



STRUCTURAL DYNAMIC RESPONSE MEASUREMENT DEVICE: DESIGN AND TESTING

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Abstract. *One of the main demands of mechanical engineering is currently obtaining, in mathematical terms, a way to describe the dynamic behavior of a system with significant physical variables. The ways to control and verify these dynamic characteristics of real systems are as important as the design phase. In this context, Modal Analysis is a process whereby a structure is defined in terms of its dynamic characteristics: natural frequency, damping, and mode shapes. One important technique explored in this study is the Operational Modal Analysis (OMA) that has been a growing field since the last decade. OMA is the most practical solution in many situations because it can be applied to structures in operation and does not require a well-controlled excitation source, which is practical for many large structures under variable loads. This study proposes an affordable concept of a linear acceleration data-logger capable of making important evaluations of the dynamic characteristics. The device was developed following a product design methodology, which is subdivided into informational, conceptual, preliminary and detailed design. The main needs for product development were found as well as its necessary characteristics for the operation and main concepts. With preliminary tests, the low cost solution proved to be capable of acquire, store and manipulate the linear acceleration signal using only open source software and hardware.*

Keywords: *datalogger, structural dynamics, vibration, accelerometer, modal analysis.*

1. INTRODUCTION

Checking and controlling vibration can be crucial to maintaining performance, efficiency and safety in driving cars and industrial machinery. Consequently, considerable efforts are dedicated today to the study, measurement and control of vibration and shocks generated by internal factors or external to the evaluated system. Before designing or controlling a system for good vibro-acoustic performance, it is important to understand, analyze and represent the dynamic characteristics of the system. This can be done through purely analytical means, computational analysis of analytical models, testing and data analysis, or a combination of these approaches.

The knowledge of these modal parameters (resonance frequencies, modal participation, vibration modes, and damping) can serve several purposes, including structural modification, as reported by Maia (1997), structural integrity and reliability evaluation (Melchers, 1999), pathologies or structural damage (Doebbling, 1999) and updating and refining mathematical models (Friswell, 1995). According to Lundkvist (2010) the modal analysis of a structure can be made using different practical approaches:

- Analytical modal analysis with a system of equations to describe spatial mathematical models;
- Experimental Modal Analysis (EMA) with the measurement of dynamic properties with accelerometers fixed in the structure evaluated under controlled excitation. Generally carried out in laboratories with the possibility of evaluation under free-free conditions;
- Operational Modal Analysis (OMA) with the evaluation of the structures under real operating conditions, where all effects of boundary conditions are included in the results and have considerably lower costs.

Both AME and OMA are linked intrinsically to technological advancements, miniaturization of electronic components and increased digital processing capacity. This fact is confirmed by Schwarz (1999) who reports the beginning of the popularization of the methods mentioned only with the advent of the digital spectrum analyzer in the early 1970s. In common with all these evaluations, there is a need to identify the accelerations acting on the system.

2. DATA ACQUISITION AND SIGNAL PROCESSING

The measurement of mechanical vibrations has many feasible ways of translating the motion into data for analysis. Some measurement devices, even when used in the wrong way or in situations below its capacity, will still present results.

Under these conditions, the final result induces in error or non-relevant results. Therefore, it is very important for signal acquisition and processing to understand the operational principles of the equipment, its limitations and also the main characteristics of the structure evaluated. Authors such as Sinha (2013) and Mansfield (2005) agree that there is a growing number of acceleration dataloggers since the 1990s. For these reasons, it is imperative that new solution principles for these measurements be proposed and documented with their application spectra.

2.1 Accelerometry

In the definition presented by Peres (2015), an accelerometer is a device that measures acceleration (or G-force). When stationary, it will measure the acceleration of gravity, or 9.81 m/s^2 . When vibration is imposed on the transducer, it will emit a voltage based on its sensitivity rating. Some of the popular types of sensors include piezoelectric, piezoresistive, and microelectromechanical (MEMS) accelerometers.

Each of these acceleration transducers has its operating principle, its constructive characteristics, and, therefore, specific applications. According to the table below, we can see some of these applicability and restrictions.

