

Studies on Birch Wood Viscoelastic Properties

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The paper presents study methodic on birch wood viscoelasticity. For the study, specimens of $(0.35 \times 0.04 \times 0.014)$ m dimensions were used. They were sawn in a certain order from different places of a log, called the “butt end”, “centre” and “top”. For this purpose a log of five meter was used. The studies were based on the methodic of resonance vibrations of a beam type body. Having ascertained the value of resonance frequency, dynamic modulus of elasticity (elastic properties) of the specimen and coefficient of damping $\text{tg} \delta$ (viscous properties) were calculated. In this way, dependencies of the change of these parameters in different directions of the log, evaluating the character of annual rings and distribution pattern, were obtained. It was found, that the greatest modulus of elasticity value (25201 MPa) is obtained in the centre of the log, while the least (20942 MPa) is in the butt end. Coefficient of damping going from the butt end towards the top changes from 0.011 to 0.013. In most cases elastic properties are exchanged by damping properties. The obtained data may be used selecting wood to produce separate details of wooden articles.

Keywords: dynamic modulus of elasticity, coefficient of damping, resonance vibration, birch timber specimen

INTRODUCTION

Polymeric materials, including wood, in most cases are exploited under the conditions of dynamic loadings.

The concept of viscoelasticity applies to these materials. They are neither ideally elastic bodies, nor viscous liquids, however, they pertain both types of properties. Thus, the reaction of wood, as an elastic body, to exterior impact depends on the ratio of elastic and viscous properties. Analyzing relaxation processes of such materials, it is necessary to evaluate the factor of time, i.e. to measure changing in time strains and stresses.

When elastic materials are tested in dynamic conditions, periodic loading of the specimen or article and its rest period occur. In this case the role of time factor is performed by the frequency of oscillations.

Creation of periodic loading regime is one of the main study methods of mechanical properties of polymer material. In this case mostly harmonic oscillations of a specimen or an article are used. Especially widely resonance vibrations are applied for the studies of wood materials [1 – 5].

Construction details of various wooden articles comprise a complex dynamic system. Under the impact of exterior forces of wide amplitudes and frequency range, each element of the system vibrates with the frequency of its free oscillations and amplitude. The values of these parameters are preconditioned by elastic and viscous properties of the element [6, 7].

Therefore, for the study of such dynamic systems, it is necessary to know the main parameters of separate elements, such as the dynamic modulus of elasticity and coefficient of damping. These parameters should be known to eliminate resonance vibrations or to reduce them, creating optimal structure of an article. Sometimes it is necessary to tackle an opposite task to “strengthen” resonance vibrations [2].

Thus, producing various wooden articles and selecting wood for their production, it is not enough to carry out studies to choose wood species for the production of separate details.

As far as details of an article may be produced from any part of tree log, it is very important to know, that elastic properties of wood are distributed throughout the whole log.

The aim of this research is to study the distribution of the dynamic modulus of elasticity and coefficient of damping values in birch log and to evaluate some factors affecting this distribution.

STUDY METHODS

In general, separate details of a wooden article may be analyzed as bodies having the form of a beam or a plate. They may be joined in different ways attaching them to each other with one or both ends, edges, along the whole perimeter and so on [6, 8].

Under the impact of exterior forces and during vibration of such an article, its separate details within certain limits may move in respect of each other. In this case, the details are analyzed as absolutely rigid bodies, while the whole article as a system of concentrated parameters (masses, springs and dampers).

On the other side, it is known, that each of the details in the case of resonance “changes” its form [6]. In this case the detail is analyzed as a system with distributed parameters, i.e. its viscous and elastic properties are distributed evenly throughout its volume. Under the impact of forces, there exist extremely many bend forms of details.

Fig. 1 shows a beam (a) attached by one end and its first bend form (b). Here beam point in the plane x_1 oscillates in opposite phase than beam points on plane x_2 .

Under the impact of driving force $F(t)$ the beam vibrates. Changing frequency ω of the force, resonance vibrations of the beam are induced. In this way a corresponding bend form of the beam is obtained.

