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ANALYSIS OF THE PERFORMANCE OF AN ALTERNATIVE DAQ FOR EDUCATIONAL EXPERIMENTS IN STRUCTURES MONITORING USING AN OPEN-SOURCE COMPUTER HARDWARE

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Abstract. *Standard Data Acquisition Systems (DAQ) for structural monitoring consists in an effective solution for problems where a great number of simutaneous measurings is required. However, simple laboratory analysis could be impracticable due to its higher costs. In the last few years a couple of open softwares and simple automation systems emerged as an alternative to users to develop his own tools with lower costs. Among those tools, the most common one is the Arduino, which converts byte signals to eletrical signals. A low cost Data Acquisition System with Arduino is proposed. The free vibration response of a beam sample is tested through simple accelerometers. The results are compared with a standard DAQ and also numerical results for a beam element. Finally, some discussions are performed concerning the results of the behavior, the sample rate and the numerical aproximation, aiming to test the feasibility of this alternative equipment for small tests and educational experiments in the dynamical monitoring of civil structures.*

Keywords: *Dynamical Monitoring, Data Acquisition Systems, Arduino, Open Source Hardware*

1 INTRODUCTION

The appearance of fast prototyping technology as 3D-printers, open source micro controller infrastructure and low cost consumer electronics has conquered people to make electronic projects by themselves - the called ”Makers”. Low cost, easy to use, customizable, affordable to abroad range of research labs and educational institutions are some of the assumptions of the new products that have been made all over the world (Walzik et al., 2015). Currently, given the advances in information technology and the rise in connectivity among devices, digital interfaces have emerged as the best way of manipulating sensors and to process the acquired data (Delgado-Castro and Rojas-Bolaños, 2014). Among the numerous platforms based microcontrollers that are available, some are well known among developers, can be cited the launch pad MSP430 , STM8L Discovery, Waspmote from Libelium and Arduino UNO.

One of the great contributer is Arduino - an open-source micro-controller board for hardware control and data acquisition, electronic designer and convenient platform to the rapid development of electronic devices (AL-Kadi et al., 2013, Akhmetov and Aitimov, 2015). One of the main reasons for Arduino boards have quickly emerged as an attractive option for sensor management, and also as an important resource for data acquisition, is partly because it does not involve a significant monetary investment for the user (Delgado-Castro and Rojas-Bolaños, 2014). Ferdoush and Li (2014) cite the lack of reliability, flexibility, scalability , interoperability, and the difficulty of operability and maintenance of long-term deployments as the main obstacles for the sensor technology become a transformation in the field of science and engineering.

In a technological world, a great challenge for the teachers is to know how to integrate new technologies into the classroom every day, which is often limited to theoretical training of the student. In this context, the use of technological tools can bring some innovation to the classroom. Much is said about the need to educate for the media, that is educating for the use of the tool itself in the digital world.

Using the Arduino as an educational tool can approximate the student to the study material, so that, there is greater interaction of students with the discipline, making enhanced the process of learning. It allows interaction and the application of new concepts, developing logical thinking and generating solid knowledge. This tool offers a wide range of interdisciplinary and can be used not only in traditional areas of technology (engineering , electronics, computing) but also aggregating knowledge and bringing technology into other areas, expanding the perception of both - the teacher and the student - and working the creativity to develop solutions to new problems. In the scope of the high school as well as being useful in the exploration of more interactive content - as this stage students are more scattered, but, paradoxically more interested when the new is presented - would help the student to understand their surroundings in more intuitive way.

Thus, the aim of this study is to test the use Arduino a low cost Data Acquisition System. The free vibration response of a beam sample is tested through simple accelerometers. The results are compared with a standard DAQ and also numerical results for a beam element. Finally, some discussions are performed concerning the results of the behavior,the sample rate and the numerical aproximation, aiming to test the feasibility of this alternative equipment for small tests and educational experiments in the dynamical monitoring of civil structures.

2 STANDARD DATA ACQUISITION SYSTEMS

A data acquisition system works through a process that makes the capture of the physical measurement data and then converts the results into a digital format which is handled by a computer program (Kos et al., 2012, Sumphao et al., 2012).

