DYNAMIC DETERMINATION AND USE OF VISCOELASTIC MATERIALS PROPERTIES

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Abstract. *Vibration and noise control in passenger vehicles and aircraft using passive structural damping, with viscoelastic material technology, is being increasingly used by automotive and aerospace industries. Thus, the definition of the properties of these viscoelastic materials, such as damping loss factor and Young`s Modulus, used in numerical simulation and optimization algorithms, is indispensable. This article describes the properties characterization of two viscoelastic materials used in passenger vehicles, LASD (Liquid Applied Sprayable Damper) material and Asphaltic Melt Sheet. Oberst Method is applied to obtain the properties, which are used in a numerical simulation of a cantilever beam.*
Keywords*: Oberst; Viscoelastic; Damping*

1. INTRODUCTION

Structural damping currently plays an important role in almost all areas of technological industries. In the automotive industry, as well as aeronautics, viscoelastic materials are used in structures, especially in the most flexible ones, which present the highest vibration levels. In automotive applications, damping materials are generally adhered to metal panels in order to control vibration at resonant frequencies. Appropriate lab tests and other tests regarding the vehicle structural performance, with damping materials applied, are essential for material development and specification purposes, since they allow the quick and inexpensive final determination of the vehicle damping material application.

It is therefore extremely important to quantify the damping capacity of materials, which is known as loss factor (η). The stiffness of the material applied is another factor that must be taken into account, which is quantified through the Young Modulus (E), distinguished from the static modulus of elasticity, because the structures are subject to dynamic loads.

The aim of this study is to quantify the stiffness and damping capacity of two viscoelastic materials, used for structural damping in automotive industry, at different temperatures, using the Oberst Method, and choose the one that have better properties to use in damping treatment in passenger vehicles. After obtaining the materials properties, numerical simulations were conducted and their results are compared to experimental ones, only using the elected material, validating the experimental methodology used to define these material properties.

2. DAMPING TREATMENT OVERVIEW

Some aspects about the use of viscoelastic materials on mechanical structures damping are discussed below.

2.1. Damping

Damping is an energy dissipation phenomenon of a vibration system, in which occurs the conversion of mechanical energy into heat. It depends not only on the material but also on the geometry, because different structures have distinct natural frequencies and modal shapes. Thus, for some systems, it is necessary to add damping materials, which provide reduction in vibration levels. A common objective is to obtain a maximum damping process, but, when one tries to get it, other parameters are subject to changes, such as mass and stiffness (Martinez, 2008). That is, three variables should be considered – mass, stiffness (Young modulus) and damping – to optimize the damping process.

2.2. Damping temperature dependence

The ability of a material to dissipate vibration energy is highly dependent on temperature, since the phenomenon depends on the atomic arrangement and composition of the material. With the temperature increase, the materials may suffer thermal transitions of first (fusion, vaporization) and second order (glass transition in amorphous materials and semi-crystals, change of crystal structure). Both are related to the increase of the inter-atomic distances. These factors influence the wave propagation through the material and, as a consequence, the natural frequencies of the body. In Fig. 1, the behaviors of the loss factor (η) and the dynamic Young and shear moduli (E or G) are presented.

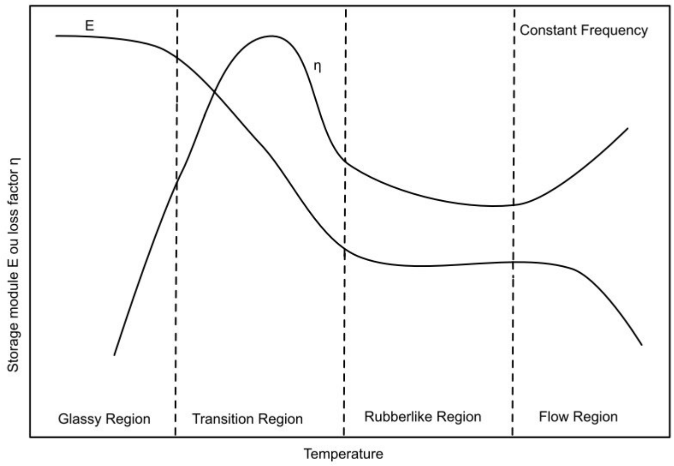

Figure 1. Behavior of loss factor (η) and Young (or shear) modulus *(E or G)* with temperature (Nashif, 1985).

