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ABSTRACT

The dynamic properties of materials are important parameters for numerical vibro-acoustics analysis of a household refrigerator. The compartment of a household refrigerator is typically composed by three types of materials: hot rolled steel, polyurethane rigid foam (PUR) and high impact polystyrene (HIPS). In this work, the mechanical properties (dynamical Young's modulus and loss factor) of these materials were determinate in order to comprehend its frequency-dependent behavior to use them properly in vibro-acoustic numerical models of household refrigerators. Experimental procedures based in impulsive responses of beams were performed for each material. Moreover, numerical models were used to fit the polyurethane rigid foam properties to experimental data. Finally, a numerical model of "sandwich" beam was built using the obtained properties. The results were compared with experimental tests performed on "sandwich" beam specimen from a refrigerator compartment. Good agreement was found for frequencies between 0 Hz to 600Hz.

1. INTRODUCTION

The interaction between the compressor and its compartment has a great impact on the overall noise generated by refrigerators, especially for frequencies between 100 Hz and 500 Hz (Carvalho, 2008).
The compartment of household refrigerator is typically composed by three types of materials: hot-rolled steel, polyurethane rigid foam and high impact polystyrene. This arrangement of materials is known 'sandwich' structure which provides good thermal insulation and structural stiffness without adding too much weight.
The static properties of these materials (Young's and shear modulus) have been used in dynamical analysis of simple sandwich structures (beams), and good agreement was obtained for first modes (Orestes, 2003). Recently, dynamical properties (Young's modulus and loss factor) of these materials have been estimated using a Finite Element (FE) model, an Amplitude Correlation Coefficient (ACC), Genetic Algorithm (GA) and experimental Frequency Response Functions (FRFs) of sandwich beams (Barbieri, 2009).
An experimental technique for complete characterization of a visco-elastic material that allows the determination of Poisson's Ratio and Young's modulus, for a beam was made with use of seismic excitation (Caracciolo, 2004). With this technique, the obtained experimental data of Poisson's ratio and Young's modulus were assembled into a single master curve using the method of reduced variables represented in a wide frequency range.
A method to measure frequency-dependent dynamic properties of complex structures was analyzed using the Timoshenko beam and the shear beam theories (Park, 2005). Wave speeds, bending and shear stiffness of the structures were measured through the transfer function method.
In the first part of the present work, statics properties of steel and HIPS (Young's modulus and Poisson) were obtained using the standards ASTM D638-77 and NBR 6673, respectively. In the second part, dynamic properties

(Young's modulus and loss factor) of PUR were determined through finite element (FEM) models and experimental tests. The dynamic properties of HIPS were obtained using standard ASTM 756-05. Finally, two FEM models of sandwich beam were developed for two boundary conditions: cantilever and free-free. The properties obtained in the first parts of this work were used in these models. Experimental and numerical FRF curves were compared to validate the model.
However, under field conditions, the material's properties can vary over the refrigerator compartment, due to the manufacturing process, e.g. polyurethane and polystyrene. In this work, studies of the dynamical properties were conducted in order to evaluate the influence of such variance on the vibro-acoustic behavior, for frequencies from 0 Hz to 600Hz.

2. FINITE ELEMENT METHOD (FEM)

The Finite Element Method is an efficient numerical tool to solve problems of continuous. The method considers that a continuous structure is formed by sets of smaller substructures, called elements, where properties are uniformly distributed.
The kinematic characteristics of each of these elements are concentrated at points called nodes. The method handles several simultaneous algebraic equations, which are solved by matrix operations. For each degree of freedom, rotation and bending have an equation, resulting in a row and a column in the matrices generated. In this context, a dynamical system can be represented by the matrix equation (Cook, 2002):

$$[M].\{\ddot{u}\} + [C].\{\dot{u}\} + [K].\{u\} = \{F\}, \tag{1}$$

It is a powerful well known method, used to solve problems with complex geometries, whose solution by analytical methods is quite complex. The results are approximate, but the errors can be minimized with proper analysis of the geometric model.

