signal preprocessing.

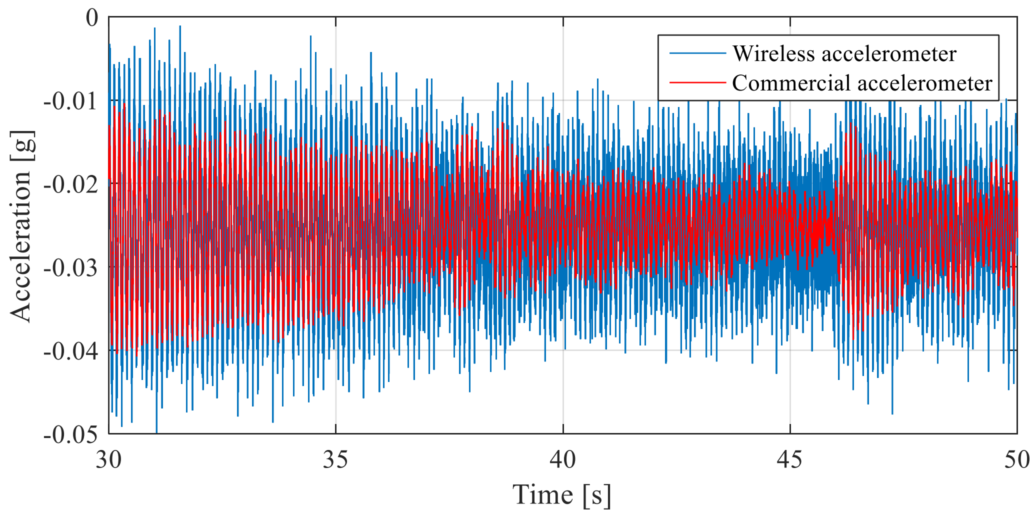

Figure 6. Signals acquired by both accelerometers (from 30 to 50s).

When it comes to a frequency-domain analysis, it is possible to observe how adequate the proposed system is. Figure 7 shows a comparison between the FFTs (Fast Fourier Transform) for both signals. Clearly, the wireless accelerometer yields the same results as its commercial counterpart. For both cases, the first two natural frequencies were correctly identified, although the second one with smaller amplitude spectrum. Nonetheless, these results are fairly in accordance to the analytical values previously calculated.

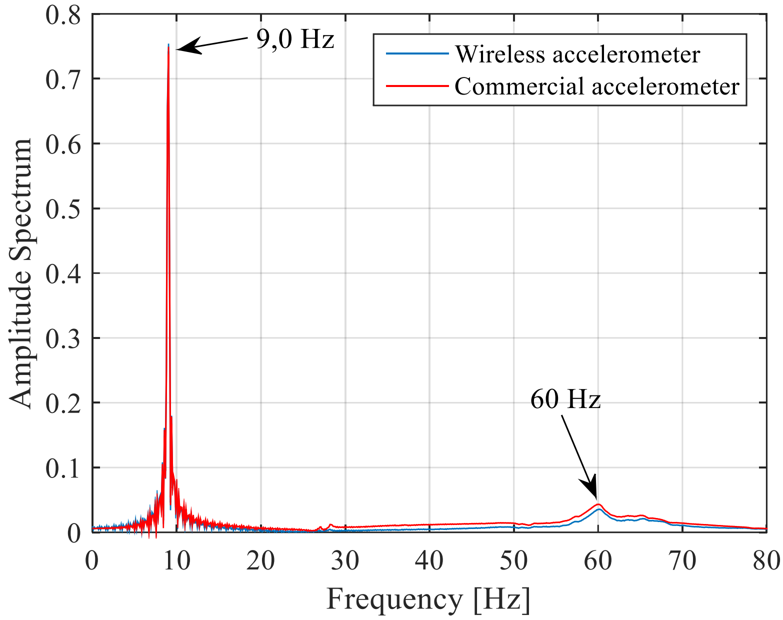

Figure 7. FFTs obtained by the low-cost wireless accelerometer and the commercial accelerometer

4 CONCLUSIONS

This paper proposed the development of a data acquisition system that uses an open-source prototyping platform (Arduino), which significantly reduces implementation costs while keeping data's integrity. The wireless communication is performed in real time through a local wireless network, responsible for sending and receiving data. The proposed system was validated by comparing its results with a commercial wired system through an experimental application performed in laboratory.

