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COMPARATIVE STUDY OF VIBRATION MEASURING TECHNIQUES APPLIED TO ALUMINUM BEAMS WITH LOCALIZED DAMAGE

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ABSTRACT

This work analyses the feasibility of using a commercial sound level meter (SLM) to measure the dynamic properties of a structural element, i.e., vibration frequencies, using acoustic output data obtained during a rover impact test carried out with rover impact hammer on small beams. The acoustic measurements are compared with those obtained with the accelerometer during the impact tests. In this case, four small aluminum beams were tested under undamaged and damaged conditions. The latter was simulated using drilled holes with different diameters at the mid span of the aluminum beams. Data from acoustic and acceleration measurements were processed to obtain the frequency content of each signal. The results allowed demonstrating if the sound level meter is able to capture the natural frequencies and monitor the damage effects on the natural frequencies of the beams.

Keywords: vibrations, natural frequency, sound level meter, acoustic, damage.

INTRODUCTION

Usually, modal data is acquired using piezoelectric sensors located on the system under analysis although frequency measurements can also be done measuring the acoustic response of the system (Randall J Allemang & Shapton, 1979). Every system has a set of vibration characteristics, such as the natural frequencies, mode shapes and damping (Ewins, 2000). These modal characteristics are affected by the physical characteristics of the system, in particular the stiffness and mass properties. A damage usually causes changes that can affect stiffness and/or mass, which directly affects the vibration properties of the system (Humar, Bagchi, & Xu, 2006).

Thus, in this study, 56 individual tests were performed to determine the effect of induced damage in the dynamic properties of small aluminum beams. The length and width of the prototype beams is 300 mm and 40 mm, respectively, with a thickness of 5 mm. From the total tests, 28 were performed using an accelerometer to measure the output data and the remaining 28 tests were performed using a sound level meter to measure the acoustic response. At first, the beams were undamaged and were tested to measure its natural frequency. Then, the beams were sequentially drilled with different diameter holes to simulate damage. The holes were located at the mid span with diameter range from 15 to 38 mm. A Finite Element Method (FEM) simulation was performed to obtain the mode shapes and the estimated natural frequencies. The main goal is to verify if the sound level meter is reliable enough to capture the natural frequencies. The secondary goal is to analyze the influence of the damage on the natural frequencies and damping ratios.

THEORY SECTION

Ewins (Ewins, 2000) defines modal testing as "the processes involved in testing components or structures with the objective of obtaining a mathematical description of their dynamic or vibration behavior". Perhaps the most used application of modal testing is measuring the system's vibration properties (natural frequencies, mode shapes and damping ratios), allowing verifying the measured data and the one used during the theoretical project (Ewins, 2000) but, also, it is an extremely important method to identify vibrations of a structure and to detect structural modifications (R. J. Allemang, 1983).

Although the Experimental Modal Analysis (EMA) is a relatively easy and cheap test to perform, some mechanisms require a special attention: the excitation mechanism, the sensing mechanism and the data acquisition mechanism (Maia et al., 1998). The excitation mechanism is, usually, a shaker or an impact hammer (Rao, 2010). The sensing mechanism is the one that obtains the vibration data from the system (usually an accelerometer) and the data acquisition and processing mechanism is responsible to obtain the signal generated by the sensing mechanism, digitize (if required) and processing it (Maia et al., 1998).

The correlation between the input signal and the output signal is usually shown as a Frequency Response Function (FRF) (Ewins, 2000). When talking about modal analysis, the FRFs represent the correlation between the input condition (usually an initial condition, such as displacement or velocity) and the system's response to it (the system's vibration). For most of materials, Maxwell's reciprocity principle can be applied to the FRFs, i.e., applying the initial condition on a point p and measuring its response on a point q provides the same result than applying the initial condition on the point q and measuring its response on the point p (Maxwell, 1890). The reciprocity of the FRFs implies that measuring a full row of the FRF matrix will provide a full column and vice-versa (Schwarz & Richardson, 1999).