Table 1. Applicability of accelerometer

COMMON APPLICATIONS	PIEZOELECTRIC	CAPACITIVE MEMS	PIEZORESISTIVE
Static acceleration (0 Hz, 1g) Gravity, Sensor orientation		✓	✓
G force (0 Hz, <25g) Rockets, Airplanes, Centrifugal Force		✓	✓
Low Frequency Vibration (<5 Hz, <25g) Human Vibration, Robotics	✓	✓	✓
General vibrations (5Hz to 500Hz, <25g) Electric Motors, Car Suspension	✓	✓	
Shocks and Impacts (<250 Hz, >200g) Drop Tests, Automotive Crash Test	✓		✓

Piezoresistive accelerometers are present in the main devices that perform impact tests as they can capture linear accelerations greater than thousands of times the acceleration of gravity. As confirmed by Allan (2010), piezoresistive accelerometers are based on strain gages, therefore, they require amplifiers and temperature compensation. However, they have a very wide bandwidth (0 hertz to several thousand hertz) and low noise characteristics. Piezoresistive accelerometers tend to have a higher monetary cost compared to piezoelectric or MEMS. Therefore, for this work, we will limit the evaluations with piezoelectric transducers and MEMS.

Piezoelectric accelerometers are the most popular and widely used for industrial applications (Allan, 2010). According to the same author, piezoelectric accelerometers have very low noise and offer superior performance to capacitive MEMS or piezoresistive accelerometers in general vibration applications. So they have a wide range of applications and are presented in various configurations: triaxial or single axis, high sensitivity for seismic applications, low sensitivity for crash tests, and even some types that can handle extreme environments, including nuclear. The main disadvantage of piezoelectric accelerometers is their difficulty in identifying low frequencies. Yet these accelerometers are generally the preferred choice for industrial testing applications. Its effectiveness is widely exploited by different companies including Measurement Specialties, Meggitt, PCB Piezotronics, Bruel & Kjaer, and Dytran.

In this context, one type of accelerometer has a large advantage in reducing size and price. Capacitive MEMS operate based on variations in capacitances between parallel seismic plates, one fixed and the other under acceleration. As its name indicates, the constructive aspect of this type of device brought a great reduction in size and with it the ease of its incorporation into our daily lives. Capacitive MEMS are present in cell phones, airbags, computers, drones, video games, etc because they are also easily mounted on printed circuit boards. According to Allan (2010), as they are powered by direct current, they are more suitable for measuring low-frequency motion vibrations and steady-state acceleration. The same author reports that one of the factors that weigh against the use of Capacitive MEMS is its characteristic noise in the signal.

2.2 Measurement errors

As with many other transducers, accelerometers are devices that are sensitive to their orientation relative to the object of study, as well as to peculiarities related to their working principle. Therefore, there are several sources capable of generating errors. In this work, the signal problems generated by accelerometers will be evaluated according to their higher incidence in MEMS capacitive sensors (noise, offset, drift, sampling, and aliasing), shown in the Figure 1.

According to the accelerometer manuals investigated in this work (ADXL 345 and MPU 6050), the existing noise sources in systems involving motion sensors can be summarized as:

- environmental noise such as fluctuations in temperature, gravity, etc.;
- unwanted movements, for example, human shocks, vibrations, and tremors which include physiological tremor and pathological tremor;
- hardware noise such as electrical noise and thermal-mechanical noise.
- offset error, characterized by the output signal being a constant value shifted from the zero value, ie there is a shift or shift of the zero point.
- drift is characterized by changes in the output signal with changes proportional to the variation of some external factor in time. Variations in ambient temperature can generate this type of error.

In practice, we cannot perform calculations using an infinite range of frequencies. The solution for identifying a lower limit to the data acquisition frequency is what the aliasing error suggests in Figure 1. In other words, the time interval Δt that separates equally spaced measurements is called the sampling interval, and the inverse reciprocal of this interval is called the sampling frequency, f_s . Figure 1 illustrates how a set of discrete data points (black circles) collected over a constant sampling interval can be caused by a higher frequency wave and its harmonics. This phenomenon is called aliasing.

