Validation of an In-House developed acquisition system using a commercial acquisition system and the theoretical model of a clamped beam

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Abstract: Vibration analysis is a technique that allows understanding through visualization of the frequency spectrum the propagation of vibrations in which a body is receiving from external forces. At a laboratory, the type of study allows the students to learn the concepts of this "invisible" force that is present in all the bodies, and it also helps to understand how the material characteristics and the sample specimen's geometry behave in these situations. Therefore, the objective of this project is the development of a didactic kit that allows the study of modal vibrations in test specimen such as beams, without the need of a vibration analysis equipment available in the market, that, in addition to the high cost, this equipment has reserved construction characteristics, that requires specialized training to understand how it works. For this validation process, the kit results were compared against the mathematical model of the beam, whose first natural frequency is around 7Hz, and a commercial hardware available in the market. With these results, it was possible to evaluate the reliability and accuracy of the acquisition system in relation to computational models.

Keywords: accelerometers; didactic kit; low-pass filters; modal analysis; vibration analysis.

1 Introduction

Modal vibration analysis systems are equipment developed with the intention to measure the vibration that a structure emits when it is excited, for example by impacts. The resulting movements are captured through accelerometers, which are the basis for the acquisition system. Accelerometers are sensors with the capacity to measure acceleration of a body in the moment they are excited. According to Levinzon [1], these electronic components are applied in several areas, such as in the geophysical field to measure seismic waves from tectonic movements and also in the mining field to search for oil. Although, the main use for these accelerometers is in industry, capable of detecting vibration modes from structures with varied materials and geometry.

Due to the harsh industrial environment conditions, that could bring chemical and physics risks to electronic components, the accelerometers are designed with armored casing to avoid deterioration and loss of precision and then leading to the equipment great longevity and improved measurement accuracy. However, this robustness prevents understanding in a didactic form about the layout of internal components, as the working principle and the interaction with the sample specimens.

This project has the main objective to develop an analysis vibration system composed of an accelerometer, analogue low-pass filters, and a microcontroller ESP 32 with A/D converter. In which, the development cost becomes lower than a commercial analysis system. In this way, the proposed project was built in the most didactic form possible to support teaching and learning of students in classrooms. Finally, this work performs the validation of the system developed in the laboratory by comparing the results against a commercial system.

2 Methodology

Accelerometers are equipment used in various sectors of the industry for an extensive range of applications, with a mechanical construction that can be varied according to the desired signal to measure. First, the way the piezoelectric cell is arranged in relation to the inertial mass, in which it is common to find two different models: the compression mode accelerometers and the shear mode accelerometers. Furthermore, according to Rodrigues [2], the way the data reading happens, the accelerometers could be classified as single axis or triaxial. Therefore, these characteristics are important for the choice of the accelerometer's model implemented. In this work the focus will be the resonance frequency reading which belongs to the single axis accelerometers.

The compression mode accelerometers were the first model to be created, their construction is simple, and they have in their interior an inertial mass pressed against a spring or a preload screw, which generates a force on the piezoelectric cell. However, they are susceptible to accelerometer base flexural and to thermal effects too. Meanwhile the shear mode accelerometers have in their interior a piezoelectric cell parallel to the inertial mass, which is compressed by an external preload ring parallel to the piezoelectric cell. According to Levinzon [1], in comparison to the compression mode, this model does not have the risks of suffering base flexural and thermal effects, because the base did not have direct contact with the piezoelectric cell. However, the compression mode, even with its disadvantages in relation to the shear mode, has a simpler construction and it also allows to capture a wide resonant frequency band.

For the study of the frequencies that will be collected by the accelerometer developed, first it is necessary to define the resonant frequency of the accelerometer and the inertial mass pre-load for the piezoelectric cell. For Beduschi, Weiss and Wolf [3] as cited by MENEZES; F.F, the resonance is the capacity of a material to vibrate spontaneously according to application of external forces above a body of these material, it means, that the resonance is a vibration with amplitude higher than the natural frequency of the system or the body the force was applied. The resonance frequency is defined by Equation (1):

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}. \quad (1)$$

In which "Fn" is the resonance frequency, "m" is the inertial mass and "k" is the material stiffness. In this project it was designed that the accelerometer will work with a 15kHz of frequency range. Therefore, using Equation (1) with an experimental mass of 7.87g of carbon steel, the resulting material stiffness is $7{,}3.10^4$ kgf/mm defined by Equation (2):

$$k = m\left(\frac{f_n}{0{,}5\pi}\right)^2. \quad (2)$$

So, with this data it was determined the pre-load screw stiffness, in which was selected a M4 hex screw with at length of 25mm, according to ISO 898-1 standard. Therefore, this calculation allows the development of a single axis and compression mode accelerometer with integrated electronics able to detect flexural frequencies from the selected specimen sample: a stillness steel clamped beam. The commercial system accelerometer compared for the validation is also a single axis and compression mode integrated circuit piezoelectric (ICP) accelerometer with 100 mV/g signal output.