Sound is defined as the variation on mass density, pressure, temperature and particle's position on a fluid along the time (Fahy, 2000). These variations can be due to a mechanical variation. A vibrating plate is an example, its vibration provokes displacement along the plate, the displacement dislocates the air particles on the fluid medium, causing the variation quoted above, generating an acoustic response (Cardoso, 2010). It is possible noticing that there is a correlation between the vibrational response and the acoustic response of a vibrating system, making possible to analyze some modal parameters (natural frequencies and damping ratios) from the acoustic response (Elwali, Satakopan, Shauche, Allemang, & Phillips, 2010) (Fahy, 2000). Sometimes the approach using the acoustic response is not possible: when the analyzed system is heavily damped the vibration will be damped before the sensing mechanism measures its response (Silva, 2015).

Damage affects a system's initial mass and stiffness condition and these parameters affects the modal behavior, so, it is correct to say that a damage affects a system's modal behavior and modal properties (Meirovitch, 1997). The changes on the mass can be associated with material removal and the stiffness changes can be associated with the variation on the moment of inertia, for example.

MATERIALS AND METHODS

The beams used during the experimental procedures are made of Aluminum alloy 6082. These beams have a rectangular cross section with 300 mm length, 40 mm width and 5 mm thickness. Initially, the beams are undamaged. Aiming to inflict a controlled damage on the beam, centered holes were drilled at mid span. The diameter has the initial value of 15 mm and is increased by 1 mm until the final value of 38 mm, these holes were distributed along the four analyzed beams, and the final data is composed by 28 tests (one for the undamaged condition and one for each damage severity on each beam). All the values used for the drilled holes (for each individual beam) are shown in Table 1.

Table 1. Perforations' dimensions.

Beam n°	Perforation diameter [mm]						
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
1	0	15	16	17	18	19	20
2	0	21	22	23	24	25	26
3	0	27	28	29	30	31	32
4	0	33	34	35	36	37	38

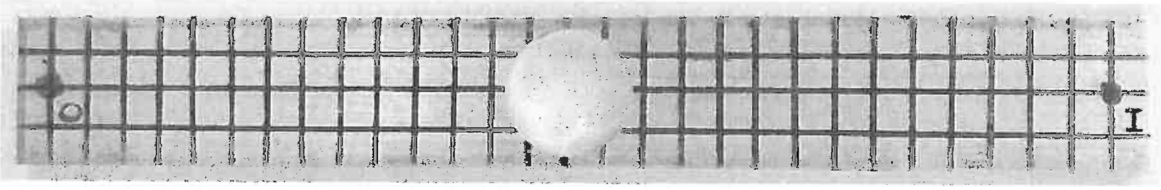
The damage will affect the mass (material removal) and the moment of inertia (the area resisting to the mechanical efforts changes). The mass variation is less than 10% and the moment of inertia variation is 95% (considering the most affected area), both from the undamaged scenario to the most severe damage scenario. The variation of these parameters implies the bending stiffness per unit of mass (EI/m), where E is the Young's modulus of the material, I ($I = bh^3/12$) *is* the moment of inertia and m the system's mass, will decrease along the tests performed, decreasing the stiffness on the affected area. IT is noticeable that the damage goes from a low severity level ($d = 15$ mm) to a high severity level ($d = 38$ mm), allowing monitoring the damage effects on the modal parameters along the tests.

Aiming to facilitate the measuring procedure and have a standard orientation for the input and output points, a grid was drawn on each beam. The grid is composed by squares (1 cm length) and was drawn using a permanent marker, avoiding damage infliction and mass loading. Figure 1 shows a damaged beam, with the grid and the excitation and measurement points drawn.

