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Experimental evaluation of a low-cost vibration sensor for modal testing applications

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Abstract. *Through modal analysis it is possible to extract parameters of great relevance from mechanical systems, such as resonance frequencies and geometrical modes of vibration. By monitoring the variation of these parameters over time, wear can be identified and failures can be predicted. However, modal analysis is usually carried out using piezoelectric accelerometers and acquisition systems that have a high cost. In this sense, the present study consists of analyzing the feasibility of implementing low-cost accelerometers, of microelectromechanical origin, for monitoring vibrations and extracting modal parameters. Experiments were conducted on a free beam subjected to impulsive inputs and instrumented by means of low-cost sensors and others of piezoelectric origin, which were used as a reference. The acceleration detected by the sensors was processed using both the conventional and the operational modal analysis technique. Comparing the results obtained by the low-cost accelerometers with those from the reference sensors, it was possible to validate the application of this first type and establish what are its limitations.*

Keywords: *Vibration analysis, MEMS accelerometer, experimental modal analysis, operational modal analysis, low-cost modal analysis*

1. INTRODUCTION

Modal analysis is a method where one can describe a structure in terms of its natural characteristics which are the resonance frequencies, damping and mode shapes (Avitabile, 2001). According to Schuler (1997), through the analysis of vibrations it is possible to extract a large number of information from mechanical systems and structures as well as to monitor civil structures as bridges and buildings. Vibration signals allows to analyze in detail the presence of defects due to wear of a machine while it remains in full operation.

Knowing the relevance of modal analysis, several authors sought alternatives to replace high-cost accelerometers previously used for monitoring vibrations in mechanical systems. Varanis *et al.* (2018) compared the signals measured by different low-cost MEMS (microelectromechanical) accelerometers with common commercial reference accelerometer models commonly used for vibration measurement techniques. The sensors were used to measure the vibrations of a structure and, comparing the results obtained for each model, the authors concluded that low-cost accelerometers were only viable to be applied in situations in which the frequency does not exceeded 50 Hz. Albarbar *et al.* (2009) used a piezoelectric sensor to assess the feasibility of using a low-cost MEMS accelerometer to measure acceleration signals generated by an impact hammer and a signal generator. Through the tests, differences were noted both in terms of amplitude and phase, allowing the authors to conclude that there is a need for further studies on the application of MEMS sensors in modal analysis.

On the other hand, some authors have obtained satisfactory results with regard to the application of MEMS accelerometers in monitoring vibrations. For example, Girolami *et al.* (2018) used LIS344ALH accelerometers to extract the resonance natural and vibration modes shapes of a beam and, after comparing the results obtained with a developed physical model, they concluded that MEMS can be used as low cost systems capable of providing information about the vibration of systems in real time.

Combining the use of MEMS accelerometers with the operational modal analysis (OMA) method, Ramos *et al.* (2011)

carried out a modal test in one of the four chimneys of Dukes Palace in Portugal, a historic building dating back to the 15th century. The aim of the paper was an attempt to apply wireless technologies for structural health monitoring (SHM). An ADXL202JE sensor was used along with PCB 393B12 accelerometers as reference for performance comparisons. The authors obtained good results in the identification of resonance, but in the detection of modal shapes they had unsatisfactory results.

Within the operational modal analysis method, there are several techniques to obtain modal parameters. Frequency domain decomposition (FDD), developed by Brincker *et al.* (2000), is one of the most configured and used in output vibration tests. For example, Amador *et al.* (2019) used the technique based on the correlation spectrum on multiple datasets to estimate the global mode shapes of a tall building in a single step. They concluded that for this particular application they had good results. Kacin *et al.* (2022), on the other hand, applied FDD as a tool to analyze the period of oscillation of a school building before and after the addition of shear walls. The authors concluded that there was a significant decrease in the first two periods with use in the framework.

In the present study, experiments were carried out on a free-free beam, instrumented by MEMS accelerometers and commercial piezoelectric accelerometers, used as a reference, with the aim of measuring the vibratory response of the system to an impulsive input generated by an impact hammer. Two different modal extraction techniques were applied with these sensors. The first one was based on the traditional peak-picking method (PP) used to extract modal frequencies and mode shapes from the estimated frequency response functions (FRFs) of the structure. The second approach was based on FDD which is an output-only modal analysis tool based on the singular value decomposition of the power spectral density matrix of the acceleration data measured in the structure. The PP and FDD algorithms were applied on the low-cost accelerometer and the professional one in order to compare the performance of both.