Also in accordance with Kos et al. (2012), there are three basic types of data acquisition systems: modular acquisition systems, systems based on autonomous instruments and computer-based systems. Modular acquisition systems are usually connected to a specific local bus, such as VXI or PXI, allowing a more powerful configuration DAQ. Is mostly used for systems with a need for future growth. The systems based on autonomous instruments are independent of the computer's bus, but has the ability to connect to it via serial or parallel communication. They are mostly used in applications that require capturing a large number of variables. Computer-based systems are responsible for performing the signal conversion analog to digital and then the computer performs the processing, storage, and viewing. Can be connected to the computer via bus or wireless depending on the application. Sumphao et al. (2012) cited the advancement of technology in integrated electronic circuits that has created a new platform in the DAQ system, the DAQ -based microcontrollers, whose popularity is associated with low cost when compared to conventional DAQ.

There are many applications for DAQ, not only in the field of industry, but also in research, as can be cited: the use of low-cost DAQ in astronomy (Kunwar et al., 2015); monitoring photovoltaic (Fuentes et al., 2014); accurate measurements (Martín et al., 2014); renewable energy systems (Kalaitzakis et al., 2003, Gad and Gad, 2015). Engineers and scientists often use the data obtained by the acquisition systems to research unknown characteristics through measurement and analysis (Martín et al., 2014).

3 ALTERNATIVE DATA ACQUISITION SYSTEM

3.1 Arduino

The Arduino was established in 2005 in the Interaction Design Institute Ivrea, Italy, as a system that allowed the students to develop interactive projects. It consists of a microcontroller set to a small printed circuit board; It is equipped with sockets to allow the connection of external devices with digital and analog input and output, as well as being open source hardware and software. Soon after its inception, Arduino began to be used in hobby projects, such as drones and robots (Mesas-Carrascos et al., 2015).

Arduino Uno is an open-source micro-controller development board based on Atmega328, whose microcontroller has a clock speed of 16 MHz. Its features include 32 KB flash memory with read-while-write capabilities, 1 KB EEPROM, 2 KB SRAM, 23 general purpose I/O lines (GPIO), 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts, serial programmable UART, a byte oriented 2-wire serial interface, SPI serial port, 6-channel 10-bit A/D converter, programmable watchdog timer with internal oscillator, USB connection and five software selectable power saving modes (Abraham and Li, 2014).

3.2 Accelerometer

A sensor is a device that is capable of measuring physical attributes and convert them into signals for the user. Such sensor networks have three basic functions : detection, communication and computing (Mesas-Carrascos et al., 2015).

A MEMS-based tri-axis accelerometer MMA7361 by Freescale Semiconductor has been chosen to measure accelerations along the x, y and z axis. According to the manufacturer, the MMA7361 sensor is a micromachined accelerometer with low power consumption signal conditioning (2.2 V - 3.6 V, $400\ \mu A$), temperature compensated , linear freefall detector and allows a selection between two sensitivities (1.5 g or 6 g), which are preset at the factory, high sensitivity (800 mV/g @ 1.5 g) and, the power spectral density is $350\ \mu g/\gamma z$ (Semiconductor, 2008, Andò et al., 2014).

4 EXPERIMENTAL METODOLOGY

Several types of sensors are used in combination with arduino with the goal to create low cost automation systems. Although there are few works using the same system as an electronic measure tool. The goal of this experiment is to test how much accuracy the sytem produces, if compared with a standard DAQ.

Metodology described above considers the free vibration of a clamped-free beam. Accelerometer is placed at the free edge and connected to Arduino. Strain Gage is placed close to the clamp and connected to Standard DAQ. Figure 1 shows the experimental scheme.

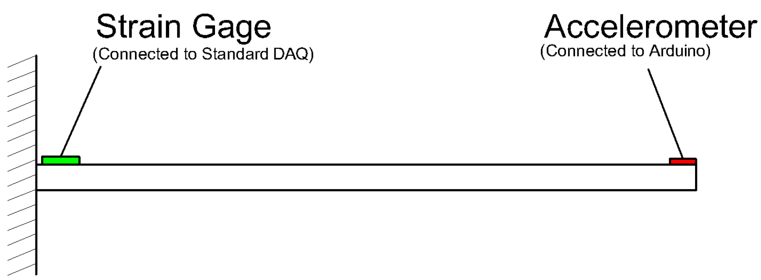

Figure 1: Clamped-Free Beam Virtual Force Scheme

4.1 The Free Vibration Phenomenon

The behavior of the structures occurs in two equilibrium states. Statical equilibrium occurs when there is no short period excitation from external forces. In this case the energy from external forces is converted into strain and no motion occurs in the deformed structure. Dynamical equilibrium occurs when a structure is disturbed from its statical equilibrium state and vibrates without any external dynamical excitation (Chopra, 1995, Cheng, 2001).

