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EXPERIMENTAL IDENTIFICATION OF DYNAMIC PROPERTIES OF CORK COMPOUND

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SYNOPSIS

The numerical simulation of sandwich plates with cork compound cores requires an accurate numerical representation of its dynamic properties, namely its storage modulus and loss factor which are frequency dependent. In this paper, an accurate experimental setup and methodology to identify the complex modulus of cork compounds in shear are presented and validated using commercially available cork compounds. The test system is based on the direct complex stiffness measurement. A numerical processing analysis is performed on the measured data in order to verify the validity of the measurement and to identify the frequency dependent storage modulus and loss factor.

1. INTRODUCTION

Natural cork is a material with a remarkable combination of properties that have been for long time used in various application like fishing boats, shoe soles and wine bottle sealers. It is obtained from the bark of *Quercus suber*, a species of oak that grows mainly in Mediterranean countries.

Cork is described as a homogeneous tissue of thin-walled closed prismatic cells, regularly arranged, without intercellular spaces. Such prismatic cells (pentagonal or hexagonal) are packed in columns parallel to the radial direction of the tree. The cellular walls are composed of lignin middle lamellae (27%), a thicker secondary layer with alternate lamellae of suberin (45%), polysaccharides (12%), waxes (6%) and tannins (6%) (Mano, 2002).

The cellular structure of cork is responsible by its singular properties, such as: low density, high thermal and acoustic insulation, and chemical resistance (Fortes *et al.*, 2004). Presently, besides its application in thermal and acoustic isolators, cork compounds are usually not considered as passive dynamic control treatments, being the anti-vibratory machine supports one of the few examples of it. However, cork compound can be used in sandwich structures, assuring a high damping property, with possible application on aeronautic fuselages and land vehicle chassis.

Although its wide range of possible applications as a passive dynamic control treatment and its unique characteristics, there is a lack of information concerning the dynamic behaviour of cork compounds, requiring a deeper analysis on its frequency dependent properties, namely, its storage modulus and loss factor (ASTM, 1990).

This paper aims to characterize the complex modulus of cork compounds for structural damping purposes. An experimental methodology is presented and applied to identify the shear storage modulus and loss factor of different commercially available cork compounds and to investigate the frequency dependence of these properties. Additionally, the effects of cork compound formulation parameters on the complex modulus are also investigated in order to identify guidelines for developing special purpose solutions for passive damping treatments.

2. METHOD

The experimental characterization methodology is based on the evaluation of the effects of the cork compound element, which represents the stiffness and damping, on the response of a dynamic system. For this purpose, it is adopted a direct approach (Allen, 1996; Kergourlay and Balmès, 2003) by using a discrete mass-complex stiffness dynamic system. The complex modulus is directly identified from the frequency response measured on the experimental setup (Moreira and Dias Rodrigues, 2005).

2.1 Analytical model

The analytical model used for the identification procedure is based on the characterization of a complex stiffness spring of a single degree of freedom system (Figure 1).

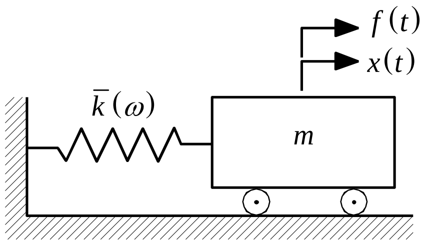

Figure 1. Single degree of freedom analytical model

The differential equation of motion for this single degree of freedom system, excited by the force $f(t)$, is defined by:

$$M\ddot{x}(t) + \bar{K}(\omega)\,x(t) = f(t) \qquad (1)$$

where M represents the system mass, $\bar{K}(\omega)$ the frequency dependent spring complex stiffness, $x(t)$ the mass displacement and $\ddot{x}(t)$ the time second derivative.

Assuming an harmonic excitation $f(t) = Fe^{i\omega t}$ with amplitude F and frequency ω, the system response will also be harmonic, $x(t) = \bar{X}(\omega)e^{i\omega t}$, allowing equation (1) to be rewritten as:

$$\left[-\omega^2 M + \bar{K}(\omega)\right]\bar{X}(\omega) = F \qquad (2)$$

where $\bar{X}(\omega)$ represents the amplitude and phase lag of the system response.