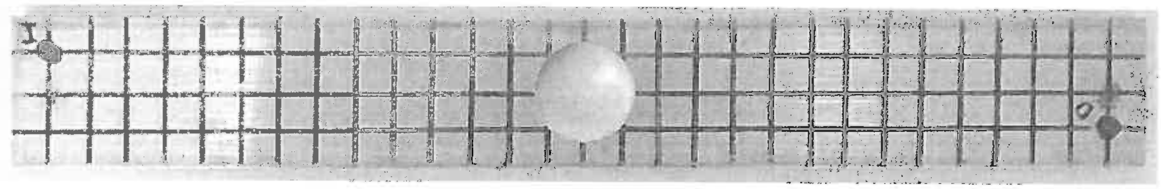
The excitation and measurement points must be chosen according to the mode shapes to be measured. Figure 1-(a) shows the input and output point chosen to the tests performed, they are very good to detect the bending modes but they are positioned on a modal line (i.e., there is no displacement on this nodes during some modes of vibration) when analyzing the torsional modes. In order to detect the torsional modes, a different position is required for the input and output points (distant from the modal line). The points shown in Figure 1-(b) were used to measure the torsional modes when required.

The numerical method used in this paper was a FEM simulation using Ansys' "modal" package and aims obtaining the mode shapes and the expected values for the natural frequencies of the beams. Every beam was tested individually and the results were obtained considering the interval between 0 and 2000 Hz.

The experimental method was composed by two parts: impact tests using an accelerometer to measure the output data (accelerometer method) and impact tests using a Sound Level Meter (SLM) to measure the acoustic response (SLM method). The experimental part aims to obtain the values of the natural frequencies for the same range used during the numerical method (i.e., 0 to 2000 Hz). During the tests using the accelerometer method, the acoustic response was measured simultaneously; allowing comparing the results obtained using both methods. Detailed tables containing the values obtained and errors associated can be seen in Silva (Silva, 2019). For both methods, an impact hammer (model E086C40) was used to provide the input signal and the beams were tested on a foam surface, simulating a "free" support condition.



(a). Excitation and output points ("I" represents the excitation and "O" the output point).

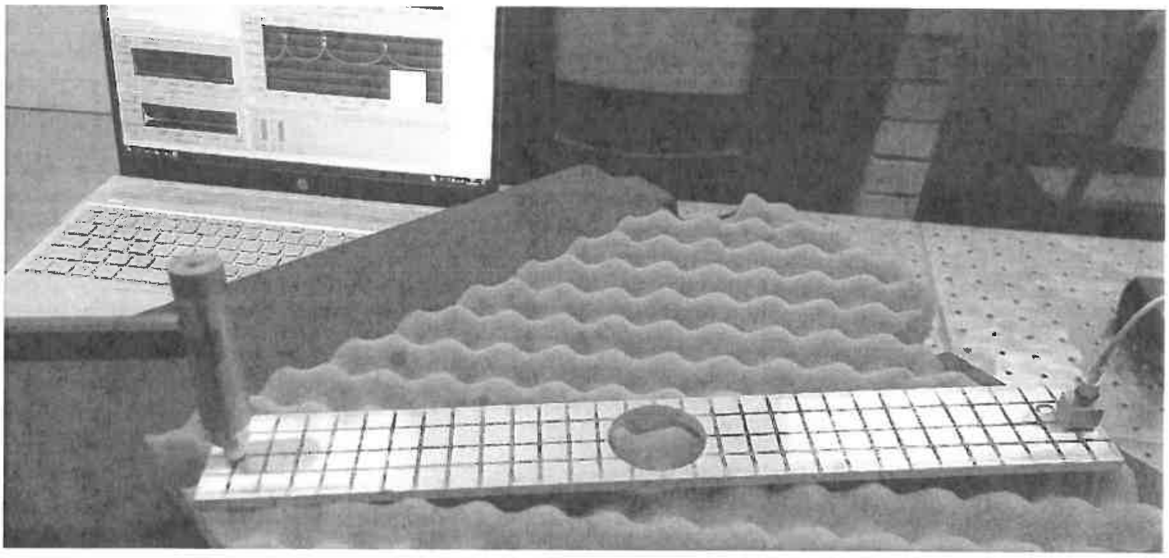


(b). Excitation and output points ("I" represents the excitation and "O" the output point).