The glass region is characterized by high E (or G) values, and values of η that grow rapidly with increasing temperature. The rubber region is where both values decrease in relatively low rates. The transition region is where the highest values of η are found, and where the values of E decrease rapidly with increasing temperature. In polymeric materials, the maximum loss factor value is located at the glass transition temperature, when occurs the mobility of the amorphous part of the chain, not changing the crystal part (in case of semi-crystal polymer).

2.3. Damping frequency dependence

For viscoelastic materials, frequency effects present inverse behavior when compared to temperature effects (see Fig. 2). The most relevant fact in this kind of analysis is that the Young modulus always grows, with increasing frequency.

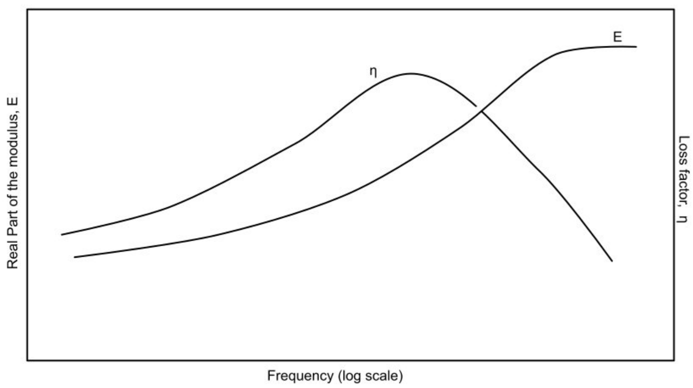

Figure 2. Behavior of Loss Factor (η) and Young Modulus *(E)* with frequency (Nashif, 1985).

2.4. Viscoelasticity

Viscoelastic materials are those which have intermediate characteristics between elastic solids und viscous fluids and, when submitted to stress, return to their original shape after completing a strain cycle. During this cycle, energy is lost.

The elastic behavior is characterized by angle and distance variations between the inter-atomic connections, and it can be idealized as a Hookean Spring, like the one presented at Fig. 3 (under simplified linear behavior, $F = k \cdot x$) (Canevarolo, 2002).

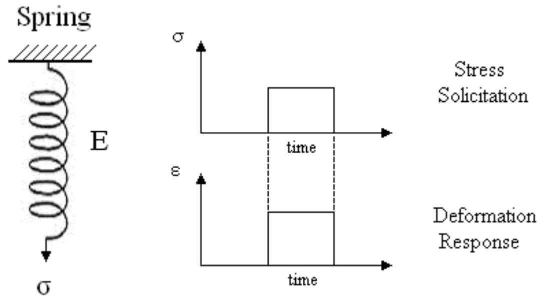

Figure 3. Elastic behavior of a material (Canevarolo, 2002).

The viscous behavior is characterized by the viscous friction between the molecules, which causes a delay on the material response, when subjected to stress, behaving as a Newtonian fluid, and the material response is directly proportional to the rate of deformation with time, see Fig. 4 (Canevarolo, 2002).

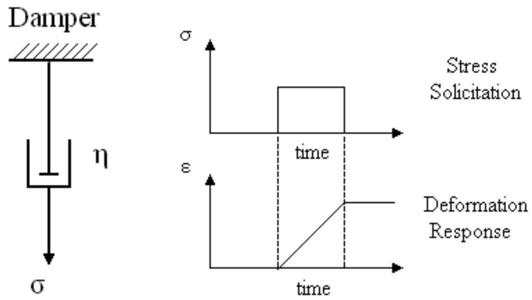

Figure 4. Viscous behavior of a material (Canevarolo, 2002).