Therefore, the receptance and accelerance frequency response functions (Ewins, 2000) of the dynamic system can be defined as:

$$\alpha(\omega) = \frac{\bar{X}(\omega)}{F} = \frac{1}{-\omega^2 M + \bar{K}(\omega)} \qquad \text{(Receptance)} \qquad (3)$$

$$A(\omega) = \frac{-\omega^2 \bar{X}(\omega)}{F} = \frac{\omega^2}{\omega^2 M - \bar{K}(\omega)} \qquad \text{(Accelerance)} \qquad (4)$$

The stiffness complex function of the test sample can be directly determined either through the inverse of the receptance function (dynamic stiffness $\mathrm{Z}(\omega)$), or the inverse of the accelerance function (apparent mass $\mathrm{M}(\omega)$):

$$\bar{K}(\omega) = \omega^2 M + \mathrm{Z}(\omega) \qquad \text{(dynamic stiffness)} \qquad (5)$$

$$\bar{K}(\omega) = \omega^2 M - \omega^2 \mathrm{M}(\omega) \qquad \text{(apparent mass)} \qquad (6)$$

In a dynamic system where the stiffness element is deformed in shear, the material complex shear modulus $\bar{G}(\omega)$ is related with the complex stiffness function as follows,

$$\bar{G}(\omega) = G(\omega)\left(1 + j\eta(\omega)\right) = \bar{K}(\omega)\frac{h}{A_S} \qquad (7)$$

where $\eta(\omega)$ represents the material loss factor and $G(\omega)$ the shear storage modulus.

The geometric parameters A_S and h represent, respectively, the test sample shear area and its thickness.

2.2 Experimental setup

The experimental setup simulates a single degree of freedom system using one sample of the cork compound that is deformed in shear, which represents the complex-valued stiffness spring.

Experimental assembly

The proposed experimental assembly, capable of representing a single degree of freedom system, and which will be used along the identification process, is depicted in Figure 2.

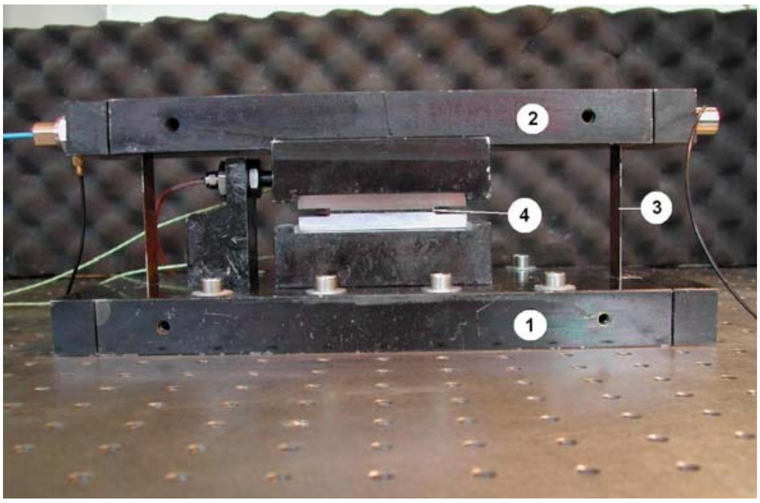

Figure 2. Experimental assembly.

This assembly is formed by a rigidly fixed base plate (1) and a moving upper plate (2) representing the moving mass. The cork compound test sample is placed between two rigid blocks, as depicted in Figure 3, and connected to each plate. The cork compound sample represents the complex stiffness of the discrete dynamic system. Additionally, two very thin spring steel blades (3), clamped at both ends of the moving and fixed plate, which introduce a very low stiffness into the system, provide the necessary restraining condition to minimize effect of spurious degrees of freedom. This solution improves the experimental setup so it more accurately represents the analytical assumed discrete system.

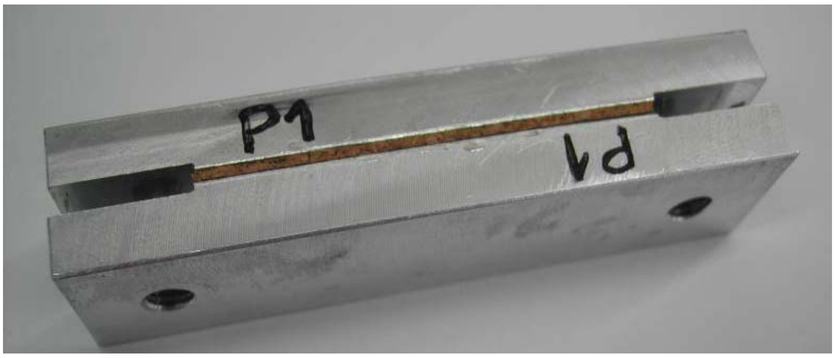

Figure 3. Test sample.