Using the results of the professional sensor as a reference, the deviation of resonance frequencies and the modal assurance criterion were calculated to observe the discrepancies between the performance of both sensors. In the conclusions of the paper, the main advantages and drawbacks on the use of MEMS accelerometers for vibration testing are presented.

2. EXPERIMENTAL SETUP

The tests were carried on a steel beam with $760 \times 29.7 \times 1,4$ [mm] suspended by soft elastics in order to simulate a free-free boundary condition. A simple structure like this was chosen due to the fact that the analytical results for this case can be easily computed, allowing to confirm the experimental results. An alternative low-cost accelerometer, which costs less than 10 dollars, was compared with a reference sensor, valued at hundred dollars, to measure the vibratory response of the system to the impulsive input, generated by an impact hammer. This experimental setup is illustrated in the Figure 1.

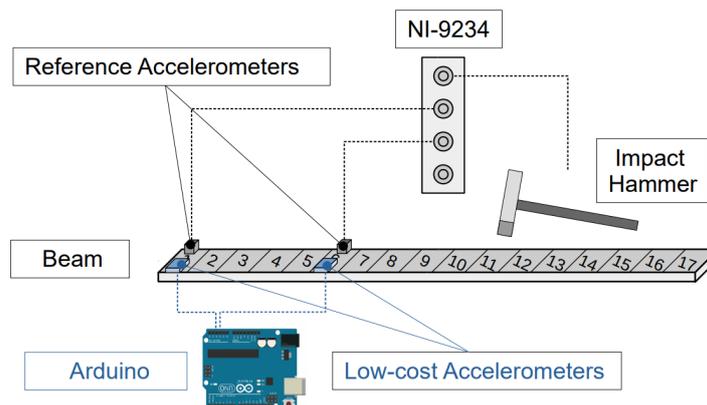


Figure 1: Experimental Setup.

For the development of this study, the following low-cost hardware devices were used:

- 2 ADXL335 triaxial accelerometers (sensitivity: 300 mV/g, measurement range: ± 3.6 g peak, frequency range: up to 1600 Hz, sampling frequency: 500 Hz);
- Arduino MEGA rapid prototyping board (15 analog pins, resolution: 10 bits).

The mentioned development board and accelerometer were already explored in a few papers to applications such as condition monitoring (Barman and Hazarika, 2019), structural health monitoring (Shiki and Franco, 2020) and the digitalization of manufacturing processes (Barbosa *et al.*, 2019). The present paper aims to further understand the limitations of this sensor in a simple test structure.

In order to have a reference measurement to evaluate the low-cost instrumentation, a basic kit for modal analysis was employed which is composed of:

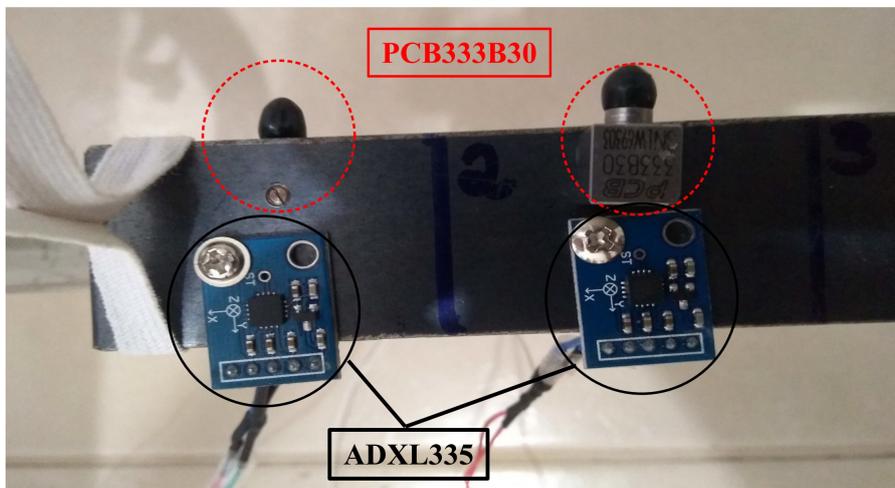
- PCB impact hammer 086C03 (sensitivity: 2.25 mV/N, measurement range: ± 2224 N peak, resonance: ≥ 22 kHz);
- 2 PCB accelerometers 333B30 (sensitivity: 100 mV/g, measurement range: ± 50 g peak, frequency range: 0.5 to 3000 Hz, sampling frequency: 12800 Hz);
- cDAQ-9178 chassis from National Instruments with NI-9234 module for measuring IEPE type sensors (4 channels, sampling: 51.2 kHz/channel, resolution: 24 bits).