Displaying graphically the behavior of the material during a stress-strain cycle, it is obtained a hysteresis loop, Fig. 5. The inside area of the ellipse represents the amount of energy dissipated during the process.

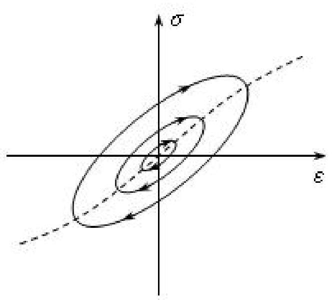

Figure 5. Hysteresis cycle of a linear viscoelastic material (Nashif, 1985)

3. OBERST METHOD

The Oberst Method consists on the determination of the materials properties in a comparative way, in the case the damping material is not enough stiff to be directly analyzed: first the properties of a base beam (uniform beam) are determined, by analysis of its vibration responses. At a second step, the viscoelastic material is added to the base beam, and new responses are obtained. Properties are obtained mathematically by equations that related the whole body (base beam and damping material).

The free-layer beam experiment was chosen (Fig. 6), in which the energy dissipation occurs by traction and compression strains. The base beams were made of basic steel ABNT-1020, the same material commonly used for car bodies, with the following dimensions: 250.00 mm x 10.00 mm x 3.30 mm, not taking into account the clamping region. The beams were submitted to a surface treatment, painting and e-coating (electronic coating), for better adherence of the damping material. This process is also applied to car bodies before the final painting. Viscoelastic materials A (LASD – liquid applied sprayable damper) and B (ASD – asphalt melt sheet) were tested. The thicknesses of the damping coatings were 1.7 and 2.4 mm, respectively, for these materials.

The loss factors can be obtained from the frequency response functions (FRF) of the systems. The determination of η, for the case of base and composite beams, is obtained by the method of the half power bandwidth. At each resonance peak, it is drawn a line 3 dB below the maximum value. Two points are located this way, defining a frequency band with width Δf. The division of this bandwidth by the peak frequency gives the value of the loss factor. Loss factor and Young modulus values of the beam, without (Eqs. (1) and (2)) and with damping material (Eqs. (3) and (4)), respectively, are obtained by the equations:

$$\eta = \frac{\Delta f}{f_n} \qquad \text{Eq. 1}$$

$$E = \frac{\left(12\rho \cdot l^4 \cdot f_n^2\right)}{\left(H^2 \cdot C_n^2\right)} \qquad \text{Eq. 2}$$

$$E_1 = \frac{E}{2T^3}\left[\left(\alpha-\beta\right)+\sqrt{\left(\alpha-\beta\right)^2-\left\{4T\left(1-\alpha\right)\right\}}\right] \qquad \text{Eq. 3}$$

$$\eta_1 = \eta_c\left[\frac{\left(1+MT\right)\left(1+4MT+6MT^2+4MT^3+M^2T^4\right)}{\left(MT\right)\left(3+6T+4T^2+2MT^3+M^2T^4\right)}\right] \qquad \text{Eq. 4}$$

where:

c = índex number: 1,2,3....($c=n$);
C_n = n-mode constant;
$D = \rho_1/\rho$, density ratio;
E = base beam Young Modulus, Pa;
E_1 = viscoelastic material Young Modulus, Pa;
f_n = n-mode resonance frequency of the base beam, Hz;
f_c = c-mode resonance frequency of the composite beam, Hz;
Δf_c = c-mode half power bandwidth of the composite beam, Hz;
H = base beam thickness, m;
H_1 = viscoelastic material thickness, m;
$M = E_1/E$, Young moduli ratio;
$T = H_1/H$, thickness ratio;
$\alpha = (f_c/f_n)^2(1+DT)$;
$\beta = 4+6T+4T^2$;
$\eta_c = \Delta f_c/f_c$, composite beam loss factor, non-dimensional;
η_1 = viscoelastic material loss factor, non-dimensional;
ρ = base beam density, kg/m³;
ρ_1 = viscoelastic material density, kg/m³.

