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EVALUATION OF VISCOUS-ELASTIC PROPERTIES OF RESONANCE MAPLE WOOD

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Abstract: The paper presents the experimental investigations regarding the viscoelastic behaviour of maple wood used in the construction of stringed musical instruments. The studied samples were classified according to the anatomical structure of the wood in the four classes of anatomical quality used by the manufacturers of musical instruments. Based on the mechanical analysis in dynamic regime, the viscoelastic parameters were determined - the preservation module E', the loss modulus E' and the damping tan δ, in conditions of constant temperature, respectively variable temperature. It was found that the determined rheological quantities depend on the anatomical structure of the wood, the frequency of the excitation and the temperature.
Key words: viscous elastic, resonance, wood.

1. INTRODUCTION

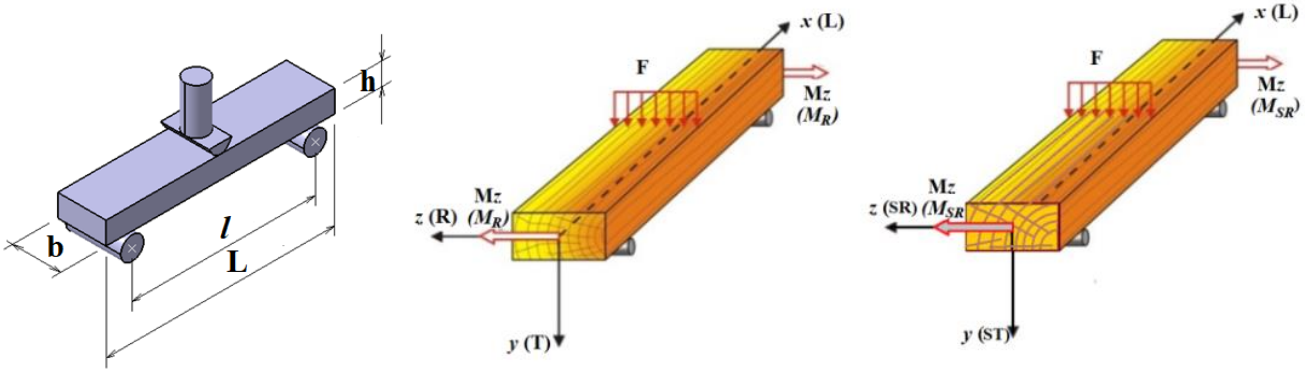
The structure of the wood and its behaviour in time under different loads at a certain humidity and temperature, gives it the condition of elastic-viscous-plastic material. For elastoplastic materials, the characteristic diagram does not express all aspects of deformation. Observations have shown that the process of deformation of wood and wood-based materials is not limited to an instantaneous change in shape, which occurs regardless of the application of loads, but there is a continuous process of deformation under loads, called latent flow. [1–5]. Under certain conditions of humidity and temperature, under the action of the loads, which are exercised for a long time, the deformations increase, reaching rupture point. After the loading period of the part with a certain load, the deformation - respectively the latent flow is characterized by three zones: the primary flow, the secondary flow and the tertiary flow. Experimental research has shown that wood and wood materials are highly sensitive to stress, temperature and humidity [4–7].
Dynamic methods for mechanical analysis (DMA) are used to determine the viscoelastic behaviour of wood. The principle of the method is to cyclically apply an oscillating force at different values of temperature and / or frequency of stress to the studied specimen. Based on the response of the specimen, the viscous behaviour of the material in the form of the loss modulus as well as the stiffness of the specimen in the form of the preservation modulus can be determined [3–6]. These properties are often described as the ability to lose energy in the form of heat (damping) and the ability to store energy to return to its original shape after deformation (elasticity). The paper aims to evaluate the viscoelastic behaviour of resonance wood. The maple wood samples were analysed by mechanical dynamic analysis (DMA), the viscoelastic response of the samples to the cyclic stresses applied with frequencies of 1, 5, 10, 50 Hz being investigated. It was found that the viscoelastic properties depend on the structure of the wood, the density of the annual rings, the degree of corrugation of the fibre, the frequency of loading.