In the free vibration phenomenon, all points of the structure vibrates in a same frequency called natural vibration frequency. Considering a single point of structure, its displacement in function of the time describes a damped sinusoid function, as shown in figure 2.

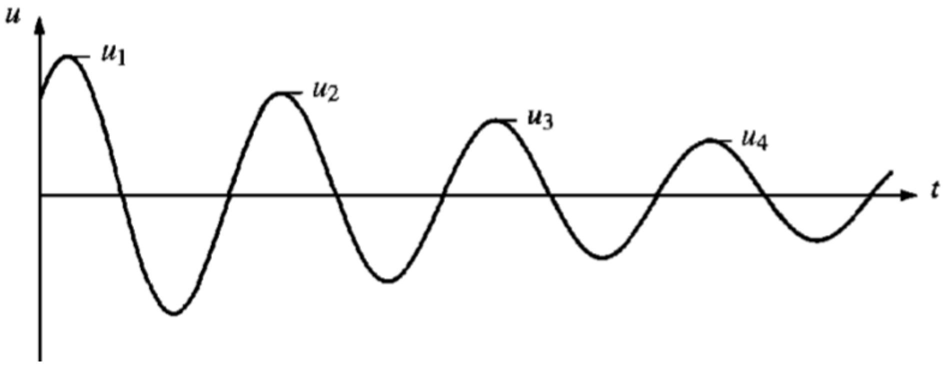

Figure 2: Damped Free Vibration Oscilation of a Single Point (Chopra, 1995)

The damping, in other words the displacements decay, is a natural tendency to return to its statical configuration. In this scope, the relation between damped frequency and free vibration frequency is considered to be the same, since damping in civil structures is underdumping, it means less than 10% decay rate (Chopra, 1995). Experimental manipulations are performed above to prove this hipothesis.

4.2 Aquisition Measures

Strain Measures

In professional DAQ, strain measures are acquired from Strain Gage model KFG-10-120-C1-11 manufactured by Kyowa and wired in quarter bridge. Information are sent to the DAQ model Lynx - ADS2000, configured to acquire data in a frequency of $100Hz$, i.e. one measure per 0.01 seconds.

Aiming to proof the compatibility between strain and transverse displacement field of a clamped-free beam, consider in its first vibration mode a transverse displacement function of the free edge descibed by a time function $u(t)$ as shown in fig. (3).

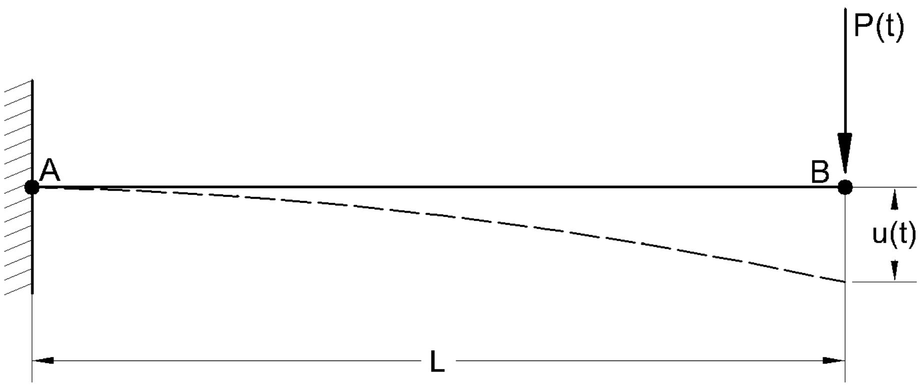

Figure 3: Clamped-Free Beam Virtual Force Scheme

The impact of $u(t)$ in a point close to clamped edge can be described by assume a virtual force acting in B which is related with $u(t)$ by development of elastic line (Lai et al., 2010) given by:

$$u(t) = \frac{-P(t)L^3}{3EI}, \tag{1}$$

where $P(t)$ is the virtual force functions, L the beam lenght, E and I respectively the Young Modulus and the Inercia Moment of the beam.