3. PROCEDURES FOR DETERMING THE PROPERTIES

3.1 Static Procedures

To determine the static properties of polystyrene a simple tensile test based on ASTM D 638-77a was performed. The standard describes the procedure and the equipment necessary to determine the mechanical properties of plastic samples. Eight polystyrene samples from different regions of the household of the refrigerator were tested by measuring the deformation of the sample with an extensometer, it was possible to directly find the values of Young's modulus (E) and Poisson's ratio (υ). The average Young's modulus found for the polystyrene was: E=1.953 GPa with an standard deviation of σ_E=0.038GPa, and a Poisson ration ν=0.3.
The Young's modulus (E) and Poisson's ratio (υ) of hot rolled steel were determined by simple tensile test using the procedures and equipment described in NBR 6673. Three samples were tested and the average result found for the three tested hot rolled steel specimens is: E=207,51 GPa with standard deviation σ_E=0.62GPa , ν=0.3 for the steel.

3.2 Density

Based on the principle of Archimedes one may obtain the density of a material, whether solid or liquid, with the use of the following equation:

$$\rho_c = \left(\frac{m_c}{m_c - m_{ap}}\right)\rho_L, \tag{2}$$

where, m_C corresponds to the mass of the material to be measured, m_{ap} is the apparent mass of the material, measured when the body is immersed in the liquid and ρ_L is the volumetric density of the water or alcohol.
The tests for determining the density of materials through the Principle of Archimedes were performed with a digital equipment. During the procedure the temperature of alcohol was kept constant at 24 ° C.
The found average density of the steel is ρ=7342 kg/m^3 with the standard deviation of σ=0.116 kg/m^3. The density (ρ) of steel quoted by Calister (2002) is ρ=7800 kg/cm^3. In this way, the value found in this research is less than 7% different from that obtained by Oresten (2003). Six Polystyrene samples, from distinct regions of the inner household were measured. The dimensions of these samples are 15x10mm, and thickness of 1.45mm. The average

density of the polystyrene is ρ=1014 kg/m^3 with standard deviation of σ=0.002kg/m^3. The average density of polystyrene obtained experimentally by Oresten (2003) is ρ= 1061.9 kg/m^3 and according Callister (2002), ρ= 1050 kg/cm^3. These values are in agreement with the one obtained in this research.

For the polyurethane, the specimens were cut with approximate dimensions 10 x 10 x 10 mm. These samples were separated in two groups: samples from the bottom of the enclosure and samples from each side. This was done because of the expected difference caused by the injection of PUR. The average density of the polyurethane on the bottom of the household is ρ=41.06 kg/m^3 with standard deviation of σ=7.96kg/m^3 and for the samples on the side of the household, ρ=34.30 kg/m^3 with standard deviation of σ=1.78kg/m^3. The average density of the polyurethane obtained experimentally by Carvalho (2008) and Oresten (2003) is ρ= 28.5kg/m^3, and according to Callister (2002) is ρ= 32.0kg/m^3. Callister (2002) describes rigid polyurethane with a possible variation from 28 kg/m^3 to 50 kg/m^3. The values found in this research are in agreement with those references.

3.3 Dynamical Properties

In this section, the measurement procedures, used to determine the dynamical behavior of each material under study, are described. The process of determining of Young´s modulus consisted in measuring the driving frequency response to determinate the resonance frequencies. A major concern for vibration measurements is the preparation of the structure to be tested. Care must be taken in order to avoid errors in the measurement procedure. The locations of the sensors, failures on digital signal processing, etc, might impair the quality of data obtained experimentally. The first decision to be made is at which condition the structure will be tested, free or clamped. In a clamped structure it is difficult to ensure that the boundary condition is effectively rigid. Free boundary conditions should be preferred if possible, which is not the case in this research.

3.3.1 Polyurethane Rigid Foam(PUR)

In the acquisition of the frequency spectra, the boundary conditions chosen for the beam of polyurethane was a cantilever beam (Figure 1(a). The process of evaluation of Young's modulus was repeated on five different samples in order to the household, Figure 1(b). With this procedure it was possible to evaluate the dispersion of the density values along the household. The PUR sample analyzed had the following dimensions: 10 mm of thickness, 20mm of width and 270 mm of length. A base at one end of the beam was made with epoxy glue, to minimize any deformation that the polyurethane could suffer when fixed. A non-contact sensor (laser vibrometer) was used to determine the frequency response of polyurethane beam, in order to avoid the gauge mass effect. The excitation of the beam was performed with non-contact magnetic actuator to avoid the excessive deformation a hammer could cause to the foam (Ewins, 2000).