The excitation force is applied by the electromagnetic shaker (LDS-201), connected to one side of the moving upper plate by a stinger, and it is measured with a piezoelectric force transducer (B&K 8200). The system's response is measured in terms of acceleration on the opposite side of the moving plate by a piezoelectric accelerometer (B&K 4371) as well as by a proximity probe (Philips-PR6423) that measures the relative displacement between the moving plate and the fixed one, where it is mounted.

The excitation force signal type is random and is generated by the FFT spectral analyser (B&K 2035) generator module and amplified by the power amplifier (LDS-PA25E). The signal conditioning and the frequency response functions determination are also performed by the referred spectral analyser.

The electromagnetic shaker and the experimental assembly are rigidly fixed to the surface of a granite block (Figure 4) which is supported by four silicone rubber pads in order to minimize the rigid body modes frequencies of the assembly.

Figure 4. Experimental setup.

Material samples

The experimental work was developed for three different cork compounds with different grain sizes and densities as illustrated in Figure 5.

Specimen P1

Specimen P2

Specimen P3

Figure 5. Cork compound samples

The shear storage modulus and loss factor were computed for three different test samples which characteristics are listed in Table.1.

Table.1 Test samples characteristics.

	Thickness [mm]	Mass [g]	Area [mm^2]	Density	Grain
Specimen P1	1.2	63	997.67	high	fine (0.5-2mm)
Specimen P2	1.2	63	1006.83	low	fine (0.5-1mm)
Specimen P3	1.2	63	993.79	high	coarse (2-4mm)

The measurements were performed at a room temperature of approximately 25ºC.

3. RESULTS

A set of four accelerance frequency response functions (FRFs) and a set of four receptance FRFs were measured for each specimen. For each set of FRFs, two of them were measured in bandwidth [0-400]Hz and the other two in the bandwidth [200-400]Hz. Figure 6, Figure 12 and Figure 18 overlap the accelerance FRFS measured, respectively, for specimens P1, P2 and P3, while Figure 7, Figure 13 and Figure 19 represent the receptance functions.

By using equations (5)-(7), the complex shear modulus was identified from which the shear storage modulus and the loss factor were calculated. Figures 8-11 represent the distribution of the shear storage modulus and loss factor along the frequency range of the analysis for specimen P1. The results obtained for specimens P2 and P3 are represented, respectively, in Figures 14-17 and Figures 20-23.

3.1 Specimen P1

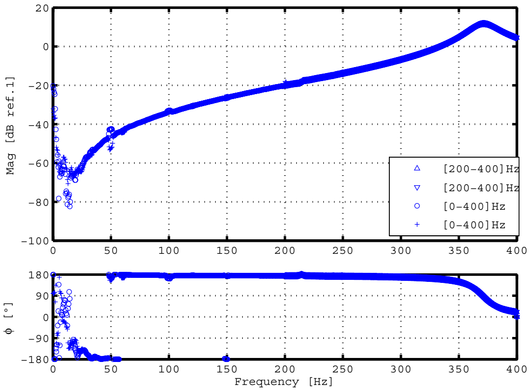

Figure 6. Measured FRFs (accelerance)

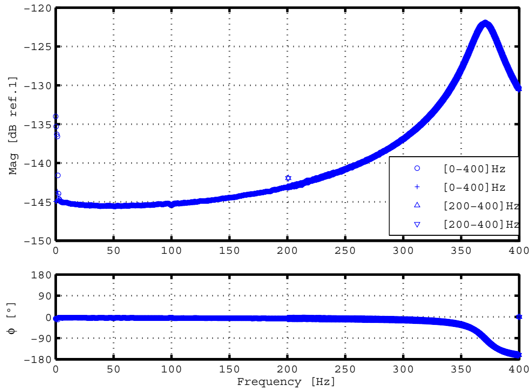

Figure 7. Measured FRFs (receptance)