By the acting of virtual force $P(t)$, the moment in the clamp is given by:

$$M_A = \frac{-u(t).3EI}{L^2}. \tag{2}$$

Following pure bending and considering linear elastic material, the strain in the clamp is written as:

$$\epsilon_x(t) = \frac{2h}{2L^2}.u(t) \tag{3}$$

where h is the height of beam's cross section. As parameters h and L are strictly dependent of beam's geometry:

$$\epsilon_x(t) \propto u(t). \tag{4}$$

Equation (4) shows that measures of the strain field in the clamp leads to the same results as measures of the displacement field in the edge. The system differs in terms of wave amplitude but the oscilation properties as vibration frequency and damping ratio are equally acquired.

Acceleration Measures

In alternative Arduino DAQ, acceleration signals are sent to computer every $32ms$. The results are collected and stored as accelerations in function of time. Mathematical concerning treatment as a system filter, time could be stored as a linear space with 32 miliseconds step.

As the strain, acceleration field can be also tied with displacement by using of the second derivative of a damped motion. Considering no inicial displacement, the motion of a single point in the structure could be descibed as a single degree of freedom motion. The displacement equation, adapted from expressions developed by Chopra (1995) and Rao (2005) given by:

$$u(t) = [\frac{\dot{u}(0)}{\omega_n}]\, e^{-\zeta\omega_n t}\, sin(\omega_n t) \tag{5}$$

where ω_n is the natural vibration frequency of the single point, ζ is the damping ratio and $\dot{u}(0)$ the inicial velocity given to the system.

The velocity field (first derivative of eq. 5) is given by:

$$\dot{u}(t) = \dot{u}(0)\, e^{-\zeta\omega_n t}\, cos(\omega_n t) + \zeta\dot{u}(0)\, e^{-\zeta\omega_n t}\, sin(\omega_n t). \tag{6}$$

The terms related with cossine vanishes in the second derivative. Acceleration fiel is given by:

$$\ddot{u}(t) = [(-1-\zeta^2)\dot{u}(0)\,\omega_n]\, e^{-\zeta\omega_n t}\, sin(\omega_n t). \tag{7}$$

since the terms ζ, ω_n and $\dot{u}(0)$ are constants:

$$\ddot{u}(t) \propto u(t) \propto \epsilon_x(t) \tag{8}$$

Equation (8) shows that strain and acceleration measures can be compared with each other, since those functions represents the same motion behavior.

4.3 Mathematical Treatment

Signal filtering by a Discrete Fourier Transform are performed, aiming to read accurate frequency results. Fourier Transform descomposes the wave into a sum of sinusoids with different frequencies (Brigham, 1988).

Given a function $u(t)$ with N discrete samples, Fourier Tranform is defined in $u(t) \rightarrow F(f)$ and given by:

$$F_n = \sum_{k=0}^{N-1} u_k \, e^{-2\pi i n k/N} \tag{9}$$

This transformation changes the time domain to frequency domain. Natural vibration frequencies are defined on the transformed wave peaks (Oppenheim et al., 1999)

4.4 Statical Test

Material's Young Modulus is obtained by experimental procedures. A known force is applied in clamped beam's free edge and Young Modulus is determined in function of maximal deflection. The maximal deflection in a clamped-free beam with a single force acting in the free edge is described by eq. (1) with no transient parameters, or:

$$u_{max} = \frac{-PL^3}{3EI}. \tag{10}$$

With known geometric properties L and I, the impact u_max of the known force P determines E.

There's a high amount of technology to find accurate values of Young Modulus. A complete reference of these technologies is approached by Alves et al. (2013). By an educational scope, this work presents a simple and easy method to find E.