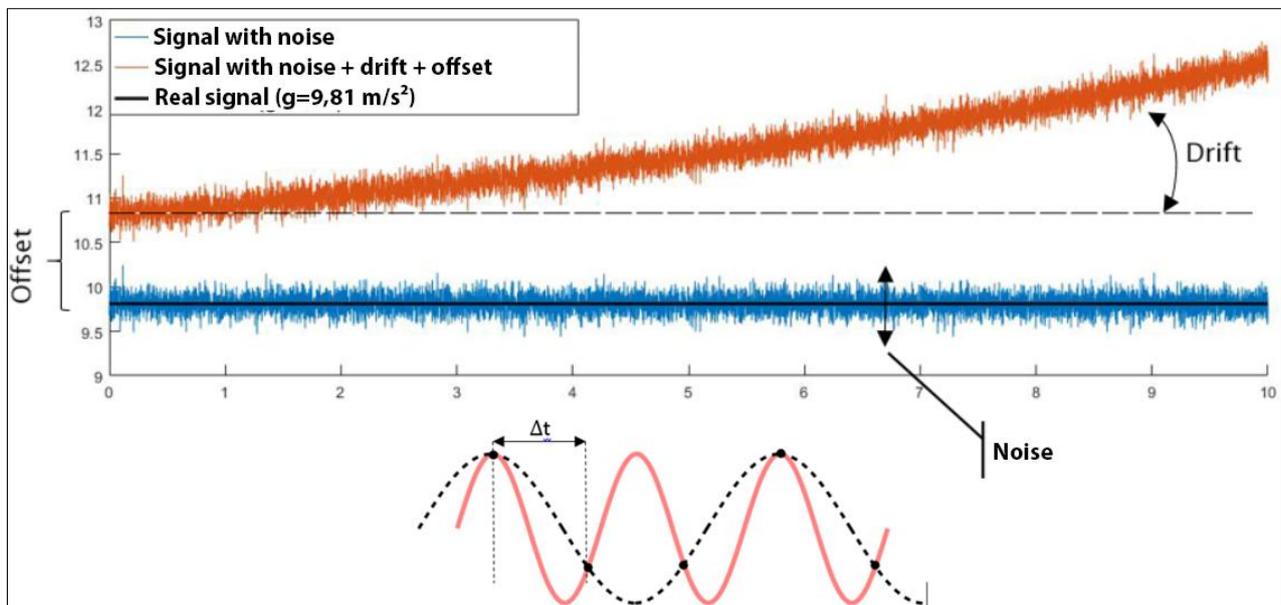


Figure 1. Examples of measurements errors.

A sampling frequency of $2f$ is the minimum required to detect a sine wave of frequency f . Therefore, the sinusoidal displacement must be sampled at least twice during its period. The highest detectable frequency in a signal is called the Nyquist Frequency, indicated by the symbol f_{Nyq} (Jenkins,1968). Therefore, the sampling frequency f_s will be at least twice the Nyquist Frequency.

$$f_{Nyq} < \frac{1}{2}f_s = \frac{1}{2\Delta t}, \quad (1)$$

Another common source of error is generated by the operator when not respecting the device's measurement scale. In other words, the measured quantities are greater than the accelerometer's capacity, as evidenced by Coultate (2007). In this regard, the MEMS accelerometers benefit from the possibility of changing the range through programming their controller. That is, depending on the application, the MEMS accelerometer can measure between $\pm 2g$, $4g$, $8g$, or $16g$, as is the case with the InvenSense MPU 6050 accelerometer used in this work. However, this range scale is a cost-benefit relationship since the wider the scale, the lower its resolution. This happens because the amplitude of capacitance variation remains constant.

Given the error sources described above, digital processing of the signal acquired by capacitive MEMS sensors is mandatory. In this study, only the errors described were considered, as they are frequently present in the readings of this type of accelerometer.

3. DATALOGGER DEVELOPMENT

According to Pahl et al. (2005), the project methodology can be classified as a planned procedure with steps to be followed in the development of technical systems design. These stages involve knowledge in the fields of project, psychology and also technical knowledge. Therefore, different methodologies for product development should not be applied "blindly". Instead, they serve as a guideline to finding the best solution in different problems.

The methodology followed for the data logger project proposed in this work was based on a reference model presented by Romano (2003). His methodology is divided into three macro phases, each subdivided into distinct phases with the purpose of guiding and organizing the development of an industrial product. In this paper, only relevant topics to the main decision-making of the project will be commented.

