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MECHANICAL MEASURENTS WITH MEMS SENSORS: AN EDUCATIONAL APPROACH

Anderson L. Silva
Federal University of Paraná, Curitiba, Paraná, Brazil
anderson.langone@outlook.com

Marcus Varanis
Federal University of Grande Dourados, Dourados, Mato Grosso do Sul, Brazil
marcusvaranis@ufgd.edu.br

José Manoel Balthazar
Federal Technological University of Paraná, Ponta Grossa, Paraná, Brazil
balthazar@utfpr.edu.br

Abstract. In this paper the Ardunino Mega 2560 board is used together with low-cost MEMS sensors for the instrumentation of mechanical systems. To perform the experiments was utilized an ultrasonic distance sensor, gyroscope and accelerometers for the instrumentation of mechanical vibrations and an amplifier module with strain gauges for strain measurement. The results show that the system is suitable for instrumentation of mechanical systems with educational purposes, presenting good precision.

Keywords: MEMS sensors, Arduino, mechanical measurements, low-cost data acquisition.

1. INTRODUCTION

Low cost microcontrollers have been widely used in a large range of applications, from hobby activities to industrial process control. Among the most used microcontrollers are the Arduino boards, which due to be commercialized in a ready-to-use format, has become one of the most widespread development platforms. The main purpose of the Arduino is to be an easy-to-use tool for assembling electronic circuits and small electromechanical systems.

This paper aims to present the Arduino board and low cost sensors as an alternative to conventional instrumentation systems. The proposed system is applicable both in educational experiments, which can be performed even in the classroom, (Varanis *et al.* (2016)), as well as in applications that require good precision, such as in Ratcliffe *et al.* (2008), where low cost accelerometers are used for damage detection. The proposed system provides versatile data acquisition systems for undergraduates in order to measure their own experiments at a low cost.

It is clear that in practical classes the student has the opportunity to apply the theory assimilated in classroom in everyday problems, such as determining the frequencies of a system, measuring the vibration level or the deformation of an shaft. These activities allow the student to observe the theoretically treated phenomena and absorb them more easily, but often the necessary equipment is expensive and complex to operate.

It is possible to find in the literature several works that make use of the Arduino and low cost sensors for the instrumentation of mechanical systems. In Iacono *et al.* (2017) the MPU-6000 accelerometer was used for vibration monitoring of the Himera viaduct in Italy, Varanis *et al.* (2016) applied several low cost sensors for mechanical vibration instrumentation, in Varanis *et al.* (2018b) low cost accelerometers are used in the instrumentation of an m-dof system and Varanis *et al.* (2018a) analyzed the performance of several low-cost accelerometers. In Silva *et al.* (2019) the Arduino board was used together with strain gauges for strain measurement in mechanical systems.

This paper is structured into some sections. The section 2 presents the characteristics of the proposed acquisition system and of the utilized sensors, section 3 presents the test benches used to evaluate the sensors and the section 4 presents the experimental results obtained. In the section 5 the final considerations of this work are presented.

2. DATA ACQUISITION SYSTEM AND SENSORS

In this work the Arduino board, model Mega 2560, is used to perform the instrumentation of mechanical systems by means of low cost sensors, such as accelerometers, gyroscope, ultrasonic distance sensor and strain gauges. The choice
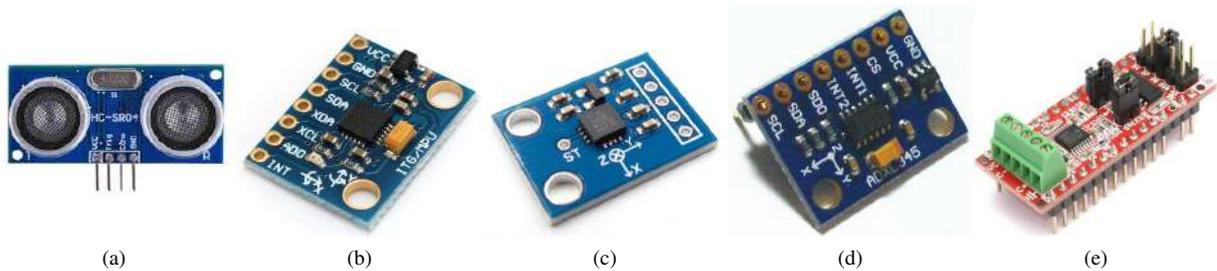
Figure 1: Utilized sensors in this work: 1a ultrasonic distance sensor, 1b MPU-6050 accelerometer and gyroscope, 1c ADXL-335 accelerometer, 1d ADXL-345 accelerometer and 1e Nanoshield LoadCell.