4.5 Analytical Comparisons

The results of the natural vibration frequencies can be compared with the analytical solution of the differencial equation which describes the free vibration of the Euler-Bernoulli Beam. The solution, developed by Petyt (2010), is given by:

$$cos(\kappa_r L).cosh(\kappa_r L) + 1 = 0 \tag{11}$$

where L is the beam lenght and κ_r a coeficient determined by:

$$\kappa_r = \sqrt[4]{\frac{\omega_r^2 \rho A}{EI}} \tag{12}$$

where ω_r is the natural vibration frequency, given in rad/s, A the cross sectional area, ρ is the specific mass.

The solution to eq. (11) is given by Zeng (1998b), where the first root is:

$$\kappa_1.L = 1.87510407 \tag{13}$$

which lead to the expression:

$$\frac{\omega_1 \rho A}{EI} L^4 = 12.3623634 \tag{14}$$

The first analitcal vibration frequency is determined as:

$$f_1 = \frac{12.6323634 \; E \; I}{2\pi \; \rho \; A \; L^4}. \tag{15}$$

5 EXPERIMENTAL RESULTS

5.1 Specimen Properties

The specimen used in the experiment has its properties given by Table 1. Cross sectional area is retangular with base $b = 5cm$ and height $h = 0.57cm$.

Table 1: Specimen Properties

Property	Value
Beam Lenght (L)	$0.86\ m$
Cross Sectional Area (A)	$2.85E - 4\ m^2$
Inercia Moment (I)	$7.71E - 10\ m^4$
Specific Mass (ρ)	$711.67\ kg/m^3$
Young Modulus (E)	$15.73E + 9\ Pa$

Properties L, A and I are acquired by geometric measure, ρ by scale and E by eq. (10).

5.2 Analytical Solution

Replacing the properties shown in Table 1 in eq. (15), the analytical vibration frequency is:

$$f_1 = 5.896901 Hz \tag{16}$$

5.3 Results From Standard DAQ

Three tests with the same specimen are performed in standard DAQ. Measured frequencies in the tests are given by table 2:

Table 2: Free Vibration Results from Standard DAQ

Test Number	Vibration Frequency - f (Hz)
1	5.89354
2	5.90985
3	5.9215

Figure 4 shows the strain field of a test performed with the standard DAQ. Figure 5 shows the same results treated with Fourier Transformation.