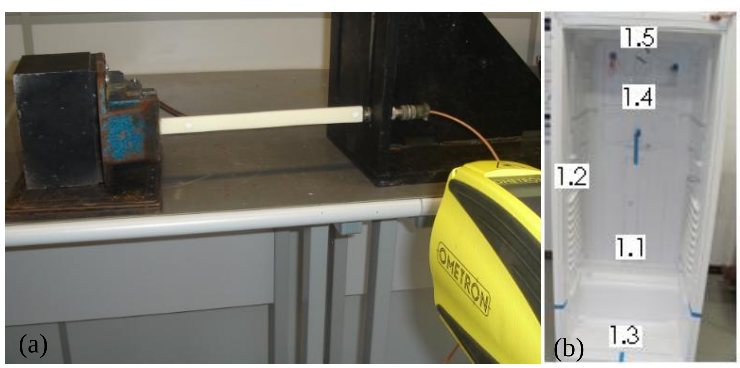

Figure 1 : (a) - Regions from which the samples were extracted from the household. (b) – Bench to measure the frequency response function of the PUR beam.

To analyze and understand the experimental results, numerical simulations were performed using a finite element software, with a solid element type. The flexural wave velocity was calculated to determinate the wave length (λ), and the element size was at least smaller than $\lambda/6$, for the frequency range of 0-1 kHz. The element size for calculating the frequency response of the PUR was of $4mm$.The natural frequencies found experimentally was compared with the natural frequencies obtained through numerical modal analysis in Figure 2 for a polyurethane beam with the same dimensions and properties found by Oresten (2003) and Villar (1998): $E = 6MPa$ and $\nu = 0.45$.

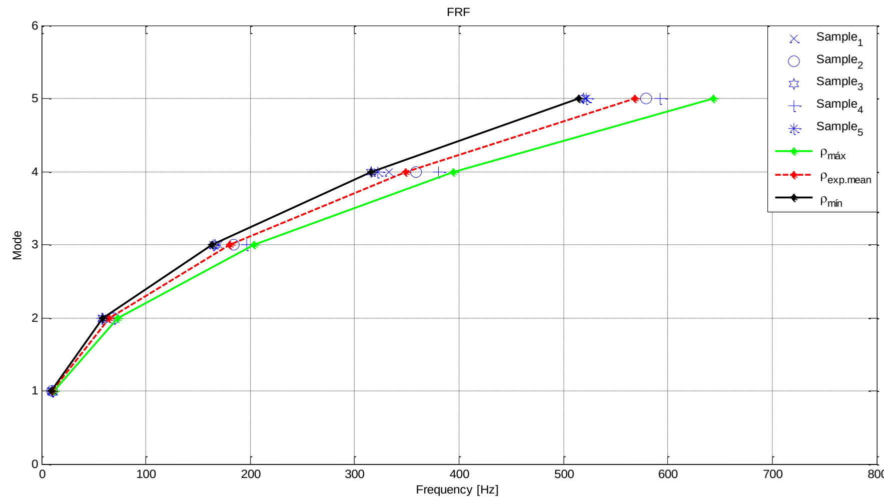

Figure 2 : Analysis the results of experimental modal analysis of five samples of polyurethane.

In Figure 2, green and black curves represent the results of numerical analysis performed using the modal densities $\rho = 28\ kg/m^3$ and $\rho = 50\ kg/m^3$, respectively. These curves represent the minimum and the maximum values found by Villar (1998). The red curve is the result of numerical modal analysis using the experimental average density (Section 3.2), $\rho = 41\ kg/m^3$. Items in blue, in the Figure 2, represented the results found experimentally.
The values of natural frequencies found experimentally have a considerable dispersion. When compared with the natural frequencies found numerically, it can be seen that this dispersion occurs by variation of the density of the material throughout the enclosure. It is also possible to observe that the values of the density found by Villar (1998) are between the minimum and maximum values found experimentally. So concludes through this analysis that the density varies along of refrigerator compartment, the sides have lower density and bottom higher density. The average value of loss factor is $\eta = 0.0315$, found by the method of half-power band.
For experimental validation of the PUR, numerical harmonic analyses were performed. The density values were used according to the location of each sample, $\nu = 0.45$ and the Young's modulus (E) as found by curve fitting $(E = 6\text{MPa})$.