The steel beam was divided into 17 equal elements to better organize the experiment. One sample of PCB333B30 and ADXL335 sensors were fixed to the first element of the beam as a reference measurement. For the experimental test, the roving accelerometer technique was used (Fu and He, 2001), in which the hammer was used to hit the 11 element during all the tests and the accelerometers were moved from one test to the other in order to map the complete length of the steel beam.

For each and every position of the accelerometers, 10 impulses were applied to compute average results from each analysis of the test data. In order to capture the entire impulse response, a total of two seconds of input and output signals were captured during each hammer testing. The Arduino MEGA board was set to capture the ADXL335 signals with a sampling rate of 500Hz. Meanwhile, the input force data captured by the sensor embedded in the hammer and the reference acceleration captured by the PCB333B30 sensor were sampled with 12.8 kHz by the cDAQ-9178. Figure 2 illustrates a photo of the setup with the attached sensors used during the modal testing.



(a) Top view of the steel beam with the elastics.



(b) Detailed view of the sensors attached to the beam.

Figure 2: Photo of the experimental setup with the sensors used in the study.

3. MODAL PARAMETER EXTRACTION TECHNIQUES

In this section two different modal parameter identification tools are presented. The first one is based on the calculation of the frequency response functions (FRFs) of the vibrating structure and the estimation of resonance frequencies and mode shapes through the peak-picking method (PP). The second methodology applied in the present paper was based on an output-only technique called frequency domain decomposition (FDD).

3.1 FRF-based modal identification with peak-picking method

The peak-picking is one of the most used methods in classical modal analysis for extracting modal parameters, due to its practicality of implementation. This method needs the calculation of the FRFs of the system describing the input-output relationship in the frequency domain of the system. In this paper, the classical H_1 estimator was used (Shin and

Hammond, 2008):

$$H_1 = \frac{[S_{xy}]}{[S_{xx}]} \quad (1)$$

where S_{xy} represents the crosspower spectrum between the input and output signal, and S_{xx} is the autopower spectrum of the input signal. In the present paper, the input signal is the force measured by the load cell in the impact hammer and the output signals is the acceleration measured by the accelerometers. In this sense, equation 1 is used to estimate the FRFs considering the 17 accelerations in the different spatial regions of the beam depicted in Figure 1 as well as for both vibrations sensors: the PCB333B30 reference device and the ADXL335 tested in the present research. The complex vector representing the 17 FRFs can be assembled in a 3d array:

$$[\mathbf{H}(\omega)] = [H_{1,11}(\omega), H_{2,11}(\omega), H_{3,11}(\omega), \dots, H_{17,11}(\omega)]' \quad (2)$$

where $[\mathbf{H}(\omega)]$ is the FRF array, and $H_{i,j}(\omega)$ is the FRF considering the input applied in the j -th element of the structure and the i -th output.

According to Fu and He (2001), after extracting the FRFs of the system, the method performs the treatment of data at the vicinity of a magnitude peak as being the data of a system with a single degree of freedom, allowing the extraction of natural frequencies and mode shapes. However, it is worth remembering that the FRF peak value is very difficult to be measured accurately and that the PP method is suitable only for lightly damped FRF data with well-separated modes and good frequency resolution, which is the case of the present study.

3.2 Output-only technique based on frequency domain decomposition

With regard to output-only modal analysis, frequency domain decomposition (FDD) is widely used in large civil structures, because the identification of modal properties is based only on the output information, while the input signal is often the excitation of the environment or system itself.