of the Arduino microcontroller is due to its low-cost, versatility and facility of programming.

The Arduino Mega 2560 is based on the Atmel ATmega2560 microprocessor that have 54 digital I/O pins, of which 15 pins can be used the PWM outputs, 16 analog inputs, 4 serial ports and can be powered by the USB port of a computer or by means an external source. The connection between the computer and the Arduino is performed through the USB port and the Arduino receives the data from the sensors through its analog and digital ports. In Varanis *et al.* (2016) detailed information about the Arduino Mega 2560 is provided.

In this work is utilized the Invensense MPU-6050 accelerometer and gyroscope, the Analog Devices ADXL-345 and ADXL-335 accelerometers and an ultrasonic distance sensor, model HC-SR04. For strain gauge instrumentation, the Nanoshield LoadCell module, manufactured by Circuitar was used for amplification and digitization of the signal. The specifications of the utilized sensors will be provided on the next subsections. In Fig. 1 are presented the utilized sensors in this work.

2.1 HC-SR04 ultrasonic distance sensor

The ultrasonic distance sensor measures the distance of an object through the reflection of sound waves. The operation of this sensor is explained in detail in Varanis *et al.* (2016).

The sensor used was the HC-SR04 (Fig. 1a) which according to the datasheet can measure distances from 2 to 400 *cm* with an accuracy of 3 *mm*. Unlike the other sensors used in this work, the ultrasonic sensor is the only that does not require contact with the mechanical system.

This sensor works based on the sound speed in the air, it determine the distance to an object measuring the time between the emission of a sound wave and the reception of a reflected one by an obstacle. Positioning the sensor in a proper manner it is possible to measure the instantaneous position of an object.

2.2 MPU-6050 accelerometer and gyroscope

The Invensense MPU-6050 is a device that integrates three-axis accelerometer and gyroscopic sensors. The accelerometer of the MPU-6050 measures static and dynamic accelerations and the gyroscope measures the angular velocity due to the Coriolis effect. In addition, the maximum sampling frequency of the accelerometer and the gyroscope is 1 *kHz* and 8 *kHz*, respectively. The accelerometer operates in a measure range of up to ± 16 *g* and the gyroscope has a working range of up to $2000^{o}/s$. The obtained signals are digitized by an 16-bit ADCs for both sensors.

As this sensor already digitizes the signals, the samples are transmitted to the Arduino digitally by I2C communication. The sampling frequency in this case, besides having the limitations of the sensor ADC, is still limited by the speed of the I2C connection.

2.3 ADXL-335 Accelerometer

The Analog Devices ADXL-335 sensor is an analog accelerometer capable of measuring dynamics and statics acceleration in the three axes in a range of ± 3 *g* with a signal conditioning voltage output. In this work the signal from the ADXL-335 is digitalized by the 12-bits ADC of the Arduino and the sampling frequency is limited by the board oscillator clock.

2.4 ADXL-345 Accelerometer

The Analog Devices ADXL-345 accelerometer is also triaxial, capable of measuring static and dynamic accelerations in a user-programmable range up to 16 *g*. The ADXL-345 signals are digitized by an 13 bits ADC and the acquired data is sent to the Arduino by means of the I2C or SPI protocols. This sensor has a maximum sampling frequency of 3200 *Hz* and the data pass through a low pass filter with a cutoff frequency of half the sampling frequency.