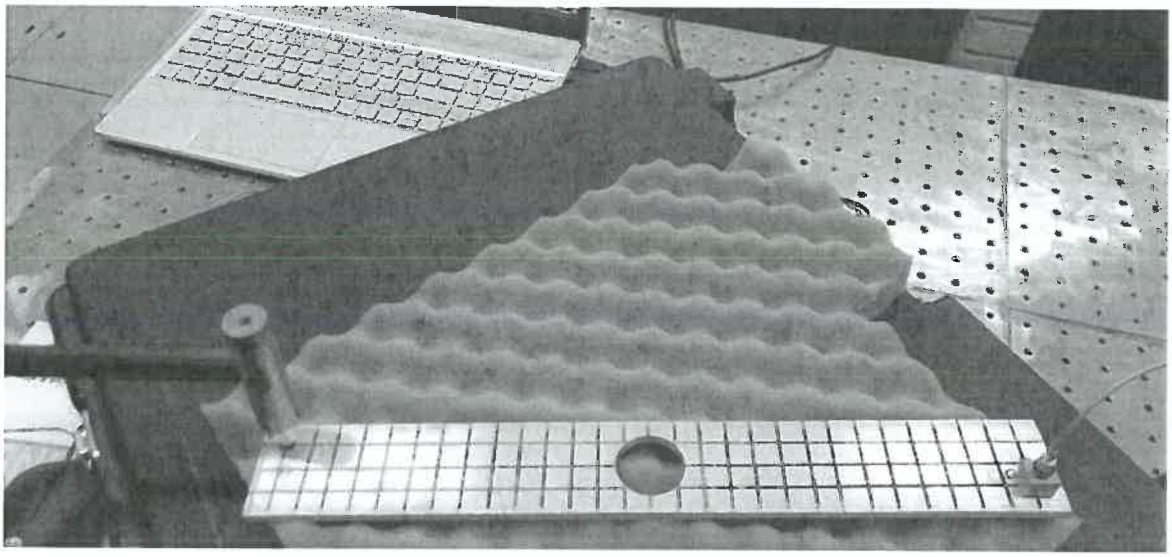
Figure 1. Location of excitation (input) and output points for the rover impact tests.

The impact tests using the accelerometer method was carried out using an uniaxial accelerometer (type 4508, made by Brüel & Kjær), plugged into a PHOTON+ dynamic signal analyzer which was connected to a pc via an USB cable, allowing the data processing using the RT Pro Photon software. The tests performed using the accelerometer method was carried out using a Single-Input Single-Output, i.e., only one input and one output was used during these tests.

Looking Figure 1 it is possible noticing that two sets of points were used to provide the input and measure the output signal: one using two aligned points (a) and other using points dislocated from the centerline (b). The setup using the (a) points as a reference are not capable of obtaining the torsional modes of vibration when using the accelerometer method so, in order to obtain the torsional modes, the setup showed in (b) was adopted. Figure 2 shows the difference between the setups during a real simulation using the accelerometers to obtain the output signal.



(a). Representation of a standard test using an accelerometer as an output source.



(b). Representation of a test to obtain the torsional natural frequencies.

Figure 2. Impact test using an accelerometer as an output source.

The impact tests using a SLM to measure the output data aims to capture the acoustic signal generated by the beam's vibration when it is impacted. To obtain the acoustic signal a free-field microphone (type 4189, manufactured by Brüel & Kjær), connected to a Hand-held analyzer (type 2250, G-4, manufactured by Brüel & Kjær) were used. This method allows obtaining the natural frequencies of the analyzed beam. This method discards the need of using two setups of points (unlike the tests using the accelerometer method) because every mode acting on the beam's vibrations contribute to the sound generated and it is captured by the microphone. The microphone was positioned perpendicular to the beam's surface, 5 cm distant from it. A representation of a test performed on the beams can be seen on Figure 3.

The acoustic response was processed using the hand-held analyzer and returned the values of the natural frequency on the analyzed range. It is possible to compare the data obtained using both methods and to calculate the error between them.