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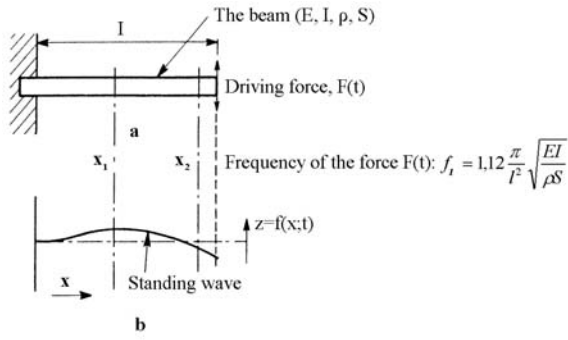


Fig. 1. Scheme (a) of a beam fastened at one end and its first bend form (b): E – modulus of elasticity, I – moment of cross-section inertia, ρ – density, S – cross-section area, $F(t)$ – driving force, f_1 – frequency of the first beam bend form

Beam deflection z depends on the coordinate x and time t .

For the function $z(x, t)$ the following equation is written [1]:

$$\rho \cdot S \frac{\partial^2 z}{\partial t^2} + E \cdot I \frac{\partial^4 z}{\partial x^4} = 0, \quad (1)$$

where $\frac{\partial^2 z}{\partial t^2}$, $\frac{\partial^4 z}{\partial x^4}$ in the second and fourth order derivatives of the z with respect to t and x accordingly.

Solution of equation (1) is searched in the form of harmonic function:

$$z = Z \sin \omega \cdot t, \quad (2)$$

Z is the amplitude, ω is the cyclic frequency.

Inserting this value in (1) equation, we obtain:

$$Z^{(IV)} - \frac{\rho \cdot S \omega^2}{E \cdot I} Z = 0, \quad (3)$$

where, $Z^{(IV)}$ is the fourth order derivative of the Z with respect to x .

Solution of equation (3) is obtained in the following form:

$$Z = A \cdot \sin \alpha \cdot x + B \cdot \cos \alpha \cdot x + C \cdot \text{sh} \alpha \cdot x + D \cdot \text{ch} \alpha \cdot x. \quad (4)$$

Constants A, B, C, D are ascertained according to initial conditions at the ends of the beam. For function Z we have two conditions at the fastened end of the beam:

$$\text{when } x=0, Z=0 \text{ or } \frac{dZ}{dx}=0 \quad (5)$$

$$x=l, \frac{d^2 Z}{dx^2}=0 \text{ or } \frac{d^3 Z}{dx^3}=0$$

In this way from (4) we obtain four equations:

$$\begin{aligned} B + D &= 0, \\ A + C &= 0, \\ -A \cdot \sin \alpha \cdot l - B \cdot \cos \alpha \cdot l + C \cdot \text{sh} \alpha \cdot l + D \cdot \text{ch} \alpha \cdot l &= 0 \\ -A \cdot \cos \alpha \cdot l + B \cdot \sin \alpha \cdot l + C \cdot \text{ch} \alpha \cdot l + D \cdot \text{sh} \alpha \cdot l &= 0 \end{aligned} \quad (6)$$

Having worked out the determinant of this system, we equate it to zero:

$$\begin{vmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ -\sin \alpha \cdot l & -\cos \alpha \cdot l & \text{sh} \alpha \cdot l & \text{ch} \alpha \cdot l \\ -\cos \alpha \cdot l & \sin \alpha \cdot l & \text{ch} \alpha \cdot l & \text{sh} \alpha \cdot l \end{vmatrix} = 0. \quad (7)$$

After stretching (7) out, we obtain:

$$\text{ch} \alpha \cdot l \cos \alpha \cdot l = -1. \quad (8)$$

The least root of this equation equals:

$$\alpha \cdot l = 1.875. \quad (9)$$

Eigenvalue of the frequency of the first beam bend form is obtained:

$$\omega_0 = \frac{3.52}{l^2} \sqrt{\frac{E \cdot I}{\rho \cdot S}}. \quad (10)$$

After applying (10) expression, knowing beam parameters and having measured frequency ω_1 , modulus of elasticity E of beam material is calculated.

Having ascertained amplitude-frequency characteristics of the beam, viscous properties – coefficient ($\text{tg} \delta$) of damping are evaluated [8]:

$$\text{tg} \delta \approx \frac{\Delta f}{f_0}. \quad (11)$$

where f_0 is the resonance frequency of the beam, Hz ($\omega_0 = 2\pi f_0$), $\Delta f = f_2 - f_1$ is the width of the resonance curve, f_2, f_1 are frequencies obtained when the amplitude of beam oscillations decreases $\sqrt{2}$ times, δ is the angle of losses.

Thus, having induced resonance oscillations of the beam, according to their parameters it is possible to evaluate elastic (E) and damping properties ($\text{tg} \delta$) of the beam material.