2.5 Strain measurement proposed system

For the deformation measurement experiments the Nanoshield LoadCell module, manufactured by Circuitar based on the ADS1230 amplifier, was used. The Nanoshield board includes an amplifier, a filter and a 20 bits ADC with a sampling frequency up to 80 *Hz*, which makes the module a high-resolution tool for converting analog signals, especially those from load cells and Wheatstone Bridges, because these systems return low amplitude signals.

3. EXPERIMENTAL PROCEDURES

For the execution of the experiments three different benches are used. For the evaluation of the systems for mechanical vibrations instrumentation the experiments are carried out in a cantilever beam and in a shear building with three degrees of freedom. In the case of the system for measuring deformation the experiments are performed on a cantilever beam under flexion and in a shaft under torsion. The benches used are presented in the next subsections. In Fig. 2 the systems instrumented in this paper are presented.
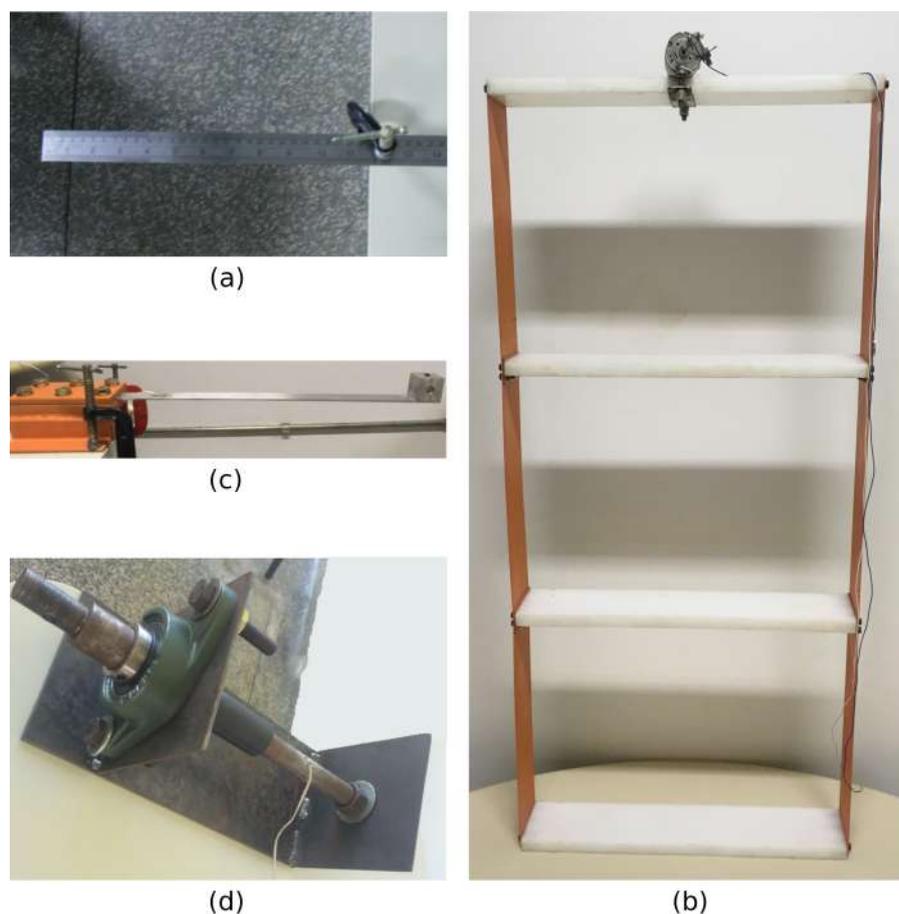

Figure 2: Mechanical systems instrumented in this paper: 1a cantilever beam for the vibration experiment, 1b shear-building, 1c cantilever beam for the strain experiment and 1d crimped-supported shaft.