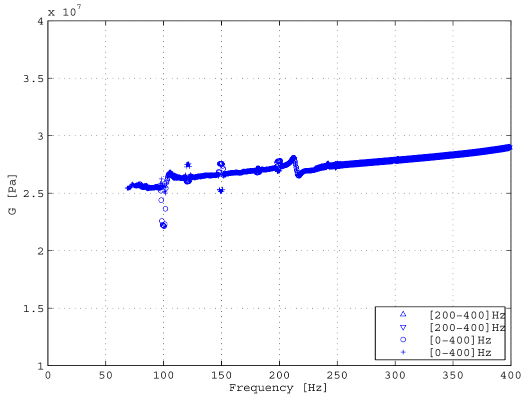

Figure 8. Shear storage modulus identified with accelerance FRFs

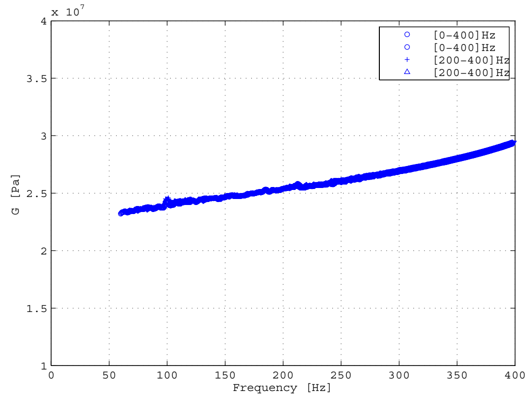

Figure 9. Shear storage modulus identified with receptance FRFs

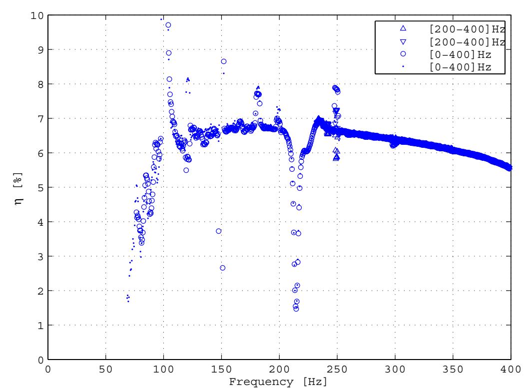

Figure 10. Loss factor identified with accelerance FRFs

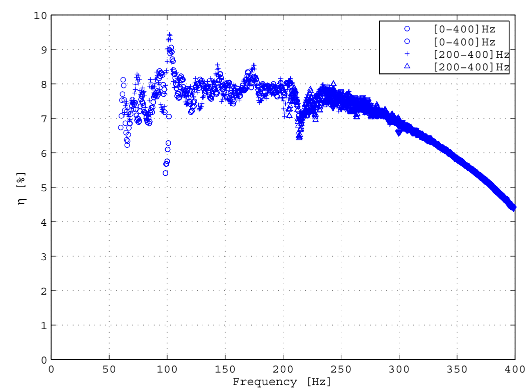

Figure 11. Loss factor identified with receptance FRFs

3.2 Specimen P2

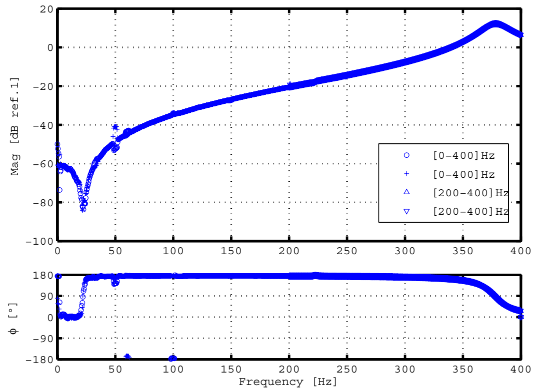

Figure 12. Measured FRFs (accelerance)

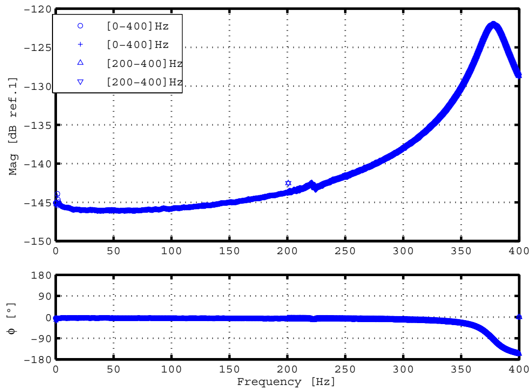

Figure 13. Measured FRFs (receptance)