2. MATERIALS AND METHOD

2.1 Materials

During the dynamic mechanical analysis, the viscoelastic behaviour of the resonant maple wood was investigated. The samples were cut with the geometric shape shown in figure 1a, with length L = 50mm ± 0.5; width b = 10 mm ± 0.3; thickness h = 4.8 mm ± 0.5 and the distance between the supports according to the calibrated size of the machine device, l = 40 mm. The tested specimens belong to the category of resonance wood, all classes of anatomical quality defined according to [8–10] being investigated. The force is applied perpendicular to the longitudinal axis of the samples (denoted L or x) producing a radial or semiradial bending moment (denoted by MiR and MiSR) as shown in figure 1, b, c. In table 1, the physical characteristics of wood samples tested at DMA are summarized. These samples were prepared

taking into account that, in the stringed musical instruments industry, there is a classification of musical instruments according to the anatomical quality of the wood in their construction, this aspect being revealed in the final price of the instrument. The classification of quality raw materials for the manufacture of stringed instruments has been presented and analysed in detail in the papers [8].



a) b) c)

Fig. 1. Geometry of dynamically tested samples: a) geometry of sample for DMA; b) radial orientation of the wood fibre direction; b) semi-radial orientation

Table 1. Physical characteristics of samples for DMA testing

Code sample		No of samples	Moisture content (%)	Density (g/cm^3)	Remarks
Pa_R(AI)	1.1-1.4	4	7±1.5%	0.610	radial, quality class A, very dense fibre,
Pa_R(AII)	2.1-2.4	4	7.2±1.5%	0.600	radial, quality class A, sparse fibre,
Pas_R(AI)	3.1-3.4	4	7±1.2%	0.616	semiradial, quality class A, very dense fibre,
Pas_R(AII)	4.1-4.4	4	7.3±1%	0.620	semiradial, quality class A, sparse fibre,
Pa_R(BI)	5.1-5.4	4	7±1.5%	0.591	radial, quality class B, very dense fibre,
Pa_R(BII)	6.1-6.4	4	7.2±1.5%	0.581	radial, quality class B, sparse fibre,
Pas_R(BI)	7.1-7.4	4	7±1.2%	0.612	semiradial, quality class B, very dense fibre,
Pas_R(BII)	8.1-8.4	4	7.3±1%	0.615	semiradial, quality class B, sparse fibre,
Pa_R(CI)	9.1-9.4	4	7±1.5%	0.590	radial, quality class C, very dense fibre,
Pa_R(CII)	10.1-10.4	4	7.2±1.5%	0.600	radial, quality class C, sparse fibre,
Pas_R(CI)	11.1-11.4	4	7±1.2%	0.616	semiradial, quality class C, very dense fibre,
Pas_R(CII)	12.1-12.4	4	7.3±1%	0.620	semiradial, quality class C, sparse fibre,
Pa_R(DI)	13.1-13.4	4	7±1.5%	0.630	radial, quality class D, very dense fibre,
Pa_R(DII)	14.1-14.4	4	7.2±1.5%	0.624	radial, quality class D, sparse fibre,
Pas_R(DI)	15.1-15.4	4	7±1.2%	0.628	semiradial, quality class D, very dense fibre,
Pas_R(DII)	16.1-16.4	4	7.3±1%	0.615	semiradial, quality class D, sparse fibre.

2.2 Method

Dynamic mechanical analysis was performed using the dynamic mechanical analyser Netzsch DMA 242 C. This analyser allows the determination of viscoelastic properties as a function of time, temperature and frequency of stress (static or oscillating force), using a "bending in three points" procedure. The sample is subjected to a forced oscillation defined in the software of the test machine: a sinusoidal force (input signal) applied by a pushing rod, leads to a deformation of the sample (output signal). It also produces a sinusoidal but out-of-phase oscillation, which is then recorded using a displacement transducer (LVDT electronic sensor - Linear Variable Differential Transformer) [9–10]. These oscillations are reduced to an extremely low noise level signal in the DMA controller by Fourier analysis. A stainless-steel container facilitates measurements in various environments (immersion tests or variable temperature). By using a thermocouple, it is also possible to perform tests at higher temperatures. Some of the samples were tested in isothermal conditions (temperature T was kept constant at 30°C during the tests, due to the controlled environment in the oven of the test apparatus), applying a pulsating oscillating force with an intensity of 6 N, with different frequencies, applied successively (f = 1 Hz; 3.3 Hz; 5 Hz; 10 Hz; 50 Hz). Another set of