According to Brincker and Ventura (2015), the technique is firstly based on the calculation of the power spectral density (PSD) matrix of the system:

$$[\mathbf{S}(\omega)] = \begin{bmatrix} S_{y_1,y_1}(\omega) & S_{y_1,y_2}(\omega) & \cdots & S_{y_1,y_N}(\omega) \\ S_{y_2,y_1}(\omega) & S_{y_2,y_2}(\omega) & \cdots & S_{y_2,y_N}(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ S_{y_N,y_1}(\omega) & S_{y_N,y_2}(\omega) & \cdots & S_{y_N,y_N}(\omega) \end{bmatrix} \quad (3)$$

where the diagonal terms S_{y_n,y_n} are the PSDs and the off-diagonal terms S_{y_n,y_m} are the cross-PSDs, n and m are integer numbers such that $n, m \in [1, N]$ and N is the number of output signals that are being processed by the FDD algorithm. The singular value decomposition (SVD) of the $[\mathbf{S}(\omega)]$ matrix is then calculated for each frequency ω :

$$[\mathbf{S}(\omega)] = [U][\Sigma][V]^T \quad (4)$$

where $[U]$ is an $N \times N$ unitary matrix, $[\Sigma]$ is a $N \times N$ diagonal matrix with the singular values, and $[V]^T$ is an $N \times N$ matrix with the singular vectors.

By plotting the singular values of the SVD it is possible to identify amplitude peaks, which represent an approximation of the eigenvalues of the structure. Thus, for each frequency a singular vector is generated that can be considered an approximation of the shape of the vibration mode of the system in question. The method works if certain assumptions are made, such as stationary white Gaussian noise input, lightly damped structures, and geometrically orthogonal shapes in close ways (Brincker *et al.*, 2000).

4. RESULTS AND DISCUSSION

Figure 3 illustrates a curve with an impulse-type input generated by the hammer, used for the excitation of the structure, and the acceleration signals measured by the two accelerometer models, also shows the input and output in frequency domain. Since the commercial sensor captures higher-frequency data there is a visible difference in the magnitude scale.

The ADXL335 output in the frequency domain shows a peak at 180 Hz which is not present in the professional accelerometer output. The authors believe that it is due to Aliasing, as some frequency must have appeared in which the 500 Hz sampling frequency used could not be detected satisfactorily.

The data measured by the sensors were processed in the MATLAB R2019a software, through specific routines for analyzing the problem. Regarding conventional modal analysis, it was necessary to circumvent the difference in sampling frequency between the input signal and the signal measured by the MEMS sensor.

The data collected during the experimental tests were processed by signal processing algorithms, both using the classic modal analysis methodology and through operational modal analysis. In addition, there is a discussion and comparison of the results obtained through the two types of analysis.

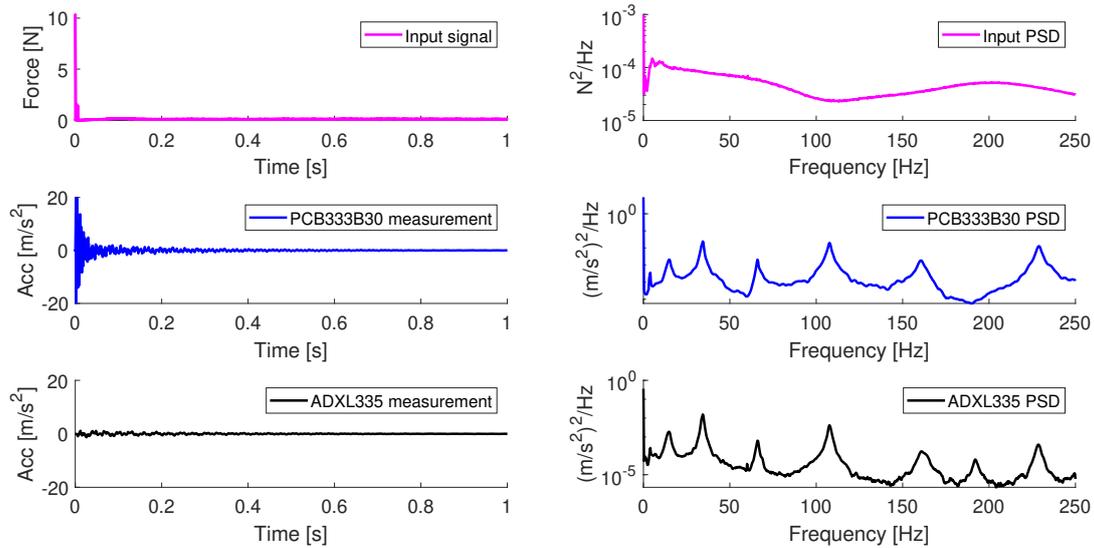


Figure 3: Input and output signals in time domain and frequency domain.