3.1. TEST CONDITIONS

The beams were clamped at one end, at a very rigid structure, and then subjected to the Oberst Method, as can be seen in Fig. 6 (c). To avoid great insertion of mass in the system (the basic mass of the beam is approximately 110 g, relatively small), a magnetic non-contact shaker and a mini-accelerometer (0.6 g mass) were used. Better results were obtained when the accelerometer was positioned near the clamped end, approximately 3 cm from the clamping point [1]. Under this condition, significant mass addition influences are perceived only after the fourth natural frequency (approximately 1340 Hz) (Martinez and Jordan, 2008).

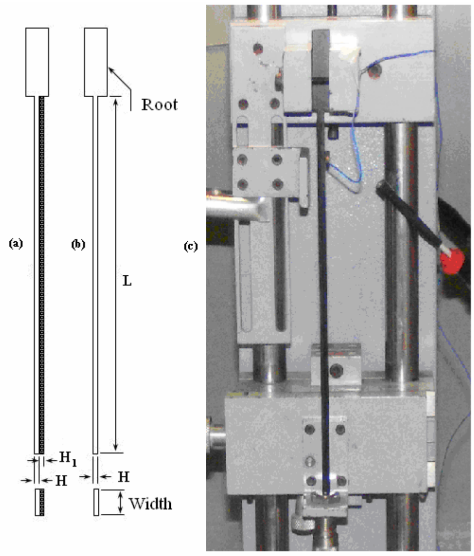

Figure 6. Characteristics of: (a) beam with viscoelastic material (Nashif, 1985);
(b) base beam (Nashif, 1985); (c) test setup. Beam under test in thermal chamber.

A quick-drying glue was used to attach the accelerometer to the beam, ensuring a wide frequency measuring range. A random signal generated by the Pulse signal analyzer was chosen, that was amplified before feeding the shaker. A schematic representation of the experiment is shown in Fig. 7.

To obtain the behavior of the materials at various temperatures, the measurements were done inside the thermal chamber located at the Laboratory of Acoustics and Vibration of UFSC, which has two thermocouples: one attached to the metal structure under use and another suspended inside the chamber, both near the beam. To ensure the temperature stabilization of the whole apparatus, before each test the temperature was maintained constant for 30 minutes.

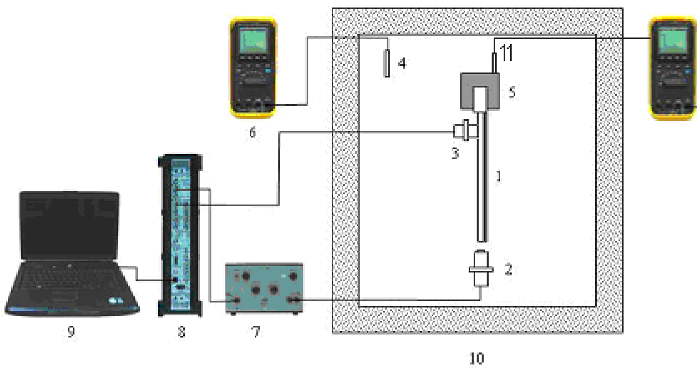

Figure 7. Experimental apparatus of Oberst test: 1 - beam with viscoelastic material; 2 - non-contact shaker;
3 – accelerometer; 4 - air temperature thermocouple; 5 - beam support; 6 - temperature meter;
7. power amplifier. 8. signal processor, with input and output modules; 9. computer;
10 - thermal chamber. 11. beam thermocouple (Martinez, 2008).

The measurement of the base beam density (7833.33 kg/m3), value to be used in the equations, was conducted at UFSC Labtermo laboratory, through the Archimedes method, using a scales and a tank of water. The densities of the viscoelastic materials were supplied by the manufacturer, since in this case the method of Archimedes fails, due to their high porosity (densities of materials A and B are, respectively, 1470 and 1900 kg/m3).