3.1 Mechanical vibration tests

To evaluate the sensors used for the instrumentation of mechanical vibrations was used a stainless steel stud and a shear building with three degrees of freedom. Discrete analytical models of these systems can be found at Varanis *et al.* (2019)and Inman and Singh (1994).

The signals of the cantilever beam were obtained from the MPU-6050, acquiring data of acceleration and angular velocity, and the ultrasonic distance sensor. The dimensions of the beam are 27.74 *mm*, 1.04 *mm*, 300 *mm*, respectively width, height and length. In this experiment the beam is excited only by an initial displacement.

The shear-building was instrumented only with the accelerometers mentioned in the previous section. The shearbuilding consists of four polypropylene plates with dimensions of 400 x 76.2 x 15 *mm*, and six ASTM A-36 steel plates with dimensions of 300 x 76.2 x 1.75 *mm*. The complete structure possesses dimensions of 900 x 400 *mm*. Figure 2.(b) show the shear-building studied.

On the top floor there is a DC motor unbalanced with a mass of 6.59 *g* at a distance of 15 *mm* from the axis of rotation,

but in this paper the motor was not used.

3.2 Stress and strain measurement

In order to evaluate the proposed system for strain measurement was utilized two systems: a cantilever beam and a cantilever-supported shaft. In the beam was applied a force of 0.981 *N* at it's free end and the strain gauge was glued at 30 *mm* from the fixed end in the center of the upper face. In the torsion shaft experiment a torque of 3.6 *N/m* was applied and the strain gauge was glued at 45° of the axis of symmetry of the shaft. Analytical models for the strain at the points of interest of these systems can be found in Timoshenko (1940) and Beer *et al.* (2002).

4. RESULTS

In this section the experimental results are presented and discussed. The section 4.1 presents the results of the mechanical vibration experiments using the Arduino board as a low cost data acquisition system and the section 4.2 presents the results of the use of a low cost amplifier and strain gauges for strain measurement in mechanical systems.

4.1 Mechanical vibration tests

In the vibration tests performed on the cantilever beam was used 35 *Hz* as sampling frequency and 1024 points was acquired with the MPU-6050 sensor while with the HC-SR04 sensor was acquired 512 points. It is observed that the signals obtained with the ultrasound sensor are noisier than those obtained by means of the MPU-6050 and due to it the signals obtained through the ultrasonic sensor were acquired with fewer points. Was observed that after a determined set of points the signal became impregnated with noise. Nevertheless, the results shown that both sensors have good precision in the frequency domain, presenting values very close to those obtained analytically and by the finite element method.