samples was tested under dynamic temperature conditions, ranging from 30 ÷ 120°C for 45 minutes, applying a pulsating oscillating force with an intensity of 6 N, with a frequency of 1 Hz. The temperature range used in the tests was established based on studies in the literature that have shown that the phenomenon of flow of wet wood is recorded in a temperature range of 50°C - 100°C, a phenomenon that is closely related changes in the chemical transition of lignin. Hemicelluloses and amorphous cellulose from wet wood have lower softening temperatures than lignins [11–14]. Moreover, this property depends on the species of wood. As a result, the machine software returned the following parameters: preservation modulus (E'); loss modulus (E"); depreciation tan δ calculated as the ratio between the loss modulus and the preservation modulus.

3. RESULTS AND DISCUSSIONS

3.1 The viscoelastic characteristics of resonant maple wood - isothermal conditions

For samples with moderately wavy, straight and straight corrugated fibre, the preservation modulus tends to increase with increasing stress time by about 1.5% in 30 minutes of application. Contrary to this trend, samples of maple wood with highly curly fibre (class A) show a slight tendency to decrease the deformation energy conservation capacity (by about 1% in the 30 minutes of cyclic stress) (figure 2). In terms of frequency, it is found that the four types of samples from different classes respond differently to different frequencies. Thus, the highest values of the preservation modulus are recorded for the PaR (AI) samples at 1Hz and for the PaR (BI), PaR (CI) and PaR (DI) samples at 50Hz. Class B samples have the highest value for the preservation modulus (between 10050 - 10300 MPa), and the lowest value is found for the class C samples. The values of the loss modulus decrease with the rise of the frequency of stress - the ability to dissipate deformation energy decreases, so that, regarding the use of maple wood in the construction of violins, this behaviour is favourable to the dynamic response to high string frequencies. Over time, the loss modulus decreases: for PaR (AI) and PaR (CI) samples, E" decreases by approximately 11% after 30 minutes of stress; for PaR (BI) samples, E" decreases by approximately 3%; and for PaR (DI) samples, the viscous modulus decreases by approximately 28.5% after 30 minutes of stress (figure 3). From a musical point of view, it is important that the properties of the wood remain relatively constant over time so as not to alter the musical sounds. Thus, the class B tests show the best behaviour. Since the damping is the ratio between the sample response and the applied load, respectively the ratio between the loss modulus and the preservation modulus, the variation of this quantity is directly dependent on the variation of the loss modulus, which can be seen by the comparative analysis in figure 3. Also, for the samples PaR (AI), PaR (BI) and PaR (CI), at the frequency of 50 Hz, there are sudden decreases in the values of damping, which indicates changes in the response of the sample over time, at the respective frequency.