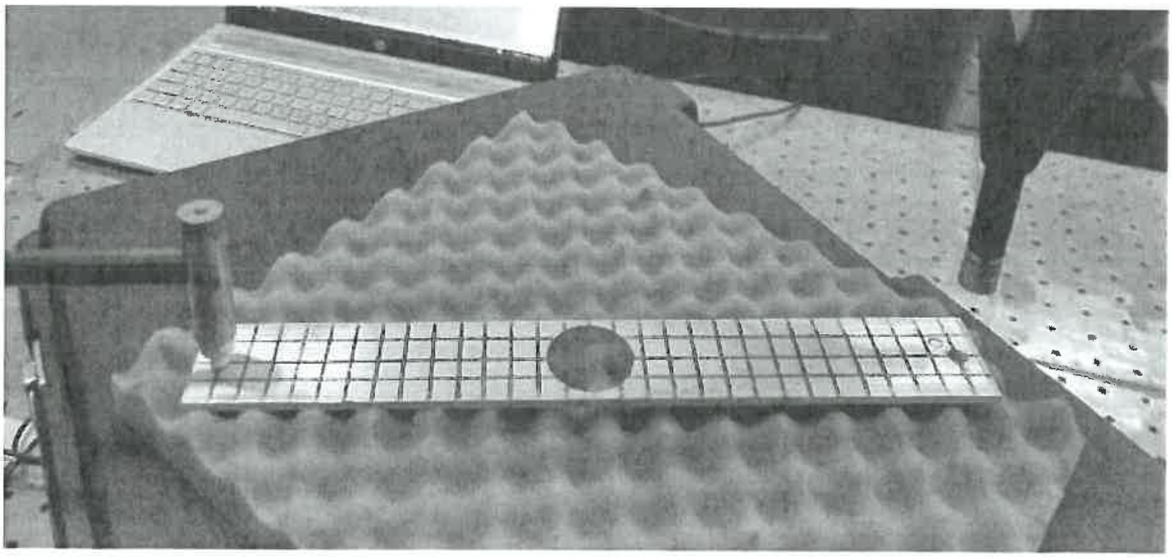


Figure 3. Impact test using a sound level meter to measure the output data.

RESULTS AND ANALYSIS

The variation of the natural frequencies due to the damage for the vibration modes detected between 0 and 2000 Hz are shown in Figure 4 to Figure 7. As expected, the natural frequencies decrease with an increase of the damage, i.e., the diameter of the drilled hole at the mid span. As can be seen, the most significant change of the natural frequencies occurs on the first and fourth modes.

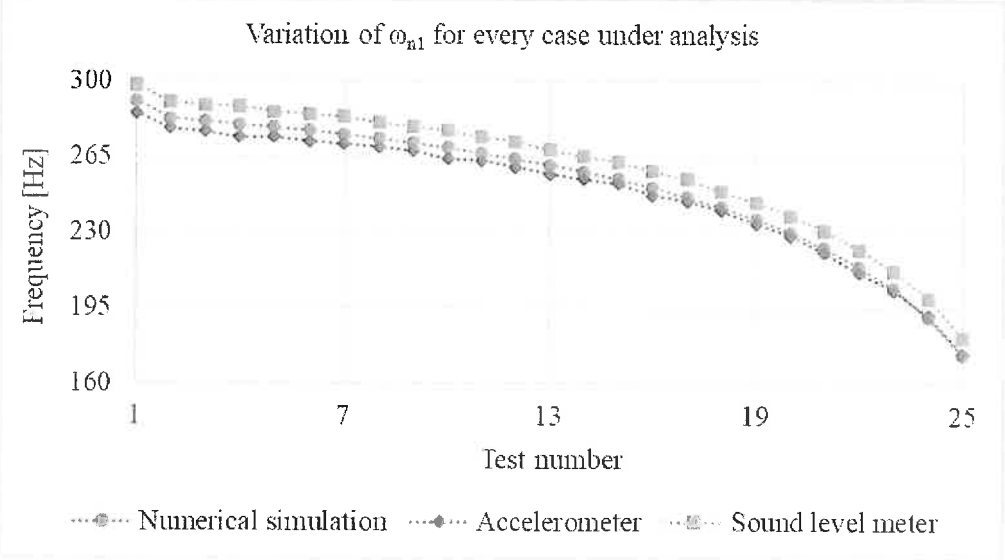


Figure 4. First natural frequency variation along the tests.