It was observed that the low-cost accelerometer had a good performance overall, especially for low signal-to-noise ratios i.e. high acceleration values. When it comes to a frequency-domain analysis, the results were identical to those obtained by the commercial accelerometer. Finally, it is important to emphasize that the proposed sensor costs between 4 to 6 times less than a commercial sensor and several modifications are under study in order to enhance its overall acquisition performance and built-in quality. One expects its application to full-scale structures soon.

ACKNOWLEDGEMENTS

The authors would like to thank UFJF (Universidade Federal de Juiz de Fora - Federal University of Juiz de Fora), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais) for the financial support.

REFERENCES

Arduino, 2016a. https://www.arduino.cc/en/Main/ArduinoBoardDue.

Arduino, 2016b. https://www.arduino.cc/en/Main/ArduinoWirelessShield.

Arduino, 2016c. https://www.arduino.cc/en/Main/Software.

Battista, R., & Pfeil, M., 2000. Reduction of vortex-induced oscillations of Rio-Niterói Bridge by dynamic control devices. *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 84, n. 3, pp. 273–288.

Cardini, A.J., & DeWolf, J.T., 2009. Long-term Structural Health Monitoring of a Multi-Girder Steel Composite Bridge Using Strain Data. *Structural Health Monitoring*, vol. 8, n. 1, pp. 47-58.

Cury, A., Borges, C.C.H., & Barbosa, F.S., 2010. A two-step technique for damage assessment using numerical and experimental vibration data. *Structural Health Monitoring*, vol. 10, n. 4, pp. 417-428.

Darus, I.Z.M., & Tokhi, M.O., 2005. Soft computing-based active vibration control of a flexible structure. *Engineering Applications of Artificial Intelligence*, vol. 18, n. 1, pp. 93-114.

Digi International, Inc., 2016a. XBee & XBee-PRO ZB Product Specification.

Digi International, Inc., 2016b. http://www.digi.com/products/xbee-rf-solutions/xctu-software/xctu.

Gautier, Y., Moretti, O., & Cremona, C., 2005. Experimental modal analysis of the Millau Bridge. Proceedings of Experimental Vibration Analysis for Civil Engineering Structures.

InvenSense Inc., 2013. *MPU-6000/MPU-6050 Product Specification*, PS-MPU-6000A-00 Datasheet, revision 3,4.

Lu, Z.R., & Law, S.S., 2009. Dynamic condition assessment of a cracked beam with the composite element model. *Mechanical Systems and Signal Processing*, vol. 23, n. 2, pp. 415-431.

MathWorks, 2012. www.mathworks.com/hardware-support/arduino-matlab.html

Pandey, S., Haider, M., & Uddin, N., 2016. Design and Implementation of a Low-Cost Wireless Platform for Remote Bridge Health Monitoring. *International Journal of Emerging Technology and Advanced Engineering*, vol. 6, n. 6, pp. 57-62.

Reynders, E., & De Roeck, G., 2009. Continuous vibration monitoring and progressive damage testing on the Z24 bridge. *Encyclopedia of Structural Health Monitoring*, pp. 2149-2158.

Sindhu, S.A., & Nirrmala, C.A., 2015. Structural Health Monitoring Using Wireless Sensor Network. *International Journal of Emerging Technology in Computer Science & Electronics*, vol. 13, n. 4, pp. 319-322.

Soyoz, S., & Feng, M.Q., 2009. Long-Term Monitoring and Identification of Bridge Structural Parameters. *Computer-Aided Civil and Infrastructure Engineering*, vol. 24, n. 2, pp. 82-92.

Torres, M.A., & Ruiz, S.E., 2007. Structural reliability evaluation considering capacity degradation over time. *Engineering Structures*, vol. 29, n. 9, pp. 2183-2192.

Xu, N., Rangwala, S., Chintalapudi, K., Ganesan, D., Broad, A., Govindan, R., & Estrin, D., 2004. A Wireless Sensor Network for Structural Monitoring. *Proceedings of the ACM Conference in Embedded Networked Sensor Systems*, pp. 13-24.