After the amplification of the signals generated by an ICP accelerometer with integrated electronics is necessary the filtering of the signals collected for the vibration analysis. One of the methods used for filtering is the use of an operational amplifier (Op-Amp), according to Pertence [4], the Op-Amp based transistor emerged in the 1940s with the intention of replacing the valves that were used before. In this project the Op-Amp will be used to build a low-pass filter, with a cutoff frequency ($\boldsymbol{\omega}$c) of 10 kHz, which is the maximum frequency value that is allowed to pass in the filter, the range inferior to $\boldsymbol{\omega}$c is the desired range for the low pass filter, also this range is called pass band. However, the range superior to $\boldsymbol{\omega}$c is called cutoff band. According to Mazanti [5], the low-pass filters can be classified in three models: Butterworth, a filter with a flat curve in pass band values, Tchebychev, a filter that make a cut in the curve of the pass band when near to the cutoff frequency, and Bessel, a filter that reduce the pass band values in a linear way until the cutoff frequency. The low-pass filter of this project (Fig. 1) was designed with the tool "Filter Design Tool" by Texas Instruments and consists of a Bessel filter model with multiple signal responses and a cutoff frequency of 10 kHz.

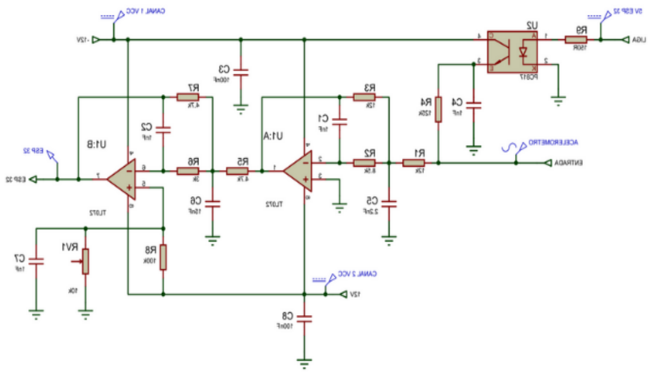

Figure 1 – Low pass filter diagram.

The assembly of the acquisition system consists of the union of the validated electronic components with the mechanical components, such as the connection of the accelerometer to the acquisition system through a coaxial cable and the connection with the ESP 32 microcontroller, responsible for collecting analog data and converting it into a digital signal for the MatLab software. This kit is shown in Fig. 2.

The acquisition was performed as follows: using MatLab with a sampling rate of 20kHz and a duration of 2 seconds, 40k samples were stored in the ESP32 buffer and subsequently sent to acquisition software via serial port and saved as a vector. A corresponding time vector was created for plotting and processing. In the digital filtering and processing of the signal, a Hanning window filter was implemented for signal periodization, followed by the FFT (Fast Fourier Transform), leading to the plotting and analysis in the frequency domain as presented in Fig. 6.

For the operation of the operational amplifier (Op-Amp), a symmetric power supply was made with +15V/-15V outputs, which allows for a greater gain compared to the +12V/-12V outputs used in the protoboard and PCB tests. After assembling the accelerometer with the acquisition system and the MatLab software, the validation process of the didactic acquisition system in relation to the commercial system shown in Fig. 3 began.

Figure 2 – Didactic acquisition system with the components arrangement.

Figure 3. Commercial acquisition system (SKF).

2.1 Calculation of the flexural natural frequency modules

For theoretical reference it was calculated the first three flexural modes frequencies in a clamped beam, which was the sample specimen for the acquisition system. The beam is made of stainless-steel alloy and has a length of 0.4 m, with a transverse section area of 49,83.10^{-6} m². The equation for the natural Frequency calculation can be seen below (Equation 3):

$$W_n = \frac{\propto^2}{L^2}\sqrt{\frac{E.I}{\rho.A}}. \tag{3}$$

In which, "W_n" is the natural frequency, $\propto$ is the constant of each flexural module," L" is the length out of clamped beam (0,4 m), E is the modulus of elasticity (193 GPa), "I" is the moment of inertia ($11{,}3.\,10^{-12}m^4$), "ρ" is the material density (8000 kg/ m³) and "A" is the transverse section area of the beam. Therefore, the Tab. 1 below presents the natural frequencies of each case:

Table 1. Beam theory results of natural Frequency modules.

Constant (α)	Natural Frequency - 0,4 m out
$\alpha_1 = 1,875$	$W_{n1} = 8,635$ Hz
$\alpha_2 = 4,694$	$W_{n2} = 54,127$ Hz
$\alpha_3 = 7,855$	$W_{n3} = 151,572$ Hz

3 Validation and results

The validation of the acquisition system happened in a controlled laboratory, with the clamping of the beam in a bench vise and the beam excitation was made by the impact of a hammer as the Fig. 3 below. The results can be seen in Tab. 2, while the frequency spectrum of the didactic acquisition system can be seen in Fig. 4 and the frequency spectrum of the commercial acquisition system in Fig. 5.