Observing Figure 4 it is noticeable a decrease of the values of the first natural frequency related with the first bending mode when the damage or hole diameter increases. The decrease between the natural frequencies measured for the undamaged case scenario and the last one is, approximately, 39.2%.

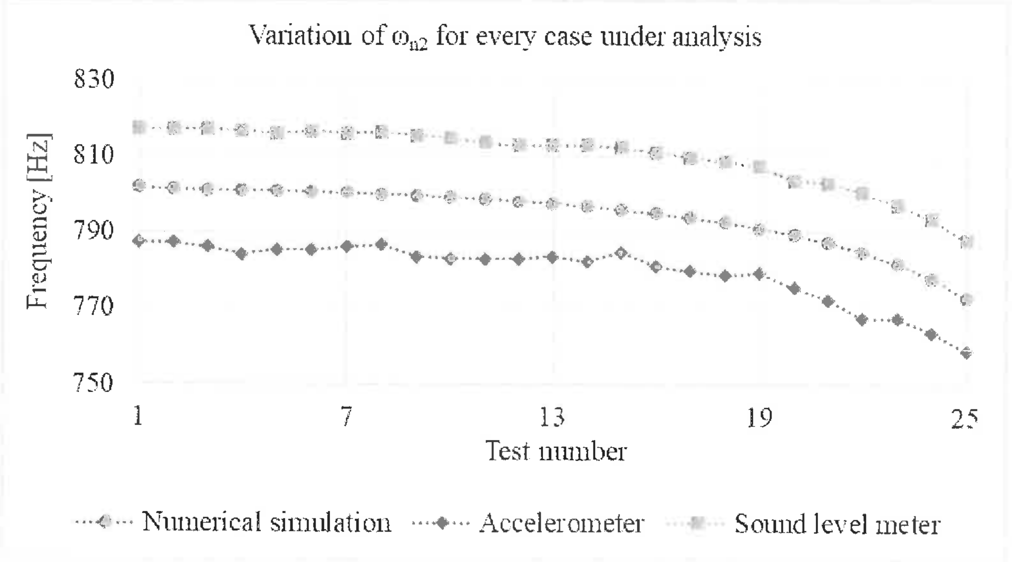


Figure 5. Second natural frequency variation along the tests.

Similarly to the variation of the first natural frequency, the second natural frequency related with the second bending mode (see Figure 5) decreases when the damage severity increases. Although this natural frequency is not as much affected as the first one (with a decrease of approximately 3.6%), a decrease is visible and can be associated with the type of damage used in this study.