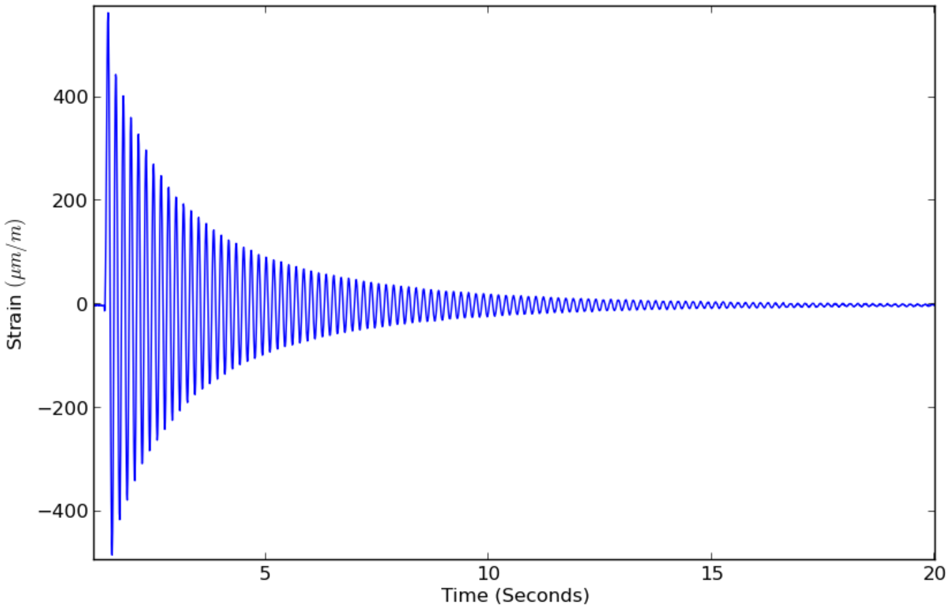

Figure 4: Vibration Test Performed in Standard DAQ

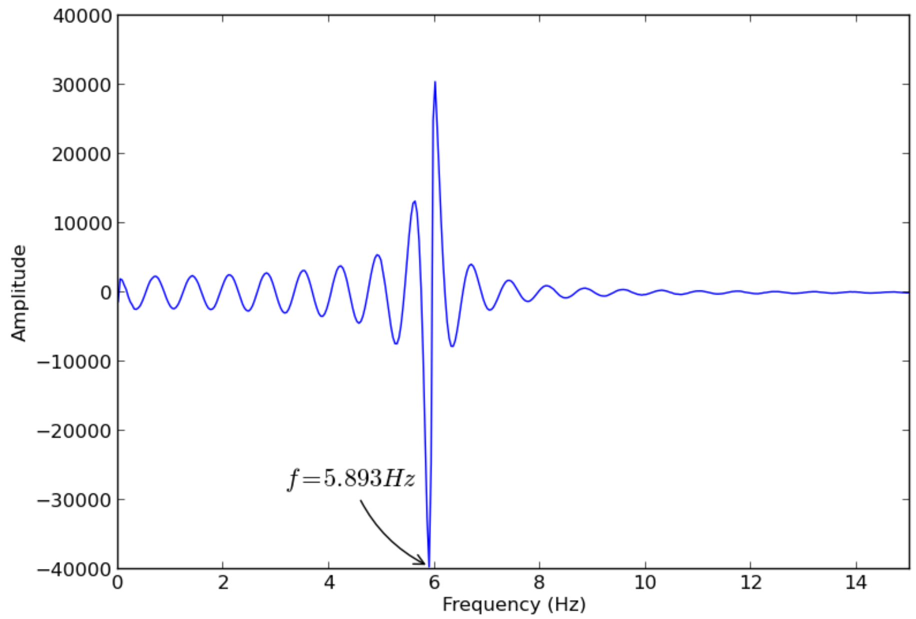

Figure 5: Fourier Tranform of Vibration Test Performed in Standard DAQ

From strain field, the damping ratio ζ can be estimated by decay of motion equation

(Chopra, 1995):

$$\frac{u_i}{u_{i+1}} = exp\left(\frac{2\pi\,\zeta}{\sqrt{1-\zeta^2}}\right) \tag{17}$$

where u_i and u_{i+1} are two consecutive wave peak values. The damping ratio value determined for this motion is $\zeta = 0.03794575 = 3.79\%$

By the relation between free vibration frequency and damped vibration frequency also given by Chopra (1995):

$$\omega_D = \omega_n\,\sqrt{1-\zeta^2} = \omega_n\,\sqrt{1-0.0379^2} = 0.999\,\omega_n, \tag{18}$$

the frequencies are proven to be close values, i.e.:

$$\omega_D \approx \omega_n. \tag{19}$$

5.4 Results From Arduino DAQ

In arduino three tests are also performed. The natural frequencies results are given in table 3:

Table 3: Free Vibration Results from Arduino DAQ

Test Number	Vibration Frequency - f (Hz)
1	5.82373
2	5.65145
3	5.910

Figures 6 and 7 shows respectively the acceleration field of a test performed in arduino and its treatment by Fourier Transform.