The frequency range in which the Oberst Method is efficient, between 5 and 5500 Hz, was considered, and the measurements were conducted in four ranges: 1) 0 to 800 Hz, 2) 0 to 1600 Hz, 3) 0 to 3200 Hz, 4) 0 to 6400. All measurements were made with 6400 spectral lines. Many of the resonance peaks do not have points exactly 3 dB below the value corresponding to the peak frequency (fn). In such cases, the two bandwidth limiting frequencies were obtained by interpolation. The corresponding standard (ASTM E 756-98) recommends eliminating the first peak, because the value of η referring the first mode of vibration is more error-sensitive.

The following equipment was used in the tests:

- mini-accelerometer PCB 352A21, SN 86995, sensibility of 0.942 $mV/m/s^2$;
- magnetic transducer (used as shaker), running under random frequency signal;
- signals analyzer Brüel & Kjær Pulse (hardware and software);
- thermal chamber, LVA/UFSC.

4. RESULTS

In the sequence, experimental and numerical results are presented. Experimental results were obtained with the Oberst Method, and the numerical ones were obtained with the Finite Element Method (FEM).

4.1. Experimental results

Figure 8 shows the behavior of the loss factors over temperature, for both tested materials. For the second and fourth modes, it can be observed that up to 20 °C the values remain almost constant. Above this temperature, the loss factor of material A grows, while for material B it remains constant.

Figure 9 shows the behavior of the loss factors over the frequency, for both tested materials, under the temperatures of 25° C and 40° C. It can be observed that at 25° C the behaviors of the materials loss factors are almost constant and very similar. For the temperature of 40° C, the loss factor of material A is always higher than for material B.

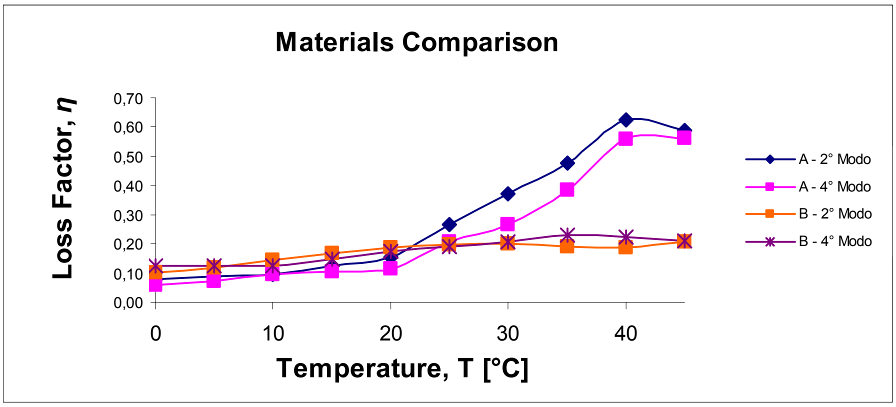

Figure 8. Comparison of materials loss factors behaviors under temperature variations.

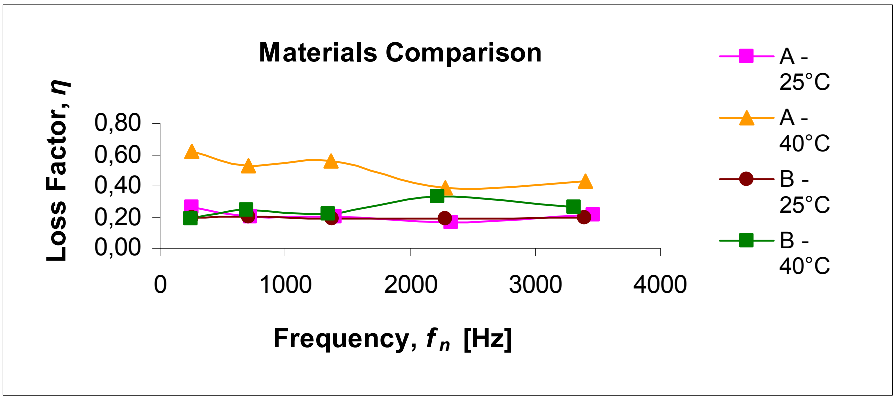

Figure 9. Comparison of materials loss factors behaviors under frequency varations.