Figure 3 presents the experimental results in the time domain and their periodogram, by means the Power Spectrum Density (PSD) technique. From the analysis of the results it is observed in the PSD of the MPU-6050 acceleration signal indicate some noise in the signal, which is not easily detectable in the time domain. The periodogram from the gyroscope signal is much cleaner than the acceleration signal periodogram. Was observed that the signal from the ultrasonic sensor is extremely noisy, both in the time domain and in the frequency domain, but also presents good results in the frequency domain.
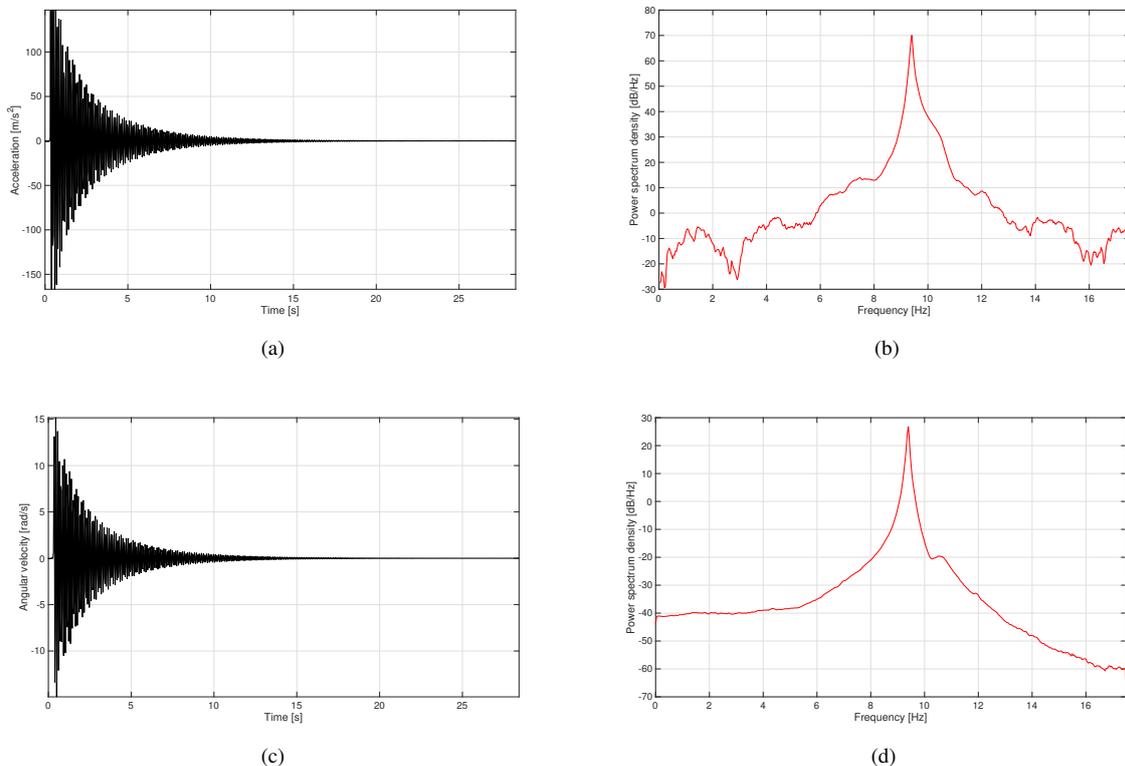

(a)

(b)

(c)

(d)

Figure 3: Beam vibration signals acquired with different sensors and their periodograms: 3a MPU-6050 acceleration signal and 3b its periodogram, 3c MPU-6050 angular velocity signal and 3d its periodogram and 3e HC-SR04 displacement signal and 3f its periodogram *(cont.)*
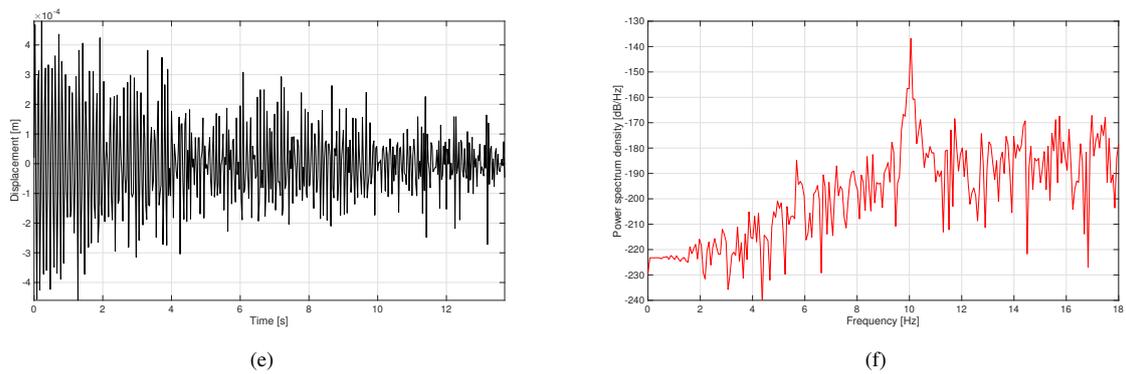
(e)

(f)

Figure 3: *Continuated.*

In the tests performed in the shear-building was utilized a sampling frequency of 1000 Hz and 8192 points were acquired. The results obtained in this experiment were also very satisfactory, although there is a small divergence with the analytical and FEM results, it is observed that both sensors used presented the same results, and the standard deviations in the samples are very close to zero.