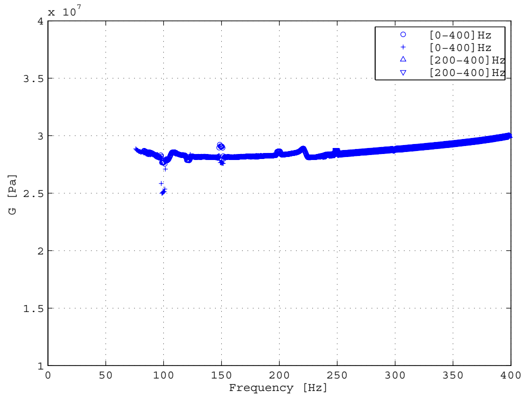

Figure 14. Shear storage modulus identified with accelerance FRFs

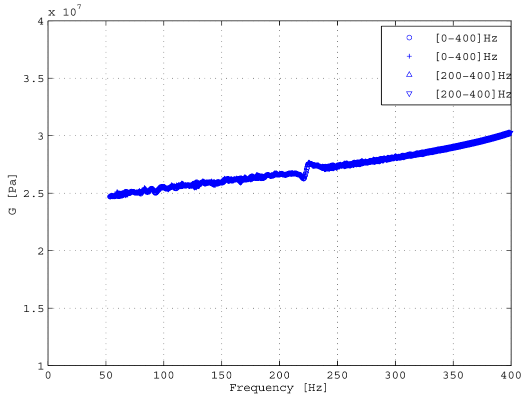

Figure 15. Shear storage modulus identified with receptance FRFs

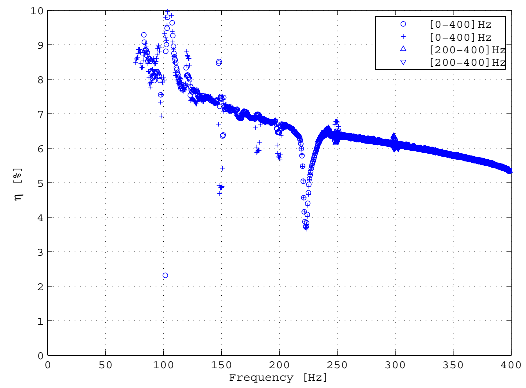

Figure 16. Loss factor identified with accelerance FRFs

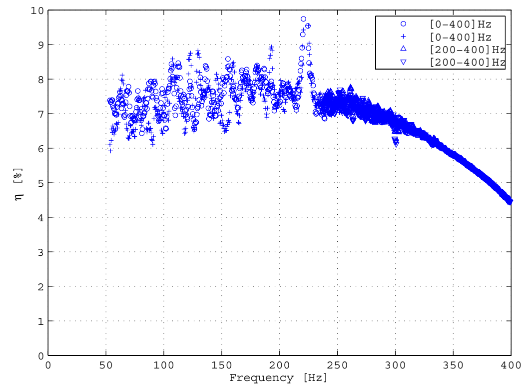

Figure 17. Loss factor identified with receptance FRFs

3.3 Specimen P3

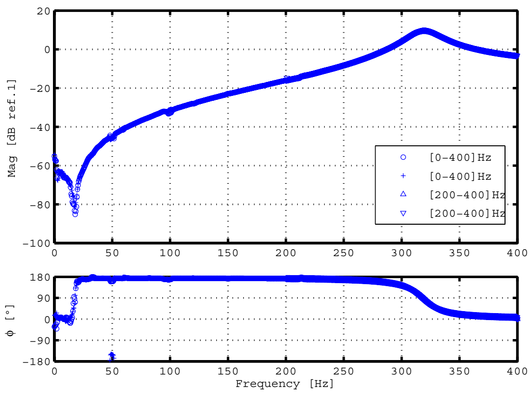

Figure 18. Measured FRFs (accelerance)

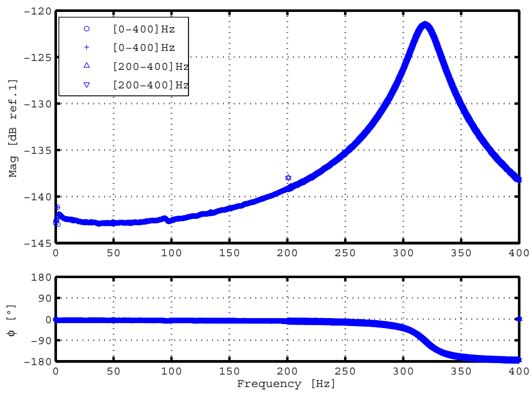

Figure 19. Measured FRFs (receptance)