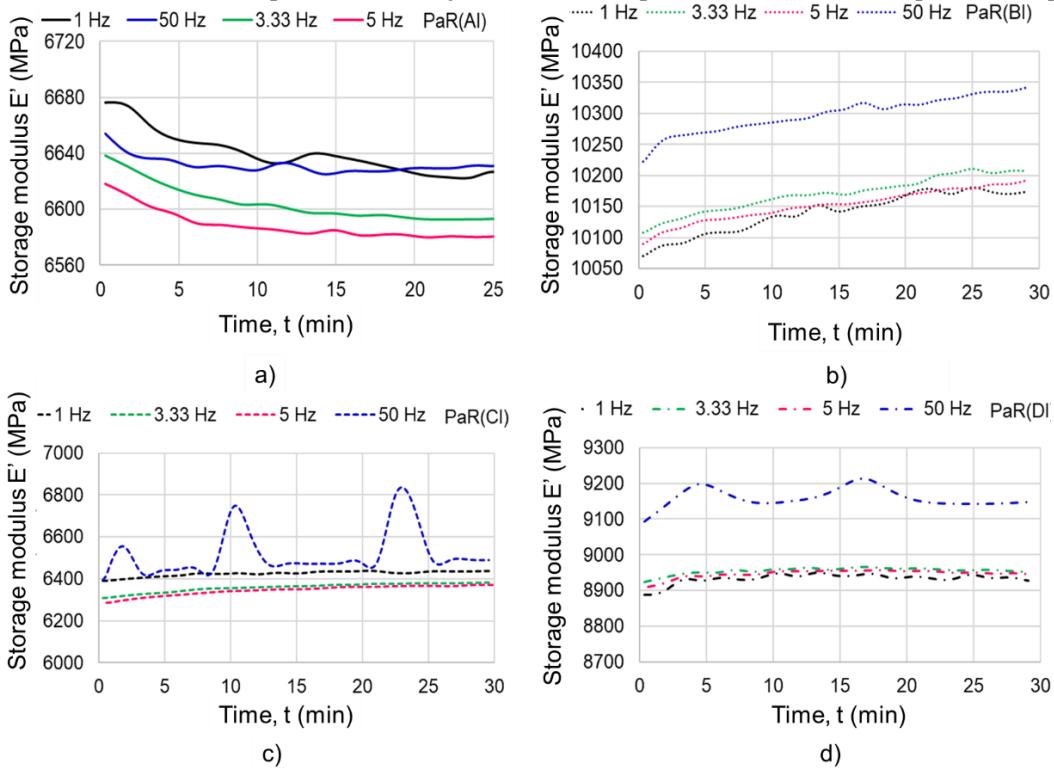


Fig. 2. The variation in time of the preservation modulus E': a) maple wood with very curly and dense fibre; b) maple wood with dense and curly fibre; c) maple wood with corrugated and dense fibre; d) maple wood with straight and dense fibre