For authors like Back et. Al. (2008) the Informational Project is where the understanding and description of the problem occurs, in a quantitative and qualitative way, providing the basis for the evaluation criteria and decision making of the following stages. For authors such as Novaes (2005) and Alonço (2004), the Mudge Diagram quantifies the degree of importance of the client requirements compared to each other. These requirements translate, in a more accurate way, the costumer's needs. Engineering students, professors, and professionals interested in the control and evaluation of structural dynamics were interviewed in order to identify the main "customer requirements". In decreasing order of importance, the requirements were: reliability; identification of the main frequencies; carry out structural evaluations; affordable price. The Mudge Diagram was the basis for the application of the next tool. According to Back et al. (2008), Quality Function Deployment (QFD) is founded on the concern that products should be designed to reflect the desires, tastes, and expectations of users. In this work, QFD was useful for translating customer requirements into their equivalents in the project specification. This tool provided several indications to allocate resources efficiently. It also served to benchmark characteristics with commercial equipment.

The Conceptual Project focused on identifying and clarifying the needs to be met, as Santos (2004) reports. Decisions about product design and the choice of the best solution against resource constraints and design constraints were also part of this phase. With this objective a functional structure of the device was generated, identifying its main functions and actions necessary to fulfill them. Novaes (2005) states that in this phase, physical solutions must be generated to meet the needs of the clients. Thus, for the comparative evaluation between different solution principles, a morphological matrix was generated. In this context, among several possibilities of compatible results, was adopted the solution shown in

Figure 2. At the end of this stage, it was defined the use of the Arduino Pro Micro development board that uses the ATmega32u4 microcontroller. With this board, it was possible to use SPI (Serial Peripheral Interface) and I2C communication protocols to control components such as the MPU 9250 accelerometer, micro-sd card module, Bluetooth module, and OLED display. The software for both device control and computational signal processing were written and tested.

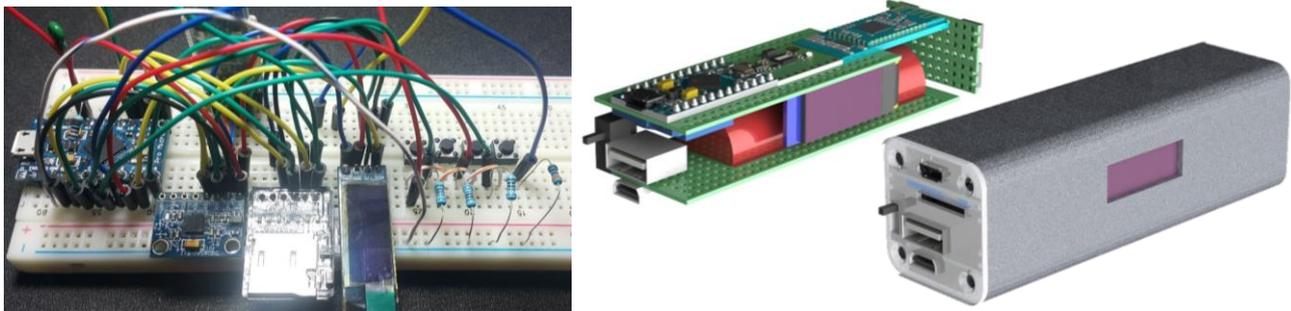


Figure 2 - Assembly for testing and digital mock-up

Finally, one of the results of the Detailed Design phase is the functional scheme of the product. The chart in Figure 3 shows the possible features and configurations of the device. It should be noted that because it is an open-source device, it is also the goal of this project to allow the user to customize and edit the source code to suit their needs in the best way.

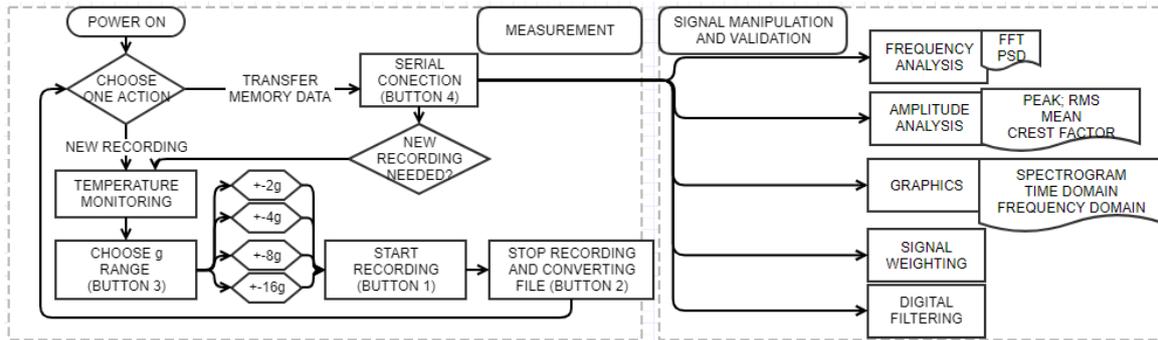


Figure 3 - Functional scheme

3.1 Description of the prototype

On the front side is the OLED screen. When the device is turned on, the internal temperature measured in degrees Celsius and the indication “MENU – Press a button” is displayed, requesting that one of the buttons on the left side be pressed. Along with the data described, the selected range scale for measurements is shown, ranging from \pm 2g, 4g, 8g, or 16g.