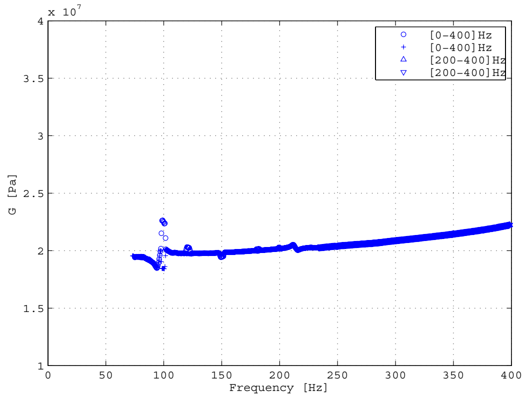

Figure 20. Shear storage modulus identified with accelerance FRFs

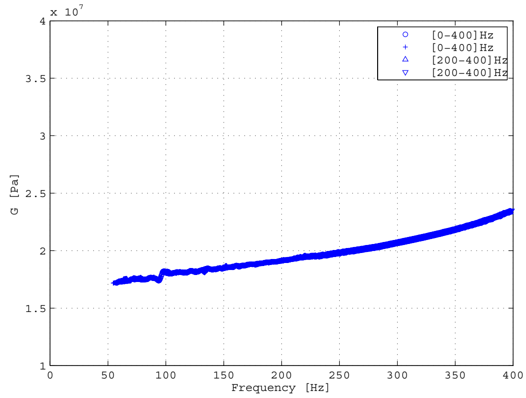

Figure 21. Shear storage modulus identified with receptance FRFs

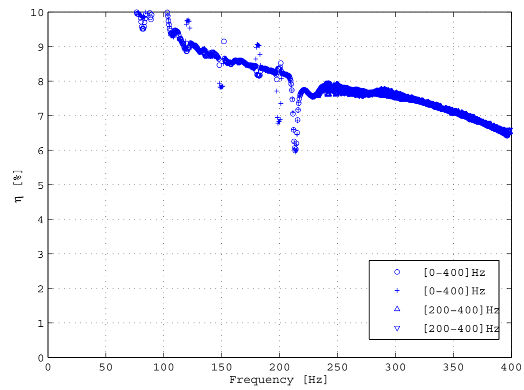

Figure 22. Loss factor identified with accelerance FRFs

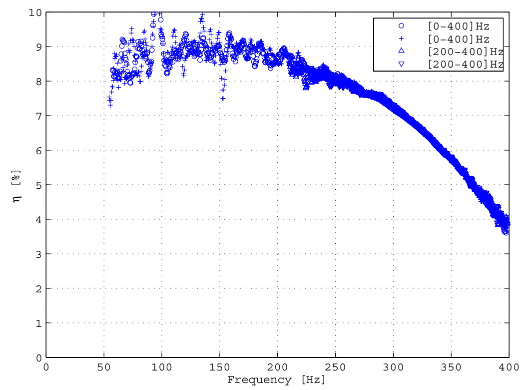

Figure 23. Loss factor identified with receptance FRFs

4. DISCUSSION

As illustrated by the accelerance FRFs, at the low frequency band these functions are affected by the presence of the rigid body modes and some measurement noise, increasing the scatter of the shear storage modulus and loss factor functions in this frequency range. Furthermore, as the identification procedure is very sensitive to measurement noise, the experimental procedure needs to be improved in order to enhance the quality of the results in the low frequency range. On the other hand, the distribution of the results in the frequency range [200-400] is smooth and shows a well defined tendency along frequency, which demonstrates that measurements and the identification methodology are consistent.

From the obtained results, the grain size influences the shear storage modulus while it has a little influence on the loss factor values (see results for specimens P1 and P3). Moreover, it can be seen that in the frequency band of analysis both the shear storage modulus and the loss factor of cork compounds present frequency dependence. Although this frequency dependence is not very accentuated, it reveals, as expected, a viscoelastic behaviour of these materials.

5. CONCLUSION

The methodology presented in this paper identifies the shear storage modulus and loss factor of a selected cork compound directly from the frequency response function of a discrete dynamic system with a single degree of freedom, which complex stiffness is materialized by a cork compound sample that is deformed in shear.

The developed experimental setup provided the frequency dependent shear storage modulus and loss factors for different cork compounds which values are essential for design purposes of passive damping treatments with these materials.

The obtained results enhance the frequency dependence of the complex shear modulus of cork compounds, as well as the influence of grain size and density on the shear storage modulus and loss factor.

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