3.3.2 High Impact PolyStyrene (HIPS)

The method used for the cantilever beam is described in the standard ASTM E-756-05. This method is often used to determine the dynamic properties of materials (viscous elastic, ceramics, rubber, plastics and metals.) such as the loss factor (η), Young's modulus (E) and shear modulus (G). The method provides results from the use of analytical equations of classical theory of beams, specifically which of a cantilever beam. The terms involving rotational inertia and shear deformation are not considered and it is assumed that plane sections remain plane after the application of force excitation.
To calculate the properties the resonance frequencies of each mode of vibration, geometry and density of the material constitute the beam are required data. The Young's modulus is obtained from Equation 3:

$$E = \frac{12.\rho.l^4.f_n^2}{H^2.C_n^2}, \quad (3)$$

where, E corresponds to the Young's modulus (MPa), ρ the density kg/m^3, l the length of the beam given in (m), n the number of the vibration mode, f_n is frequency in Hz, H is the beam thickness in (m), C_n are the coefficients for the mode n. Considering a cantilever beam, the coefficients of the vibration modes correspond to:

$$C_1 = 0{,}55959;\ C_2 = 3{,}5069;\ C_3 = 9{,}8194;\ C_4 = 19{,}242;\ C_5 = 31{,}809;. \tag{4}$$

And for n>5:

$$C_n = \left(\frac{\pi}{2}\right).(n - 0{,}5)^2 \tag{5}$$

This procedure is used in beams that have the width of 10mm, thickness between 1mm and 3mm and length between 180mm and 250mm. The experimental apparatus consists of a rigid base used to hold the beam (Figure 3 (a)), a vibration transducer (accelerometer), an impact hammer with nylon tip and an appropriate instrumentation to measure the excitation signal and response. The excitation was made from impacts on a fixed point, located near the tip of the cantilever beam, while the response was extracted on the other end of the beam and recorded in time domain for post-processing.

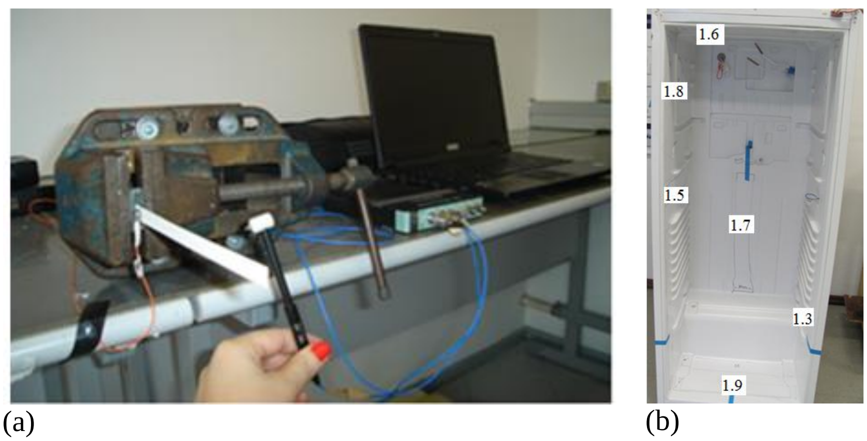

Figure 3 : (a) - Clamped beam of HIPS and (b) - Regions from which the samples were extracted.

Six rectangular specimens were tested. Their dimensions are 10mm of width, 1.45mm of thickness and 180mm of length. The samples were extracted from various parts of the household of the refrigerator (top, bottom, upper side, lower side, lower back and one last sample on the side next to depart).
Epoxy glue bases were built for the HIPS beams, which were fixed in a vise. The impulsive force and the accelerometer were applied near the edge, respectively 10mm and 5mm. Both the force and acceleration were applied and measured at the centerline of the beam, in order to measure only the bending modes. It is important to remember that the thickness varies from 1mm to 1.7mm and that the natural frequencies depend on the mass of the system.
The Young's modulus for each beam is calculated through Eq. 3. The dynamic behavior of the beams is represented by the curves in Figure 4. As a rule, the first natural frequency of each beam can be discarded due to possible problems caused by wrong mountings.