Figure 4 presents the experimental results of the shear-building free vibration tests. The signal periodograms clearly show the three shear-building natural frequencies, presenting signals free of noise.
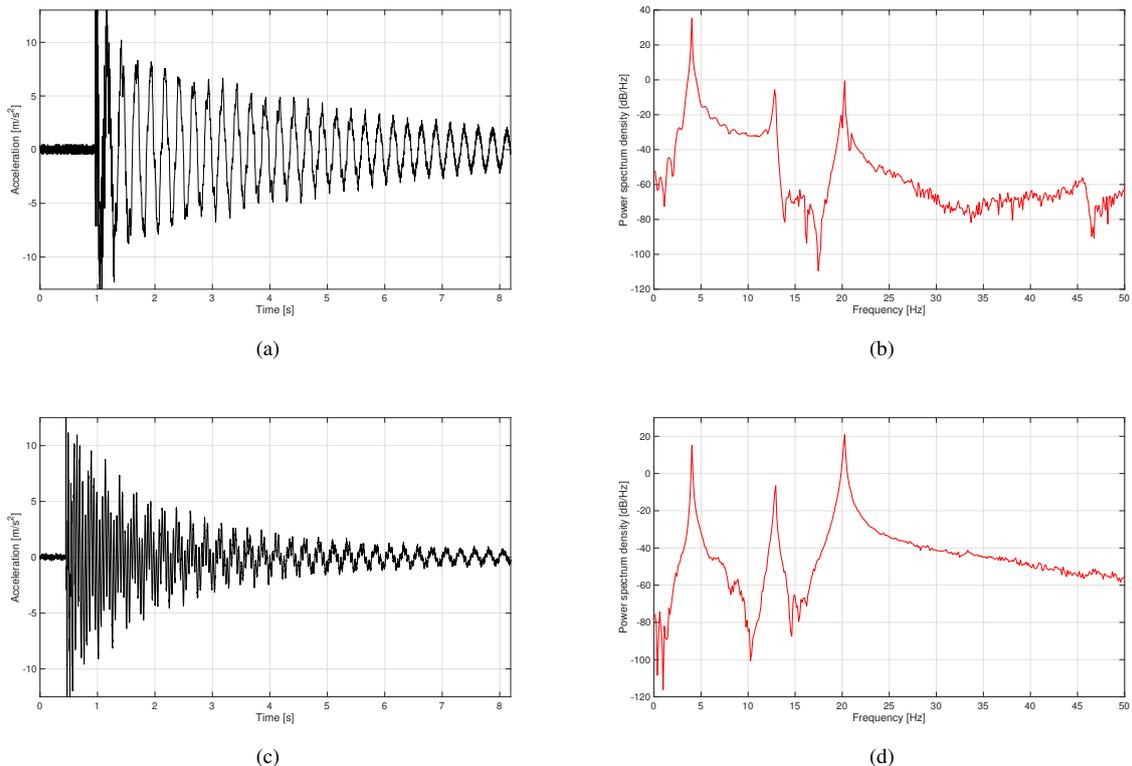

(a)

(b)

(c)

(d)

Figure 4: Shear-building vibration signals acquired with different accelerometers and their periodograms: 4a ADXL-335 acceleration signal and 4b its periodogram, 4c ADXL-345 acceleration signal and 4d its periodogram and 4e MPU-6050 acceleration signal and 4f its periodogram *(cont.)*