4.2 Numerical Results

A numerical model using FEM was done to evaluate if Oberst test is a good method to define the properties of viscoelastic material. Observing the results of Oberst test it is possible to choose the better material to use in damping treatment in passenger vehicle, for these reason just this one was chosen to evaluate numerical model.

Using MSC Patran/Nastran software a FEM model of a beam with damping material was done, see Fig 10. This model reproduces the same characteristics found in Oberst test, like boundary conditions, excitation and materials properties. For this model was used a solid element hexahedral element. The number of elements respects the rate of twelve elements for each wave length.

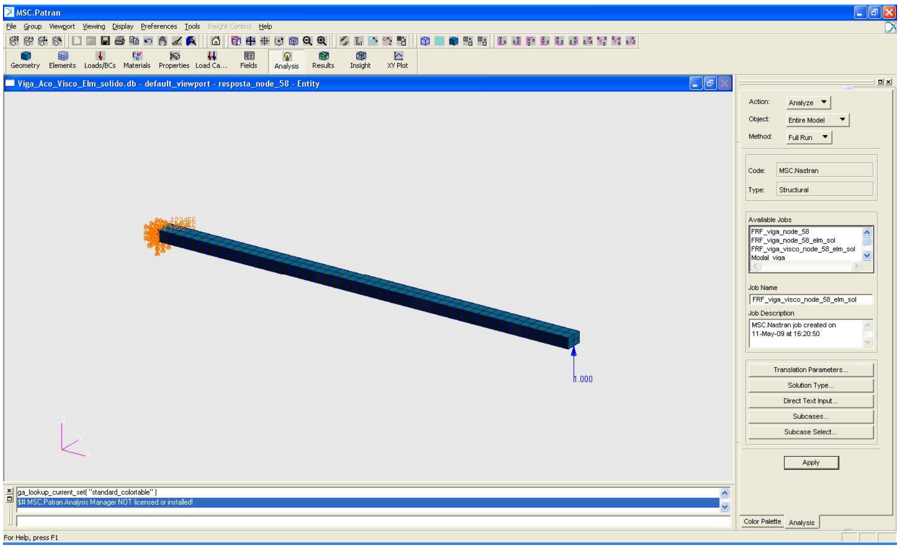

Figure 10. FEM model of clamped beam in MSC PATRAN/NASTRAN space.

Using the properties of viscoelastic material obtained by the Oberst test in this simulation, a numerical FRF was derived and compared to an experimental curve. First, at Fig. 11, were compared the curves of a clamped beam without viscoelastic material.