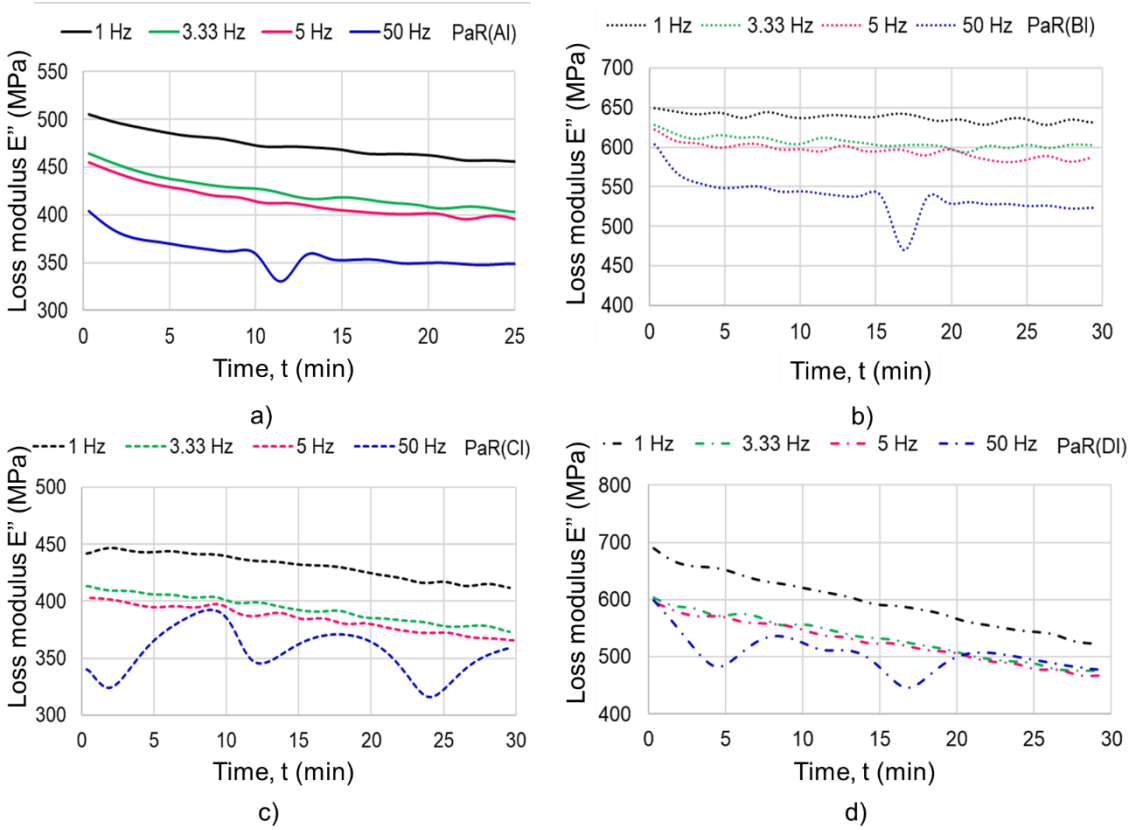


Fig. 3. The variation in time of the loss modulus E'': a) maple wood with very curly and dense fibre; b) maple wood with dense and curly fibre; c) maple wood with corrugated and dense fibre; d) maple wood with straight and dense fibre

3.2 The viscoelastic characteristics of resonant maple wood with temperature variation

The literature has shown that in wood, the energy storage module E' decreases with increasing temperature and there is a "softening" transition in the temperature range from 70 to 100°C, corresponding to the relaxation of lignin, and the maximum value of the loss factor increases with frequency, which attests to the fact that the transition temperature shifts to higher values as the frequency increases [10–13]. The anatomical and molecular features of the wood species have the greatest influence on the viscoelastic behaviour of the wood, respectively, the molecular structure of the essential components of the wood and their supramolecular architecture in the cell wall essentially influence the softening properties. This is presented in this paper, as well as in other publications on this subject [14–16]. The results obtained by [2; 13; 18] show that softening of softwood actually takes place at higher temperatures than for hardwood.

Another aspect is also important for interpretation: wood tissue is more regular in the radial direction compared to the tangential direction [16–17]. In bending tests (the load applied in the radial direction produces a bending moment in the tangential direction), the cell walls are loaded mainly with pure traction and compression, while if the load is applied in the tangential direction producing a bending moment in the radial direction, cell walls are rather exposed to bending, behaviour described by [17]. The tangential stress due to simple plane bending induces a cellular slip that most likely occurs in the middle lamella. It is now well known that the distribution of lignin along the double cell wall is heterogeneous [13]. According to [19], the lignin content is almost twice as high in the middle lamella than in other wall layers. If we consider that the middle lamella, rich in lignin, is the main element subjected to the shear stress in the tangential direction, the finding of a high tanδ value in the tangential direction is easier to understand.

The inhomogeneous structure of highly corrugated maple wood is known to be characterized by a higher lignin content than normal fibre species where lignin is 25.3% [14–15]. The higher content of lignin which is a complex aromatic polymer influences the transition temperature (noted T_g), which varies from 75°C to 100°C [13, 19]. Comparing the behaviour of dense and coarse fibre wood with that of sparse fibre maple samples, it is observed that Tg is higher in the case of wood with a lower lignin content (samples of classes C and D), reaching a value of approximately 85÷90˚C (figure 4 c and d) compared to the transition temperature reached by the curly and dense fibre samples (classes A and B), which reach values of 55°÷80˚ C (figure 4, a and b).

It can also be seen that in the case of the maple sample with very curly and dense fibre (PaR (AI)), the transition temperature T_g starts from 55°C, then the

second transition level T_g is recorded at 70°C and the final transition T_g, at 88˚C. In all four cases, the conservation module is progressively degraded. Analysing the behaviour of radially cut maple wood samples, but with sparse fibre, it can be seen that the damping increases with increasing temperature for all classes, however, the preservation module behaves differently - for samples of classes A and C, the trend is decreasing with increasing temperature, and for samples in classes B and D, the tendency is to increase the preservation modulus. For these samples also, the transition temperature registers different values depending on the quality class, the content of late wood and early wood, so that the values are lower for classes A and B (T_g=60÷80˚C), and for those with slightly wavy fibre (class C) and straight fibre (class D), T_g≥90÷100˚C.