4.1 Experimental results using classical modal analysis

For the analysis of the results using a classical modal analysis approach with both the input force and output acceleration data, the H_1 estimator (Shin and Hammond, 2008), which is presented in Equation 1, was used to calculate the FRF of the beam.

It is worth remembering that for the case of the low-cost accelerometer, the calculation of the H_1 estimator was more complex, due to the difference between the sampling frequencies of the signal generated by the hammer and that measured by the sensor. In Figure 4, it is possible to visualize the frequency response functions extracted for the analyzed beam, through the two types of accelerometers.

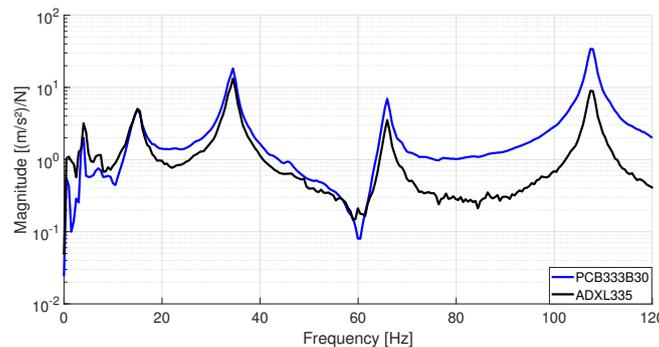


Figure 4: Frequency Response Functions.

In addition, the coherence functions, shown in Figure 5, were also calculated. Physically, coherence reflects the causal and linear relationship between the output and input, it is equal to 0 when the output is not due to the input and equal to 1 when the output is caused solely by the input (Fu and He, 2001). Note that for ADXL335 the estimate has lower coherence, certainly due to the presence of noise and the difference in sampling frequencies, which makes it difficult to synchronize the input signal and the measurement of this accelerometer. It is important to highlight that the fall in the curves at the frequency of 60Hz occurs due to the interference of the electrical network, inevitable in the experiment performed.

Subsequently, the PP technique was applied to extract the natural frequencies and modes shapes of the structure, again through the two types of sensors. Table 1 illustrates the natural frequencies obtained and the percentage difference between them for the first four modes of vibration. A reasonable agreement between both sensors is presented since a maximum difference of 3.3% was found.

In Figure 6, it is possible to visualize the four corresponding vibration modes. The modes obtained using the analytical method were also outlined for comparison purposes.

Finally, Table 2 shows the calculated modal assurance criterion (MAC) that describe the deviations present in the

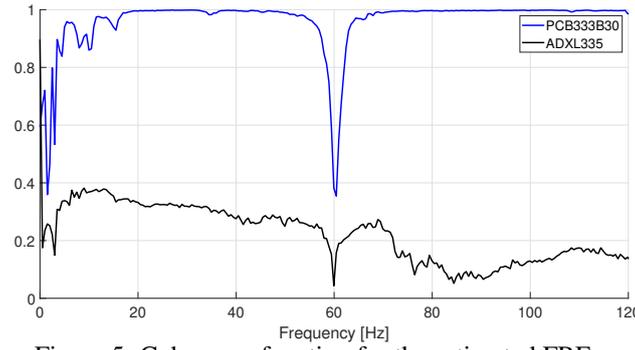


Figure 5: Coherence function for the estimated FRFs.

Table 1: Resonance frequencies extracted through the PP method applied in the FRFs of the system.