By means of the presented results was observed that the proposed measurement system is suitable for mechanical vibration analysis, providing signals free of noise. The sensor with the highest noise ratio was the HC-SR04 ultrasonic sensor, but the natural frequency is still apparent in the periodogram.
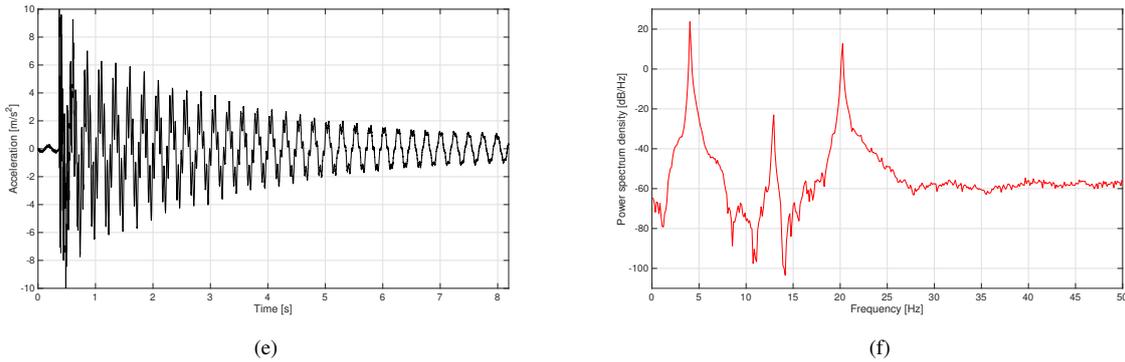
(e)

(f)

Figure 4: *Continuated.*

The results obtained are shown in Tab. 1 and are compatible with those found in the literature. In addition the sensors presented similar results and low standard deviation among the samples, showing that the acquisition system composed by the Arduino microcontroller and low cost sensors are completely suitable for mechanical vibration instrumentation.

Table 1: Analyticals, by finite elements and experimental results obtained in the mechanical vibration instrumentation experiments.

| | Cantilever beam | Shear-building | | |
	1st mode	1st mode	2nd mode	3rd mode
Analytical	9.408	4.090	12.540	19.320
Finite elements	9.356	4.750	14.698	20.367
ADXL-335 Accelerometer	—	4.280	12.940	20.260
ADXL-345 Accelerometer	—	4.280	12.940	20.260
MPU-6050 Accelerometer	9.380	4.280	12.940	20.260
MPU-6050 Gyroscope	9.380	—	—	—
HC-SR04	10.050	—	—	—

4.2 Strain measurement tests

For the strain measurement experiments by means of strain-gauges were realized static tests in both systems through the insertion of a load to the system. The data acquisition was performed with a sampling frequency of 80 Hz and 256 points per sample.

Since only static tests were performed, the signal processing was performed to obtain the strain value at the point of interest. The values obtained are presented together with the analytical results and by finite elements in the Tab. 2. The experimental results are in acordance with the literature, indicating that the proposed measurement system can also be applied in strain measurement, providing good results.

Table 2: Analyticals, by finite elements and experimental results obtained in the strain measurement experiments.

	Cantilever beam	Crimped-supported shaft
Analytical	208.83	14.02
Finite elements	207.98	14.49
Experimental	207.3	13.3

5. CONCLUSIONS

The results shown that the Arduino boards and low-cost sensors can be used safely in the instrumentation of mechanical systems, providing a portable instrumentation system, easy to use, reliable and with low cost. The results show that the system is reliable for mechanical vibration measurement, since it did not present a divergence between the values obtained by the sensors. The displacement signal obtained by means the ultrasonic sensor was very noisy, but the periodogram indicate a frequency compatible with the natural frequency of the beam.

All the tested accelerometers provided very clear signals in both experiments, indicating that such sensors can be used for instrumentation of mechanical vibrations with educational purposes.

In the case of strain measurement, it was not possible to compare the results obtained by the proposed system with other strain measurement systems, but the results were close to those expected and presented low standard deviation, indicating that the system is reliable for the proposed purposes.

In future works it is proposed the use of infrared distance sensors for displacement instrumentation in order to reduce the noise level in the signal, besides testing other sensors and open-source platforms.

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