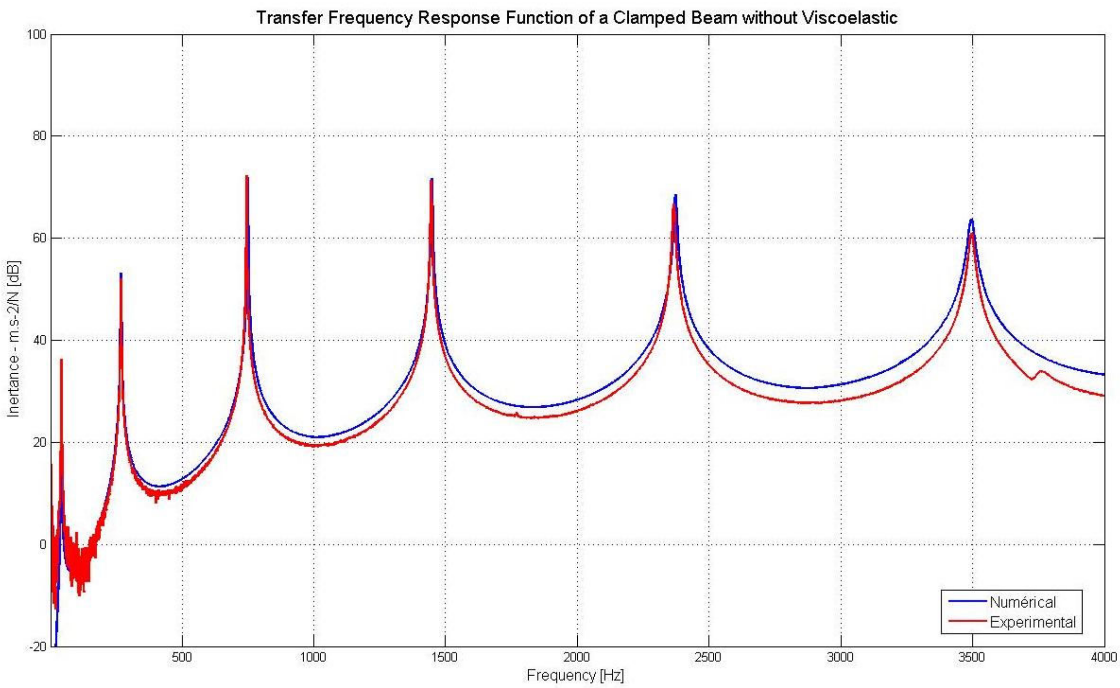

Figure 11: Transfer FRF of the clamped beam, without viscoelastic material. Frequency range 0 – 400Hz. Blue line: Numerical Result; Red line: Experimental result.

Figure 11 shows that the model is well adjusted, since its response, using the properties derived from Oberst Method, presents a good match to the experimental curve. This numerical FRF was obtained using damping and Young Modulus variable with frequency, for the same temperature. Five different values of η and E were used, after dividing the whole frequency range into five sub-ranges. These ranges cover the frequency regions that comprehend: first and second modes, and third to sixth modes individually.

After adjusting the properties of the base beam, the properties of the viscoelastic material were applied to the numerical model. The obtained results can be observed in Fig. 12, showing a very good agreement between experimental and numerical curves, using the properties derived by the Oberst Method.