Accelerometer	1 st mode	2 nd mode	3 rd mode	4 th mode
PCB333B30	14.50 Hz	33.50 Hz	65.00 Hz	107.5 Hz
ADXL335	14.98 Hz	33.97 Hz	64.94 Hz	106.4 Hz
Error [%]	3.3	1.4	0.1	1.0

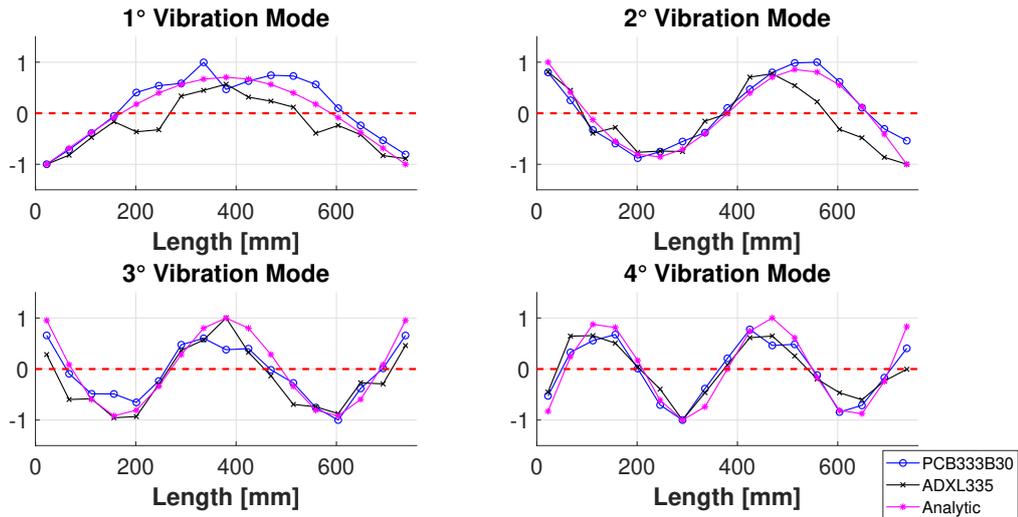


Figure 6: Mode shapes obtained through the PP method applied in the FRFs of the system.

modes under evaluation (Allemang, 2002). The closer to 1, the greater the correspondence of the data between the forms of analysis.

Table 2: Modal Assurance Criterion calculated for the mode shapes obtained through the PP method applied in the FRFs of the system.

	1 st mode	2 nd mode	3 rd mode	4 th mode
PCB333B30 vs. Analytical	0.90	0.94	0.89	0.91
ADXL335 vs. Analytical	0.71	0.71	0.75504	0.82497
PCB333B30 vs. ADXL335	0.47	0.61	0.77	0.87

The authors believe that the deviations observed in Figure 6, which are reflected in the MAC values obtained, are caused by the difficulty in fully controlling the experiment, since the free condition was difficult to be obtained. The most significant deviations, observed in the results obtained for the low-cost accelerometer, were probably generated by the existing noise and by the differences in the sampling frequency, as stated in the analysis of the calculated coherence functions.

4.2 Experimental results using operational modal analysis

Through the data extracted from the structure, considering only the accelerometer responses the FDD method was applied. In Figure 7 it is possible to view both the PSD normalized of the ADXL335 and the PCB333B30 as a function of frequency. The peaks represent the beam's resonance frequencies. As can be observed, the peaks of both accelerometers are at the same frequency, showing that the MEMS sensor is good at identifying low-frequency content.

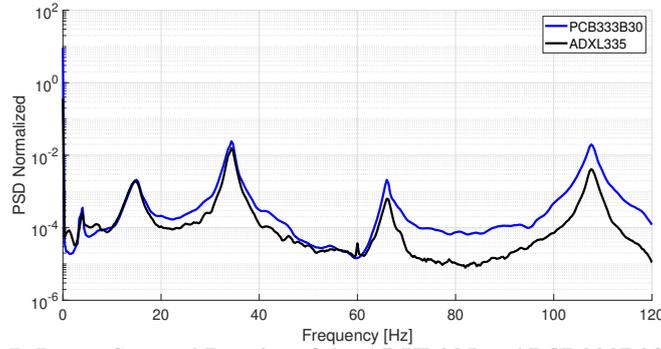


Figure 7: Power Spectral Density of the ADXL335 and PCB333B30 sensors.

Thereafter, the PP method was applied to extract the natural frequencies from PSD's and their associated vibration modes. In Table 3 shows the first four natural frequencies from both accelerometers and the error between them. Note that the frequencies values are very close one to the other.

Table 3: Resonance frequencies extracted through output-only FDD method.