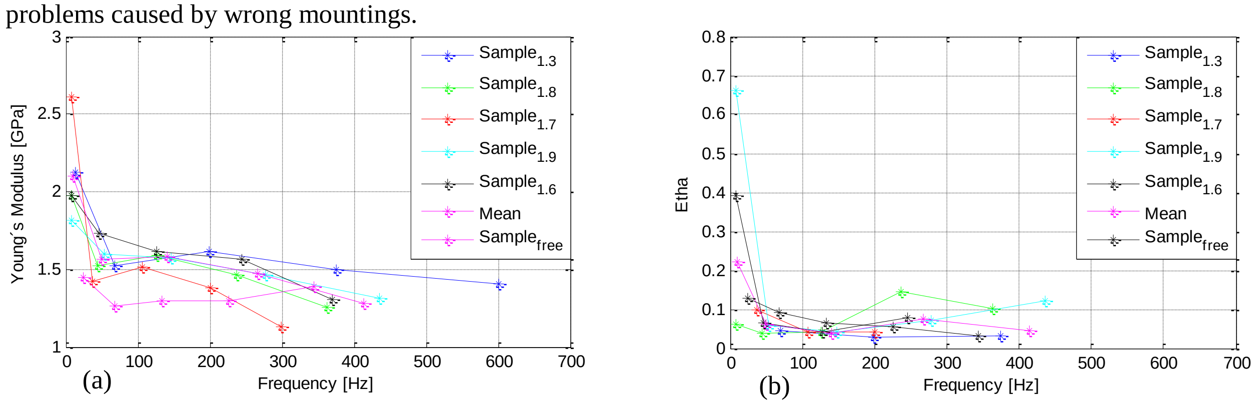

Figure 4 : (a) Young's modulus of polystyrene beam. (b) Damping of polystyrene beam.

Through Figure 4, the average Young's modulus used to numerical analysis in the sandwich beams is E=1.445 GPa and the loss factor is η=0.053, both considered constant with frequency.

3.3.3 Sandwich Beam

An experimental modal analysis was performed in the beam in free-free condition. The beam was divided into 80 points, 40 on each side. An impact hammer was used for exciting the beam in a point over the polystyrene, in the end of the beam. The response was measured in the 80 points by an accelerometer and the signals were acquired by a digital signal analyzer.

A numerical model of the sandwich beam in free-free conditions was developed using a finite element software. In Section 3.3.1, it was observed that dynamic behavior of PUR is constant in frequency, but when engaged in a sandwich beam properties E and η vary in frequency. The mean values of properties of hot rolled steel used in this model were: E=207.51 GPa (Section 3.1), ρ=7342 kg/m^3 (Section 3.2) and ν=0.3 (Section 3.1). HIPS properties used were: E=1.445 GPa (Section 3.3.2), ρ=1014 kg/m^3 (Section 3.2) and ν=0.32 (Section 3.1) and PUR ρ=45 kg/m^3 through analysis of variation of density in the middle (Section 3.3.1) and ν=0.45. Two numerical analysis were performed: modal and harmonic analysis. The experimental and numerical results were compared, but no agreement was found.

A sandwich cantilever beam was analyzed. The beam was attached to a concrete base in order to ensure the clamped condition. The experimental setup used is shown in Figure 5, the excitation of the structure was made with the similar method of the free-free beam. However, the beam was divided into 44 points, 22 on each side of the beam. An impact hammer was used for exciting the beam in a point over the polystyrene, in the end of the beam. The response was measured by an accelerometer in the 44 points.

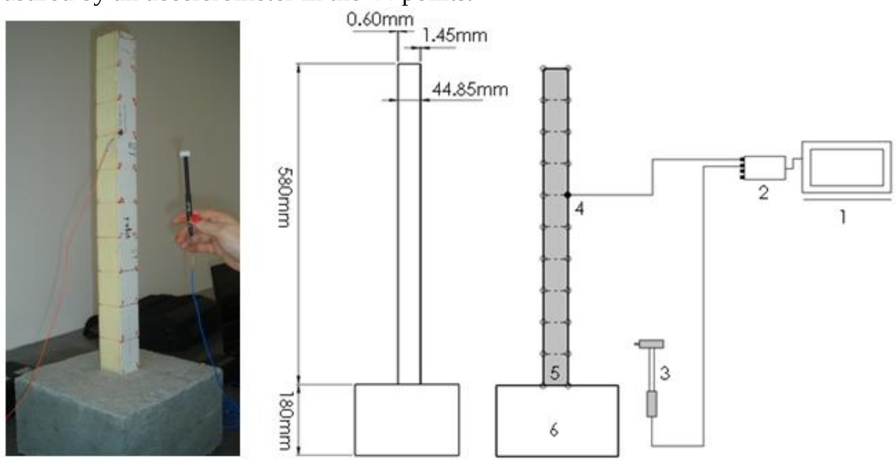

Figure 5 : Schematic of bench where: 1 - Notebook, 2 - Signal Analyzer, 3 - Impact Hammer, 4 - Accelerometer, 5 - Sandwich Beam and 6- Bench.