EXPERIMENTAL PART

For the study birch wood specimens sawn from 5 m long log were used. First of all the baulk is sawn (dotted line). From baulk the necessary specimens are sawn (Fig. 2). The specimens are sawn from the butt end, central and top parts of the log. Sawing schemes of these parts are shown in Figs. 3 (a, b, c).

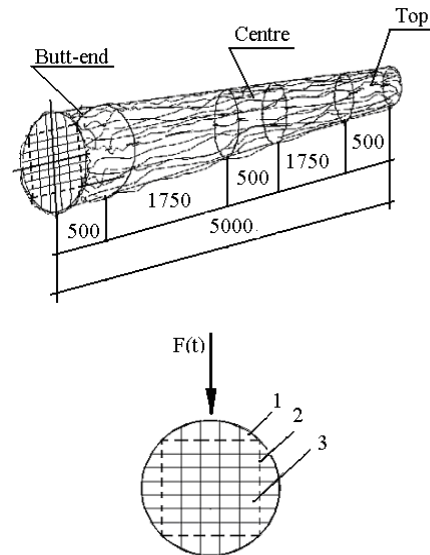


Fig. 2. Log sawing scheme: 1 – log, 2 – baulk, 3- specimens, $F(t)$ – driving force

The length of specimens (0.35 m) is measured using a ruler (accuracy 0.1 mm), width (0.04 m) and thickness (0.014 m) using sliding callipers (accuracy 0.01 mm).

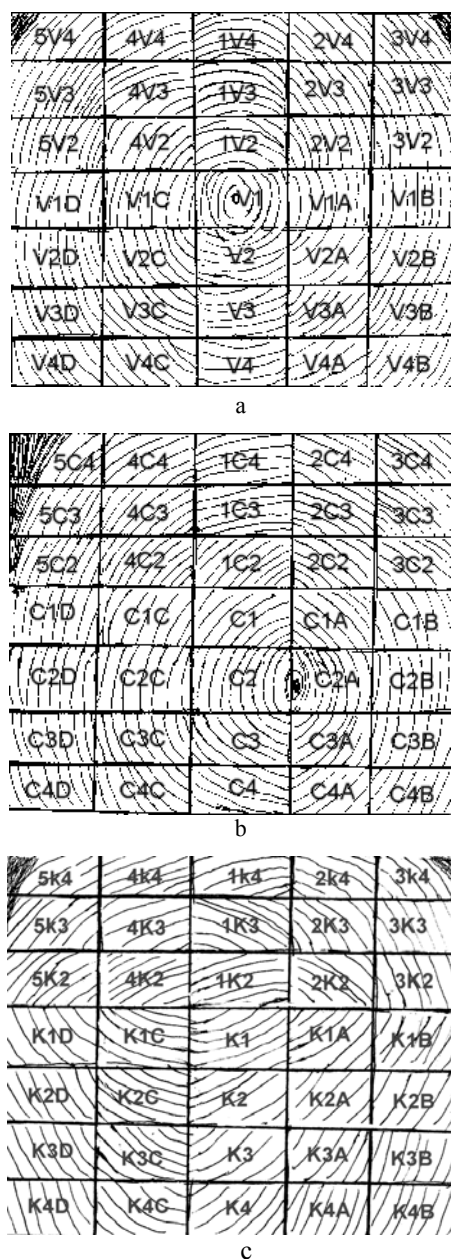


Fig. 3. Sawing schemes of the and top (a), centre (b), butt end (a)

To obtain more precise data, dimensions of the specimens were measured in several places: the length in three (the first and the third point are 10 mm from the ends, the second in the centre of the specimen); width and thickness also in three places (the first and the third point is 50 mm from the start of the specimen, the second is in the centre). The specimens were weighed using electronic scales (accuracy 0.001 g). Moisture content of the specimens was ascertained using a hygrometer. It was found, that moisture content varies within 4.7 – 6.1 % range. The distribution of annual rings in the specimens is evaluated as well. Some data on butt end, central and top parts of the specimens are presented in Table 1 (a, b, c).

As it can be seen from the sawing scheme (Figs. 3 (a, b, c)), annual rings in the specimens are differently distributed in respect of the force F (Fig. 1 (a)) direction. In some specimens annual rings are distributed at 45° in the direction of the force.