Figure 4 – Front view

On the left side is the device functions control panel. Although they allow them to be configured, a reference model was defined for the fulfillment of functionalities. In order to facilitate the operation and meet the project requirements, in each activity/process being performed on the device, there is a visual indication of it.

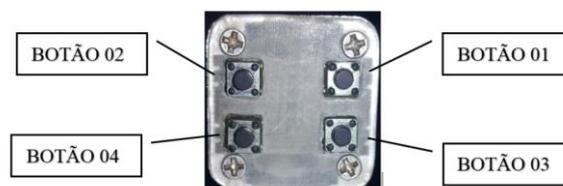


Figure 5 –Left view

The "standard functions" adopted at this stage of the prototype were:

- Button 01: starts recording the record of linear accelerations in the three Cartesian axes in binary code.
- Button 02: Stop recording. Then automatically the device performs binary file truncation and conversion to decimal base. The registration is done in a spreadsheet file with a *.csv ending. This file will be registered on the memory card, being easily read by programs such as Excel, Matlab, Octave, among others.
- Button 03: Selects the scale at which measurements are to be taken.
- Button 04: Download all recordings through the serial port.

On the right side, it is possible to identify the key responsible for turning the device on and off. At the top, the micro-USB port corresponds to communication with Arduino. Through it, it is possible to make changes to the code and/or receive the data recorded on the Micro SD card. Below the Arduino communication port is the Micro SD memory card reader and writer. Below this, finally, we have the two doors of the power bank. The USB port serves as a power source to charge other devices and the micro-USB (on the base) serves to charge the prototype's internal battery

Concluding the external observations, it is possible to observe the orientation marking of the Cartesian axes for the correct basicentric positioning and referencing of the device in relation to the system to be evaluated.

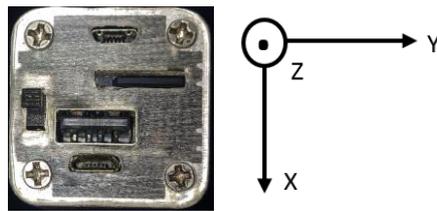


Figure 6 –Right view and cartesian orientation

Finally, we have a device in the prototype stage with a mass of 150 grams. Therefore, lighter than most cell phones, more compact, and cheaper than commercial products. At the end of the refining of the prototype's functionalities, it was possible to verify the fulfillment of the flow of activities and functions presented in Figure 3.

4. TESTS AND VALIDATION

In order to find the calibration parameters of the device as well as to attest the ability to do modal evaluations, a battery of preliminary tests was performed. In the first step, the maximum and minimum voltage values read by the sensor were converted to the extreme values of each scale range (± 2 , 4, 8, or 16g). The calibration with respect to the Cartesian reference was made by finding the correction factors for the readings of the device when in parallel with the X, Y, and Z-axes. Numerically the *factor* value, which adjusts the Cartesian axis of the accelerometer, is found as follows:

$$factor = ((read1g - 9,80655) + zero_read)/2 \tag{2}$$

where the *read1g* is the mean of the values recorded when the reference axis was in the vertical position (reading the acceleration of gravity); *zero_read* is the average of the values recorded when the reference axis was in the horizontal position. The result of this calibration is demonstrated in Figure 7.