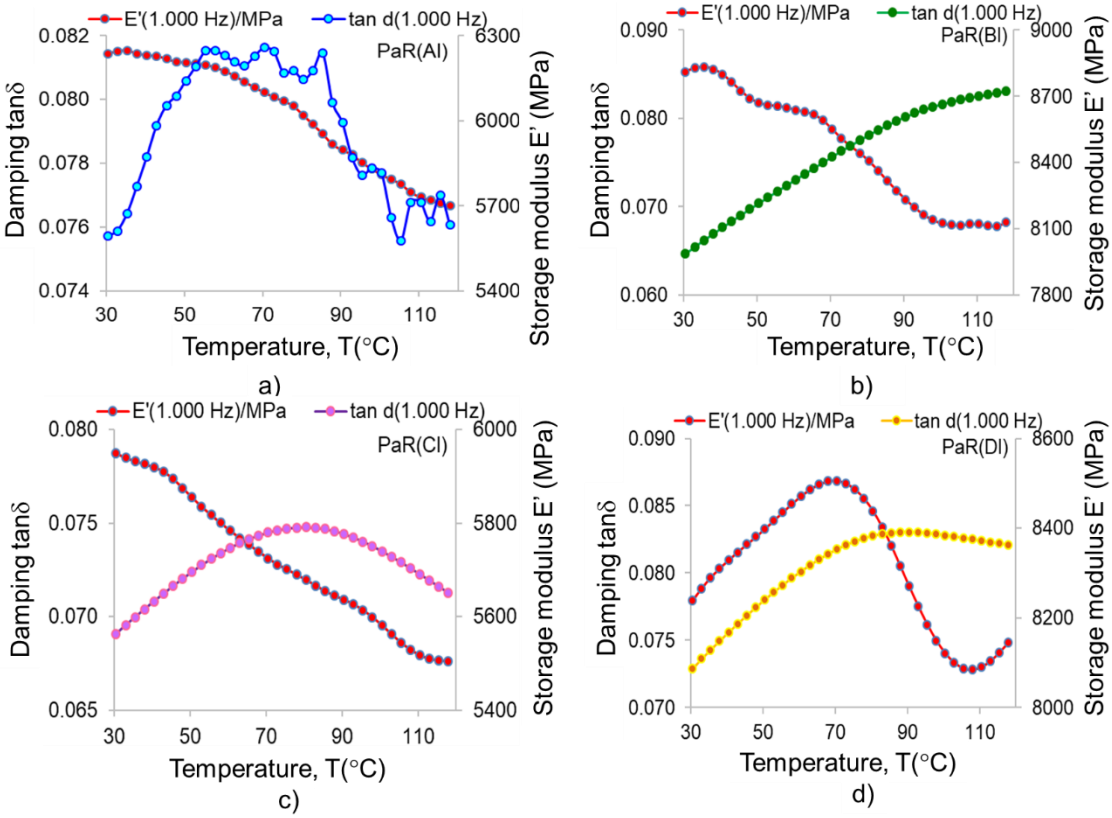


Fig. 4. Variation of damping and preservation modulus with increasing temperature, for radially cut maple samples, with dense fibre: a) class A; b) class B; c) class C; d) class D

4. CONCLUSIONS

From a rheological point of view, maple wood modifies its viscoelastic properties with increasing exposure time to periodic stresses. Thus, the samples of maple wood from class B register the highest value of the preservation module (between 10050-10300 MPa), and the lowest value is presented by those from class C. The temperature affects the stiffness and strength of the wood, which has a thermoplastic behaviour. The increase in temperature leads to changes in the complex dynamic modulus of maple wood: the transition temperature Tg is approximately 85-90˚C for samples of classes C and D, compared to the transition temperature reached by the samples with curly and dense fibre (classes A and B), which has values of 55-80˚C.

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