Figure 4. Validation of the clamped beam

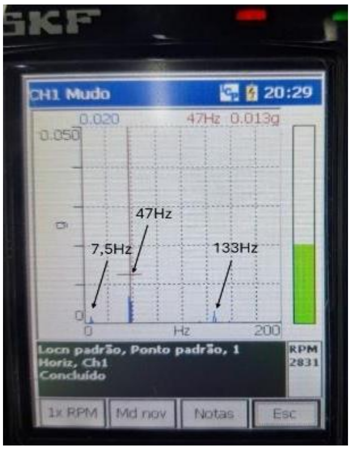

Figure 5. Frequency spectrum of the commercial acquisition system (SKF).

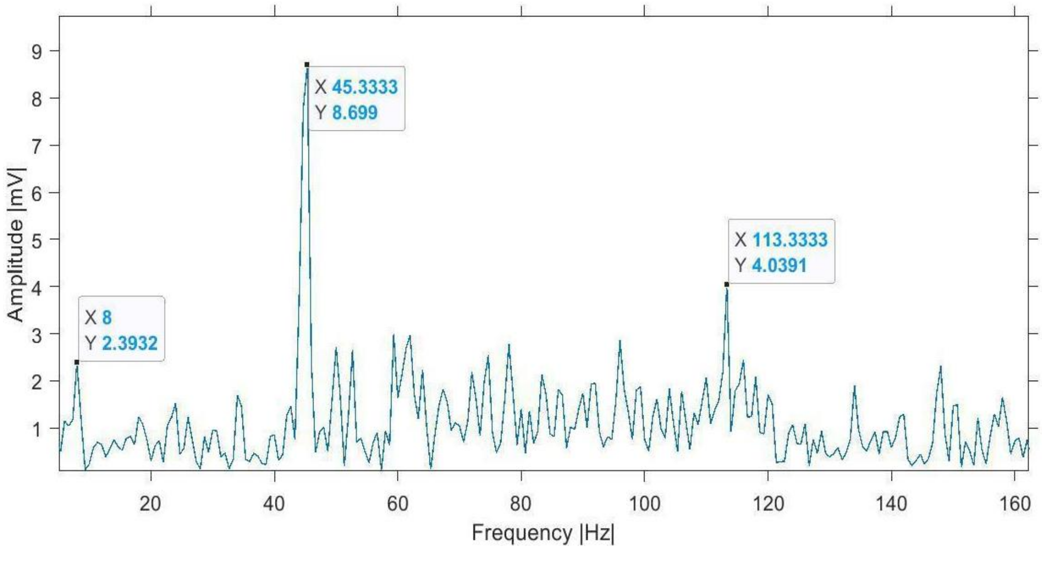

Figure 6. Frequency spectrum of the didactic system (MatLab).

Table 2. Comparison of results from the natural Frequency modules.

Flexural modules	Natural frequency (commercial system)	Natural Frequency (beam theory)	Natural frequency (didactic system)	Error % Beam theory	Error % Didactic
1º Module	$W_{n1} = 7{,}5\ Hz$ Hz	$W_{n1} = 8{,}635$ Hz	$W_{n1} = 8$ Hz	13,14%	6,25%
2º Module	$W_{n2} = 47\ Hz$	$W_{n2} = 54{,}127$ Hz	$W_{n2} = 45{,}33$ Hz	13,22%	4,44%
3º Module	$W_{n3} = 133$ Hz	$W_{n3} = 151{,}572$ Hz	$W_{n3} = 113{,}33$ Hz	12,26%	17,18%

4 Conclusion

With the development of the acquisition system of frequency spectrum and the validation in comparison with commercial acquisition system, it was possible to be seen the flexural modules of the clamped beam that presents similar frequency values, especially the first flexural module, with the calculated value of 8,635 Hz, the didactic system showed 9 Hz, and the commercial system showed 7,5 Hz. The second module has a natural frequency calculated as 54,127 Hz, the didactic system showed the value of 45 Hz, and the commercial system showed 47 Hz for the same module. Finally, the third flexural module has been calculated with a value of 151,572 Hz, the didactic system showed 113 Hz, while the commercial system showed the value of 133 Hz. With this, can be concluded that the values showed by the didactic system, the first and second flexural modules, are similar with the calculated values and similar with the values of the commercial system. Therefore, the third module showed a large distortion in relation to the theoretical and practical methods, about the developed didactic system the reason for the distortion could be due to the accelerometer fixation and the presence of noise that can be seen in the frequency spectrum image. The use of an in-house development vibration acquisition and analysis systems in academic environments leads to greater interaction of researchers with practical experiments and a better understanding of the phenomena studied. With this, the validation brings satisfying results from the experiment, however with the necessity of improvements for the noise filtering system and for the accelerometer fixation.

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