Table 1. Data of the specimens

Specimen	Width, m	Thickness, m	Length, m	Dampness, %	Density, kg/m ³	Lateral inertia moment, 10 ⁻⁶ , m ⁴	Cross section, m ²
Data on the top part of the specimens							
V4B	0.038	0.014	0.348	5.2	679.942	0.0078	0.000512
V4D	0.038	0.013	0.347	5.3	669.607	0.0076	0.000509
V4A	0.037	0.014	0.348	5.3	624.181	0.0079	0.000512
V4	0.037	0.014	0.348	5.4	591.868	0.0080	0.000509
V4C	0.037	0.013	0.348	5.5	634.076	0.0074	0.000499
Data on the central part of the specimens							
C4B	0.038	0.014	0.349	5.0	678.581	0.0080	0.000519
C4A	0.037	0.014	0.349	5.4	612.981	0.0078	0.000507
C4	0.038	0.014	0.348	5.5	585.430	0.0079	0.000506
C4C	0.038	0.013	0.349	5.2	664.341	0.0073	0.000502
C4D	0.038	0.013	0.349	5.3	693.381	0.0078	0.000516
Data on the butt end of the specimens							
K4B	0.039	0.013	0.348	5.6	646.421	0.0076	0.00052
K4A	0.037	0.014	0.347	5.6	552.919	0.0086	0.000526
K4	0.038	0.014	0.348	5.4	595.369	0.0079	0.000521
K4C	0.039	0.013	0.348	5.3	663.557	0.0076	0.000516
K4D	0.039	0.013	0.348	5.6	673.628	0.0078	0.000522

In other specimens the position of annual rings corresponds to the tangential and radial directions in respect of the force. It is obvious, that when the force affects specimens in this direction, mechanical properties of separate specimens will be different. It was found, that moving from the butt end towards the top, the width of annual rings decreases. The least width is at the top 2.1 mm (V4D), while the widest annual ring is found in the butt end (K2B).

Experiments are carried out with the help of a special stand [8]. Measurements are done with the following sequence: in the beginning resonance frequency of the specimen is ascertained, which is characterized by the greatest vibration amplitude. Changing the frequency of electric signals (at one time increasing, at another – decreasing), a corresponding them amplitude is recorded. By the help of these data wood damping is evaluated ($\text{tg}\delta$). Having measured resonance frequency of the specimen, from equation (10) modulus of elasticity E is calculated.

Later, having ascertained amplitude-frequency characteristics of the specimen and corresponding frequencies f_0, f_1, f_2 from (11) equation, coefficient of damping is found.

Some data of measurements and calculations are given in Table 2.

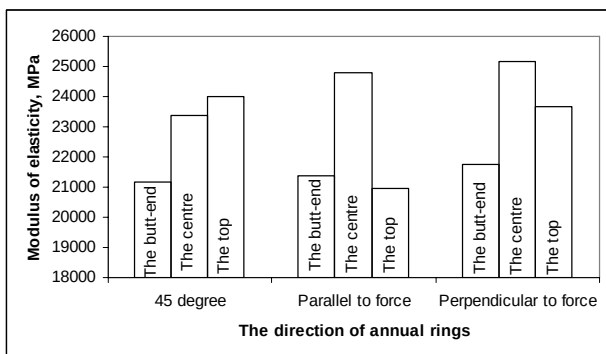
The obtained results were processed statistically. Having conducted studies, it was found, that modulus of elasticity of the specimens fluctuates from 13456.1 MPa to 27763.6 MPa.