Accelerometer	1 st mode	2 nd mode	3 rd mode	4 th mode
PCB333B30	14.33 Hz	32.67 Hz	64.66 Hz	107.3 Hz
ADXL335	14.32 Hz	32.37 Hz	64.66 Hz	107.4 Hz
Error [%]	0.10	0.91	0	0.022

In Figure 8 is also possible to visualize the comparison of the first four vibration mode from both ADXL and PCB sensors compared with the analytic modes.

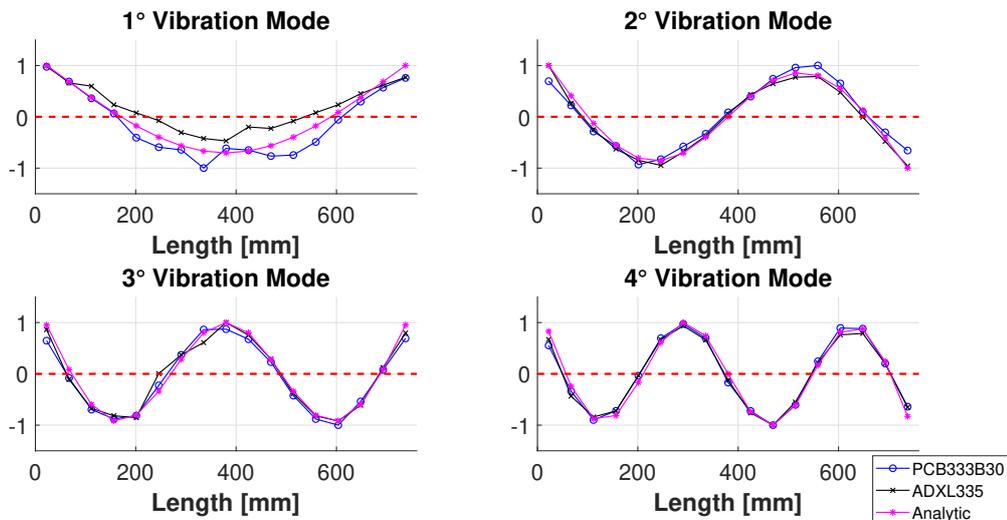


Figure 8: Mode shapes obtained through the FDD method.

As previously performed, the Table 4 shows the comparison of the MACs of each mode. The discrepancy seen in the first mode is explained mainly from use of elastics to suspend the steel beam that added additional damping to the structure.

Table 4: Modal Assurance Criterion calculated for the mode shapes obtained through the FDD method.

	1st mode	2nd mode	3rd mode	4th mode
PCB333B30 vs. Analytical	0.91	0.94	0.97	0.98
ADXL335 vs. Analytical	0.83	0.98	0.97	0.98
PCB333B30 vs. ADXL335	0.64	0.94	0.97	0.99

5. FINAL REMARKS

In the present study, the feasibility of applying the low-cost sensor ADXL335 for modal analysis was experimentally evaluated. Through tests on a beam that simulated the free-free condition and with the aid of a reference accelerometer, model PCB333B30, and an impact hammer, the natural frequencies and vibration modes of the structure were extracted, by both types of accelerometers. For data processing, a conventional method was used, through the extraction of frequency response functions and subsequent application of the peak-picking method. The results were also processed by an operational modal analysis approach through the frequency domain decomposition.

Considering the results, it was possible to notice that the natural frequencies obtained by the two accelerometer models were almost identical for both modal analysis approaches. The geometric modes were also very similar, comparing to those obtained analytically. It is worth remembering that it was expected that the MAC does not go down exactly equal to 1 comparing the sensors with the analytical method, since in this first case there is also interference from the simulation of the free boundary condition, defects in the micro-structure of the beam, among other adversities.

It was noted that the difference between the sampling frequencies used to capture the ADXL335 accelerometer signals and the impact hammer made the synchronization of input and output data a difficult task that resulted in a poor estimation of the FRFs of the system. This also resulted in limited performance of the estimation of the mode shapes of the steel beam as it is highlighted by the low values of MAC presented in Table 2. Meanwhile, the output-only technique used to extract modal parameters showed to be less sensitive to this problem since only the acceleration data were used without having to process it together with the the input force. The FDD showed to be a better approach at least in order to calculate the mode shapes of the beam with the low-cost ADXL335 sensor.

Also the stronger presence of noise in the ADXL335 reflected on the quality of the results obtained through the conventional modal analysis.

6. ACKNOWLEDGEMENTS

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