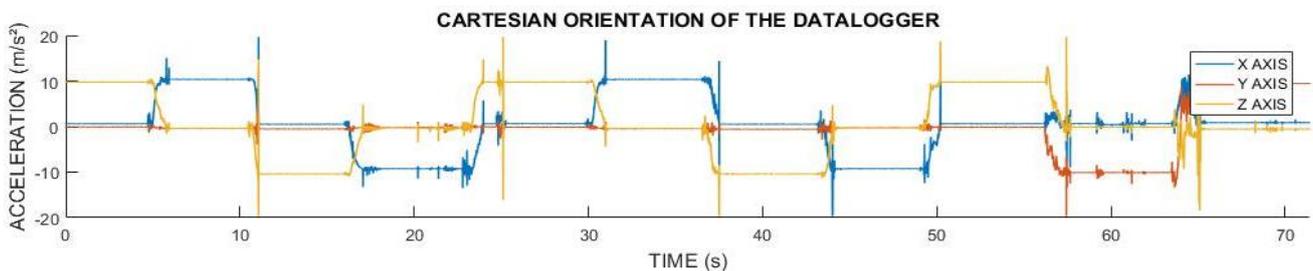


Figure 7 - Cartesian orientation

The next test proved the congruence of the frequency domain readings. As shown in the figures below, a test bench was organized. The device was attached on the vibratory base of the shaker in order to make readings of the amplified signals generated by the computer.



Figure 8 - Testing workbench

In order to assess the accuracy of the device's response, a series of specific frequencies were used. In this test, for 60 seconds, the device fixed on the Shaker was individually excited by the frequencies: 10, 50, 100, 200, and 300 Hz. The acquired signal was evaluated in the frequency domain through the Fast Fourier Transform applying the Hanning Window

with an overlap of 50%. For each of the frequencies identified, the graphs of Figure 9 were obtained. In this test, the efficiency of the device in accurately identifying the excitation frequency was confirmed. However, it is possible to observe the presence of peaks corresponding to other frequencies in the FFT's in Figure 9. This characteristic is due to the Nyquist Frequency mirroring effect, which will be presented in the next test. In the graph corresponding to the frequency of 10 Hz, larger interfering peaks are perceived due to the precision limitations of the electrodynamic Shaker equipment available for the test.