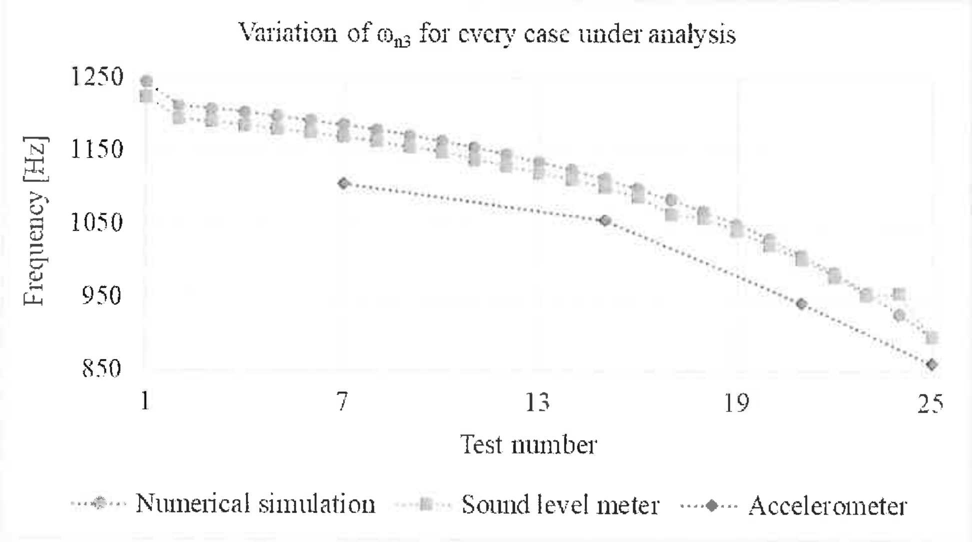


Figure 6. Third natural frequency variation along the tests.

Figure 6 shows the variation of the natural frequencies associated with the first torsional mode of vibration (with a decrease of approximately 26.7%). The lack of data obtained using the accelerometer is due to the points chosen to apply the input and measure the output, which are not able to measure the torsional mode vibration response (see Figure 1a). Some tests were repeated using the points shown in Figure 1b) and they were able to measure the output, resulting on the plot shown in Figure 6. Even with a small data sample, it is still possible to see a decrease on the value of the natural frquency.

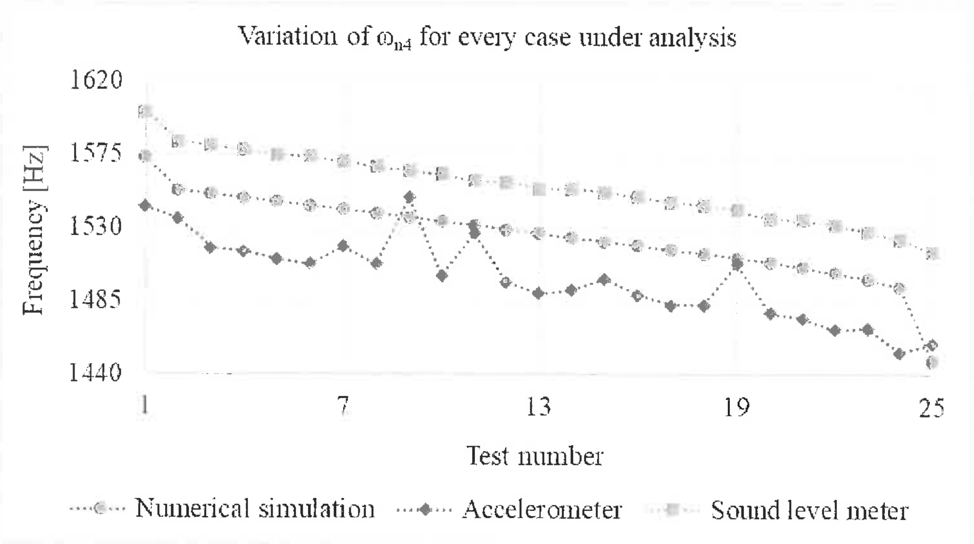


Figure 7. Fourth natural frequency variation along the tests.

Figure 7 displays the variation on the values measured for the fourth natural frequency (third bending mode). The difference of the value measured for the undamaged case to the value measured on the last test (most damaged) is around 5.4%. Some measurements mismatch the expected values (peaks) due to poor data obtained during the experimental tests. The average error between the measurements performed using the accelerometer and the SLM is of 4.0%.

CONCLUSIONS

Analyzing the data obtained with this experimental research it is possible to conclude that the SLM is a reliable equipment to measure the natural frequencies with some restrictions such as heavily damped systems in which the measurements must be done without background noise and the measurement time must be large enough to capture the frequency content of the sound wave. Also, the damage inflicted to the beams affects the natural frequencies and its value decreases when the damage severity increases, and finally the measuring points using the accelerometer (input and output) must be chosen carefully according to the modes that are been measured when.

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