A numerical model of cantilever beam was developed using solid brick elements from a finite element software. The dynamic behavior was analyzed through modal and harmonic numerical analysis. The model was performed with the same properties for the steel and HIPS, used in the previous model. However, in the case of the PUR properties a new approach was used. In order to implement the frequency-dependent Young's modulus and loss factor, the frequency response of the beam was divided into five frequency bands, grouped by the similarity of loss factor as show in Table 1.

Table 1 : Natural frequency of the cantilever beam adjusting proprieties of Polyurethane.

Mode	Band frequency (Hz)	$E(MPa)$	η
1	0-95	9	0.155
2	95-208	10	0.532
3	208-496	12	0.039
4	496-542	15	0.012
5	542-600	20	0.345

The result of this model is compared with experimental data in the Figure 6. Good agreement for flexion modes was obtained, but not for torsion modes. The disagreement in torsion modes can be due irregularity of the PUR properties. Air bubbles can be present in the PUR inherent to manufacturing process.

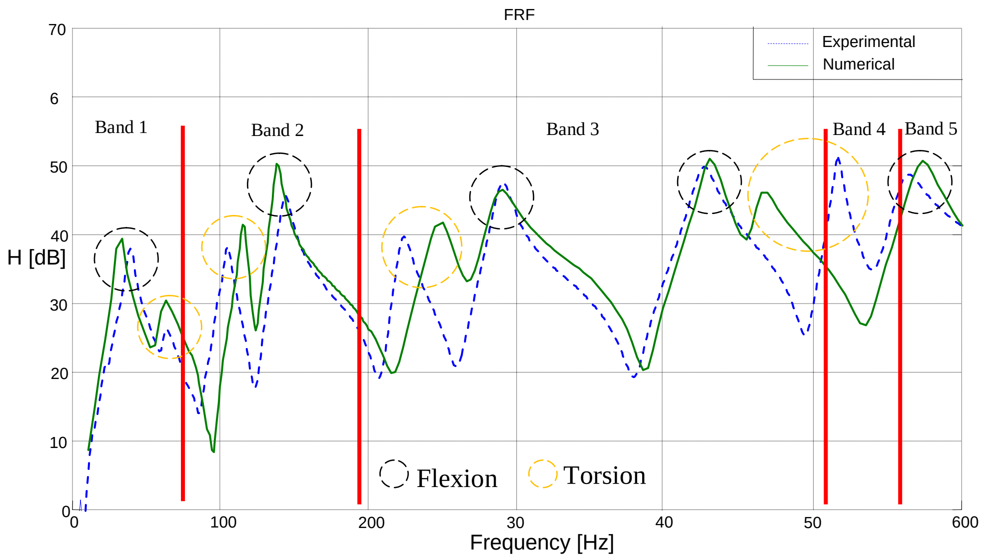

Figure 6 : Experimental and estimated FRF curves of the cantilever beam.

However, for some vibro-acoustic analysis (e.g. sound radiation) good agreement for flexion modes can be enough to achieve satisfactory results.

4. CONCLUSIONS

In this paper, the mechanical properties (Young's modulus and loss factor) of hot rolled steel, polyurethane rigid foam and a high impact polystyrene, were determinate with emphasis on its frequency-dependent behavior, in order to use them properly in vibro-acoustic numerical models of household refrigerators. Experimental procedures, based on impulsive responses of beams were made for each material. Moreover, numerical models and curve-fitting procedures were performed to determine the dynamic properties of polyurethane rigid foam. A numerical model of a "sandwich" beam was built using the frequency-dependent properties obtained with good agreement between numerical and experimental data.
The results found by Finite Element Method (FEM) are in good agreement in comparison with the experimental data. Differences in certain frequency regions were found, but are expected due to the non-homogeneity of the studs, the manufacturing process of sandwich beams and the manufacturing process of the polyurethane (injected), which can cause bubbles in the foam and the strains present wires and pipes attached to the refrigerator. Good agreement between estimate and experimental FRF`s curves was founded for a frequency band from 0 Hz to 600Hz.

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