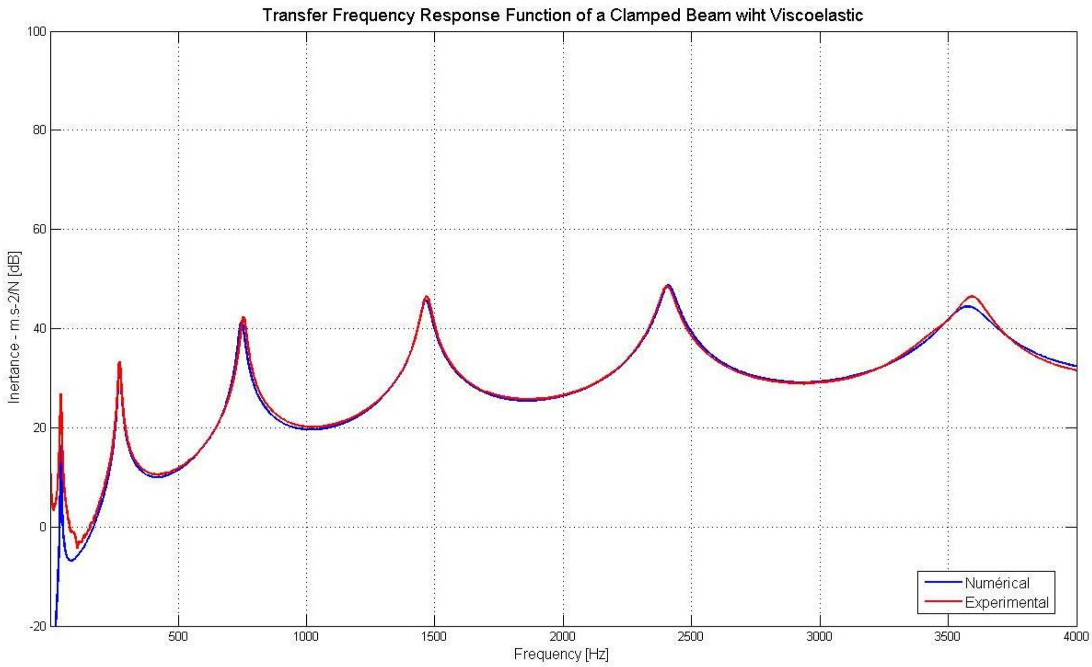

Figure 12. Transfer FRF of the clamped beam with viscoelastic material. Frequency range 0 – 400Hz. Blue line: Numerical Result; Red line: Experimental result.

Table 1 shows the results of base beam and damped beam for each resonant mode. The values of loss factor are also presented.

	Resonance Frequency [Hz]				Loss Factor	
	Base Beam		Damped Beam		Base Beam	Viscoelastic Material
	Experimental	Numerical	Experimental	Numerical	Experimental	Experimental
Mode 1	42,2	42,0	42,6	43,0	0,013	0,42
Mode 2	267,6	264,0	270,7	271,0	0,0033	0,1960
Mode 3	748,4	750,0	754,3	746,0	0,0008	0,1510
Mode 4	1434	1437	1468	1465	0,0013	0,1550
Mode 5	2389	2396	2405	2411	0,002	0,137
Mode 6	3463	3460	3591	3578	0,0057	0,2460

Table 1. Results from Oberst Beam method and the comparison of experimental and numerical results.

5. CONCLUSIONS

The influence of temperature on loss factors (see Fig. 8), in the range 0 to 40^o C, was noticed only for material A (asphalt), indicating that this material has entered the transition region. On the other hand, material B was kept at the glassy region, since minor variations on the values were observed. At Fig. 9, it is possible to see that the frequency dependence is not pronounced along the tested range (0 to 4000 Hz). Again, in this figure, the change in behavior with temperature of material A can be noticed.

Loss factors, obtained both for the steel (base beam) and the viscoelastic materials, have presented values similar to those obtained in the literature and commercial sheets. The steel Young modulus has presented a measured mean value of $1{,}9.10^{11}$ Pa, a coherent value. During the tests it was possible to determine the Young moduli of the two viscoelastic materials, proprieties that were not known previously. This fact made it possible to perform the numerical simulations.

The numerical FEM simulation was conducted with solid elements, because they provided a better way to connect the two different materials (steel and viscoelastic).

The main results of this work are summarized by Figs. 11 and 12. The good agreement of the curves, at both figures, shows that the complete cycle has come to a good term. The properties of some materials have been experimentally determined, under a normalized procedure, and the results have shown coherent values. These properties were used, then, in numerical simulations, which reproduced the experimental behavior with good accuracy.

The main objective was to check all this process with the simple straight beam, to get confidence on the experimental results of the Oberst Method. Some other damping materials may be tested, from now on. With these data it will be possible to simulate more complex structures, like a car body, to optimize the type and the spatial distribution of the viscoelastic material, in order to get the best possible damping treatment.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Canevarolo, S. V. . 2002, "Ciência dos Polímeros. Um curso básico para tecnólogos e engenheiros", 1ª ed., Artliber Editora LTDA, São Paulo, Brazil, 184 pp.

Martinez, J.A.O. ; Jordan, R., 2008, "Análise da Utilização de Sensores no Ensaio da Viga Oberst", Proceedings of the XXII Encontro da Sociedade Brasileira de Acústica, Belo Horizonte, Brazil.

Martinez, J.A.O., 2008, "Implementação do Fator de Perda na Modelagem de Painéis Reforçados com Alto Grau de Amortecimento". M. Sc. Thesis, POSMEC/UFSC, Florianópolis, Brazil.

Nashif, A. D., Jones, D. I. G. and Henderson, J. P., 1985, "Vibration Damping", Wiley-Interscience, New York, USA, 453 pp.

8. RESPONSIBILITY NOTICE