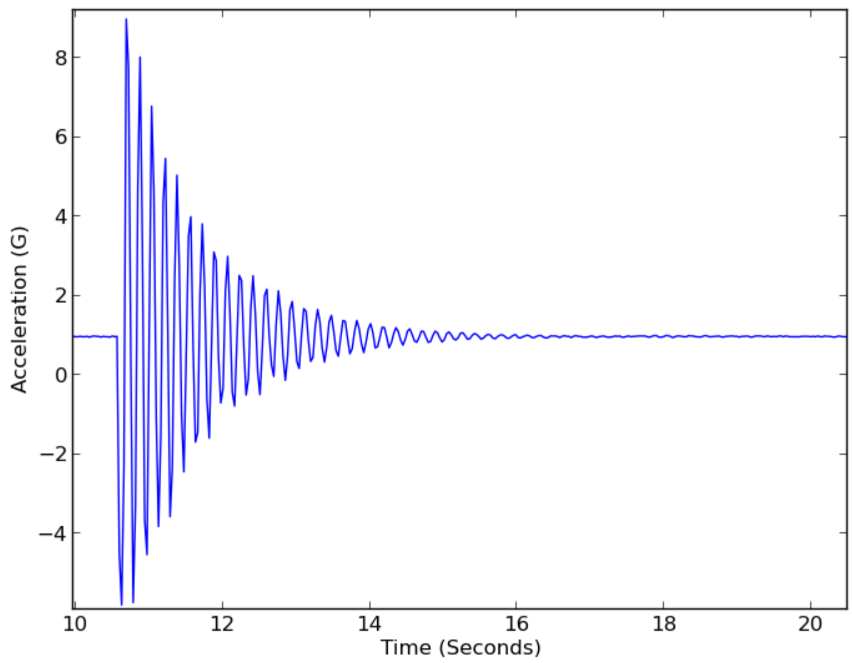

Figure 6: Vibration Test Performed in Arduino

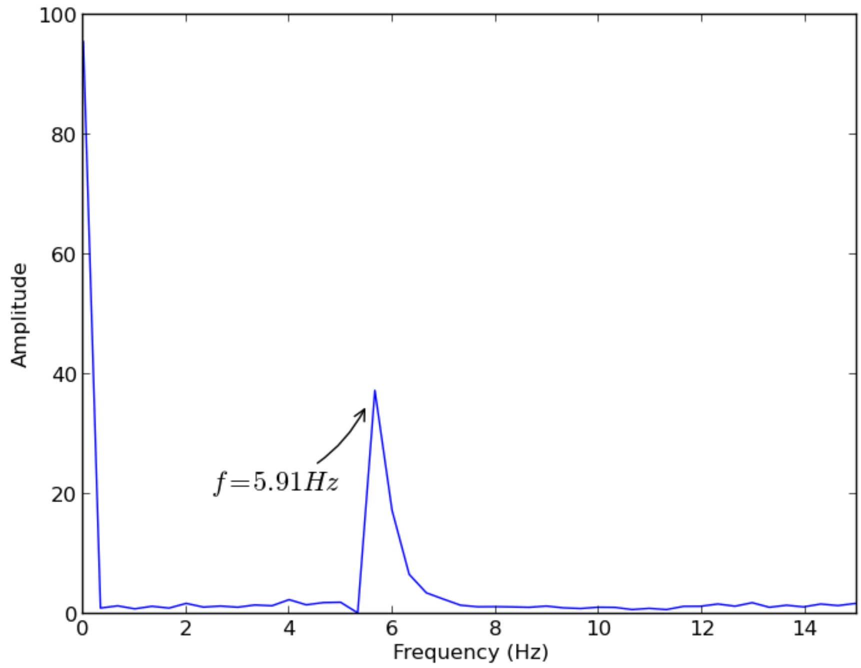

Figure 7: Fourier Tranform of Vibration Test Performed in Arduino

5.5 Error Comparisons

Results are compared with the analytical solution by relative percentual error in table 4.

Table 4: Relative Errors Between DAQs and the Analytical Solution

Test	Error by Standard DAQ	Error by Arduino DAQ
1	0.056 %	1.24 %
2	0.219 %	4.16 %
3	0.417 %	0.22 %

6 CONCLUSIONS

This work tested an alternative low cost DAQ for vibration measures based in the open-source hardware Arduino. The general view of DAQS and some technical specification were briefly described.

The experimental results shows the already expected high accuracy for the tests performed with standard DAQ. However, the Arduino tests presented acceptable results for small tests which don't require high precision.

Even in an acceptable range, the reason why Arduino results are worst than standard DAQ is related with the difference between transfer rate, which depends from computer configuration and the type of transfer. The system accelerometer plus cables could create a lamped mass system, in the free edge, being this verification a suggestion to future works in this scope. New experiences with Arduino to other kind of materials, systems and measures are also suggestion for future applications.

Arduino plus simple accelerometer was a successfull tool to acquire vibration data of a simple structural system. Transfer rate issue can be improved, aiming to increase its accuracy and feasibility to real engineering problems.

The use of Arduino not only proved to be accurate and effective as an educational tool, but also being considerable important in order to make the classes even more attractive, participatory and efficient. There is the need to openness the educational systems mind to the technological development in order to go along and steer the students formation. The idea is not to leave the blackboard, but use new technologies to improve and aggregate in the classroom.

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