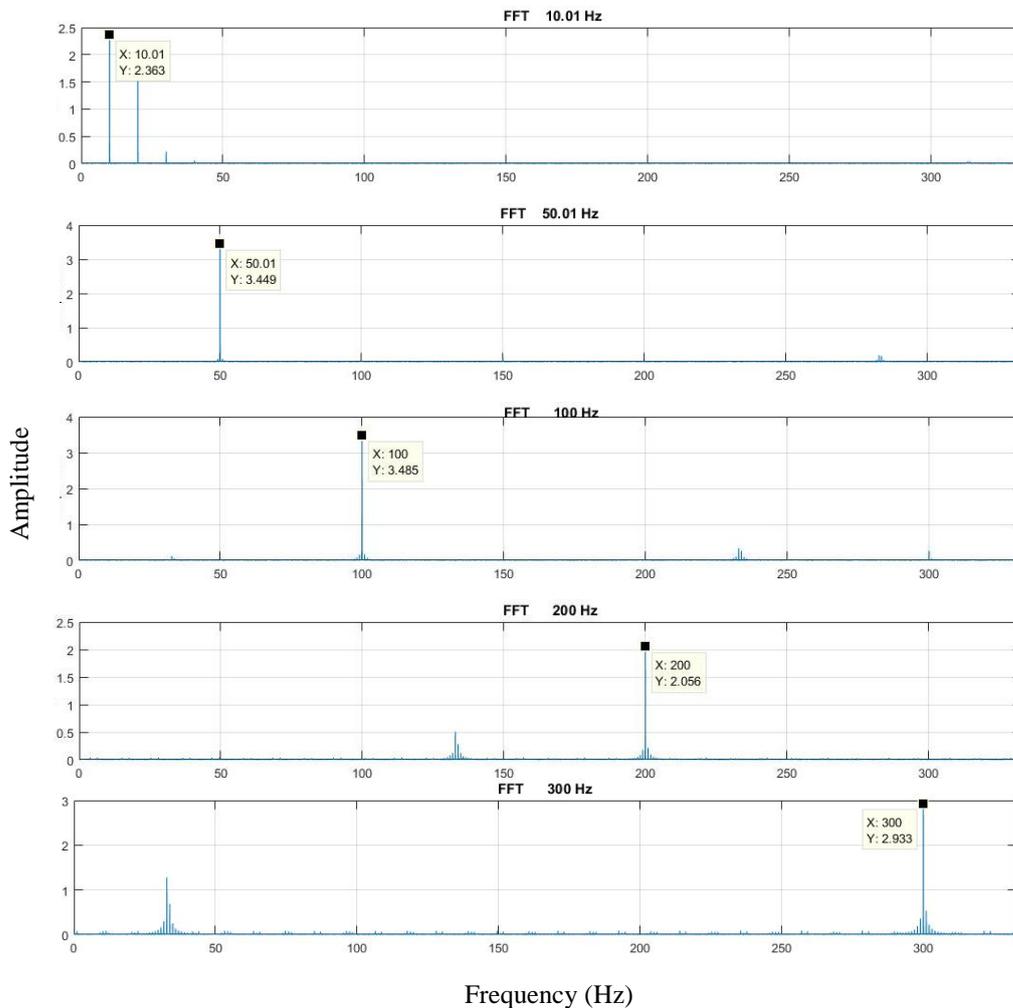


Figure 9 - Tests with specific frequencies

The prototype was excited by a sine wave of non-constant frequency. As can be seen in Figure 10, in a little more than three minutes the signal generated by the computer ran the frequencies up to 350Hz in a sine sweep. To generate this graph, the Kaiser Windowing Method was used with the parameter $\beta = 200$, Window size $M = 151$ and window overlap of 143 points. In this evaluation, the data acquisition frequency was defined in the Arduino code at 666Hz. It is possible to observe in the graph that the reflections, observed from 333 Hz, confirm the Nyquist theorem. Due to the shaker-accelerometer assembly and natural frequencies of the measuring system itself, unwanted frequencies readings occurred with less energy than the excitation source frequency. In summary, the prototype showed satisfactory performance for evaluations in the spectrum of 0-333 Hz

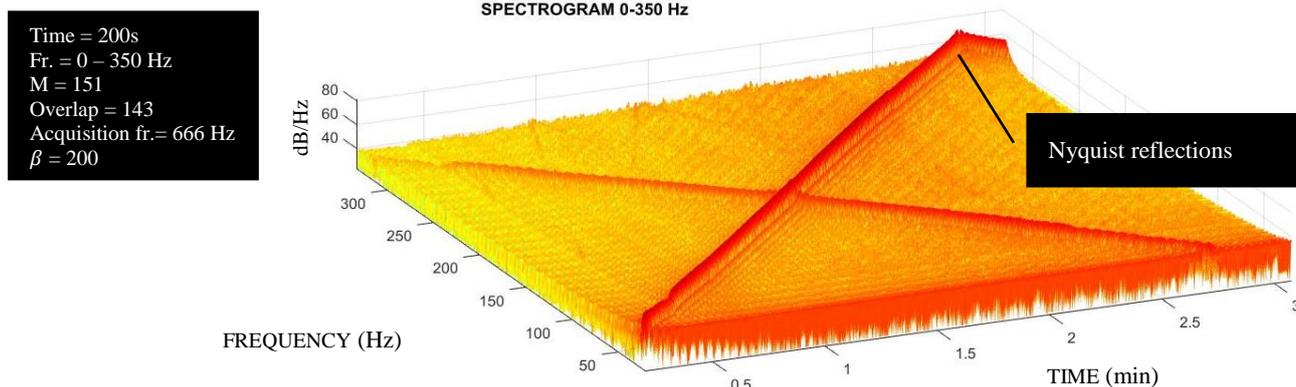


Figure 10 - Spectrogram with Kaiser Window

5. RESULTS AND DISCUSSION

Considering the amount of content involved in this work (design, dynamics, control, acquisition, and signal processing), the tests were restrained to the verification of some operational limits. In other words, this work was limited to the presentation of the chosen concept and some tests of the prototype. Nevertheless, it was possible to prove that the compact and modular structure allows operational modal evaluations. In these conditions, it is essential that the equipment is placed properly over relevant places. Its proven effectiveness within the frequency spectrum enables it for a wide application range to obtain the modal parameters that actually describe the structure under real operating conditions. Its small size and modular structure is a differential that makes the installation simple.

The methodology used for the development of the prototype was essential for decision-making and identification of needs to be met. The tools and methods used in the design provided confidence to justify each decision. Although it has lower reliability compared to commercial equipment with expensive piezoelectric accelerometers, the equipment developed in this paper presents an affordable solution for various academic or industrial applications.

However, even though the code has been refined and the libraries used have been reduced only to the necessary functions for the prototype to work, it was found that the internal memory of the ATmega32U4 microcontroller is a critical limiting factor. Both for the development of more elaborate functions and the use of more variables in your programming. In this regard, there is a suggestion for future works. Still, it was possible to comply with the requirements identified during project development.

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