Table 2. Data of measurements and calculations of the specimens

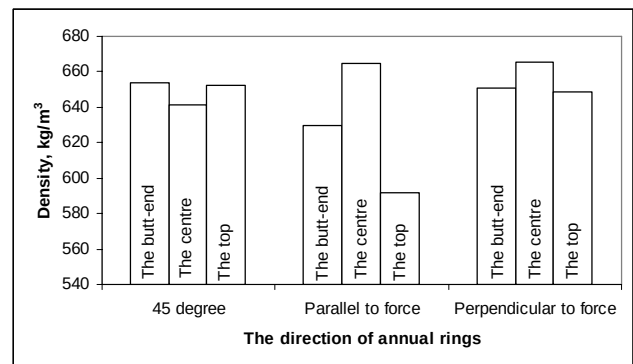
Specimen	Resonance frequency, Hz	f_1 , Hz	f_2 , Hz	Width of the band, Hz	Coefficient of damping	Modulus of elasticity, MPa
Data of measurements and calculations at the top						
V4B	113.2	111.8	113.6	1.8	0.016	26755.4
V4A	117.9	117.1	118.4	1.3	0.011	26125.1
V4	114.5	113.9	115.2	1.3	0.011	23115.3
V4C	111.5	110.8	112.4	1.6	0.014	24654.9
V4D	108.0	107.3	108.7	1.4	0.013	24646.4
Data of measurements and calculations at the central part						
C4B	111.0	110.7	111.8	1.1	0.009	25594.2
C4A	108.6	108.3	109.7	1.4	0.013	22179.7
C4	114.2	113.5	114.8	1.3	0.011	22811.4
C4C	112.9	112.3	113.5	1.2	0.011	27601.0
C4D	109.1	108.7	109.8	1.1	0.010	25882.0
Data of measurements and calculations at the butt end						
K4B	100.5	100.4	100.8	0.4	0.004	20590.7
K4A	98.1	97.6	98.8	1.2	0.012	15013.6
K4	107.1	106.7	107.9	1.2	0.011	20628.8
K4C	104.0	103.5	104.5	1.0	0.010	22549.6
K4D	94.0	93.5	94.2	0.7	0.007	18487.0

Coefficient of damping at the butt end ranges from 0.00398 to 0.01981. In the centre it is from 0.00901 to 0.02254, at the top it is from 0.00497 to 0.01836. Average modulus of elasticity of specimens is 22904.1 MPa, coefficient of damping is 0.01151.

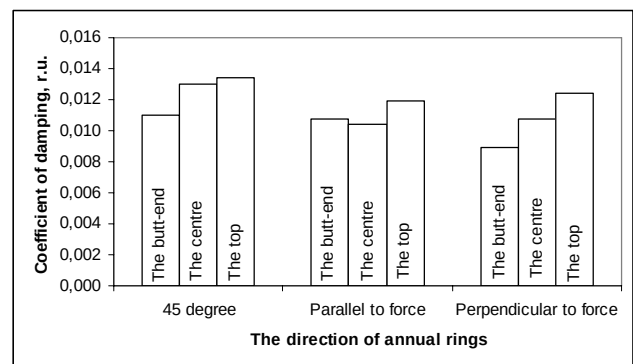
Analyzing the obtained experimental data, it was found, that modulus of elasticity, coefficient of damping and density are interrelated. Besides, the values of these parameters are extremely dependant on the direction of disposition of annual rings in the specimen – in some specimens annual rings are parallel to the direction of the force, in others – perpendicular, still in others – leaning in a certain direction. Interrelationships of these parameters are shown in Figs. 4, 5, 6.

**Fig. 4.** The dynamic modulus of elasticity distribution in respect of the direction of annual rings

As it can be seen in Fig. 4, the following tendency becomes evident: the least value of modulus of elasticity (21666.92 MPa) is obtained, when the direction of annual rings comprises an angle of 45° with the specimen bend plane, while the highest value (25155.21 MPa) – when the direction of the force is perpendicular to annual rings. However, the value (20965.08 MPa) of modulus of elasticity of the top part specimens is the least, when the direction is parallel to the rings. This deviation could be explained by the presence of defects in specimens (3V4, 5V4). In other cases specimens are waned, specimen V1 contains pith and is bent, specimens V4B, V3C, V2, V2C, V1, V1C have the knots. Item the annual rings at the top are thinner than in the lower part of the log (on an average in the butt-end the width of rings ranges 3.8 – 4.2 mm, in the centre are 3.5 mm, while at the top are 2.8 mm).

**Fig. 5.** The density distribution in respect of annual rings

Dynamic modulus of elasticity is almost in all cases directly related to wood density. Changes in wood density cause corresponding changes in the modulus of elasticity. Analyzing diagrams (see Figs. 4 and 5) it can be seen, that dynamic modulus of elasticity and density have a tendency to increase at the butt end and in the centre, at the top this regularity changes – modulus of elasticity as well as density decrease.

**Fig. 6.** The coefficient of damping distribution in respect of annual rings

Analyzing the change of dynamic modulus of elasticity and coefficient of damping along the log (Figs. 7, 8), it was obtained, that the least average value of modulus of elasticity is in the butt end (21000 MPa), the highest – in the centre (25300 MPa), while at the top it slightly decreases (23750 MPa).

As far as moving along the log to its top modulus of elasticity in general increases (from 21500 MPa to

23500 MPa), while coefficient of damping decreases (from 0.013 to 0.009), it is obvious, that elastic wood properties are exchanged by damping ones.

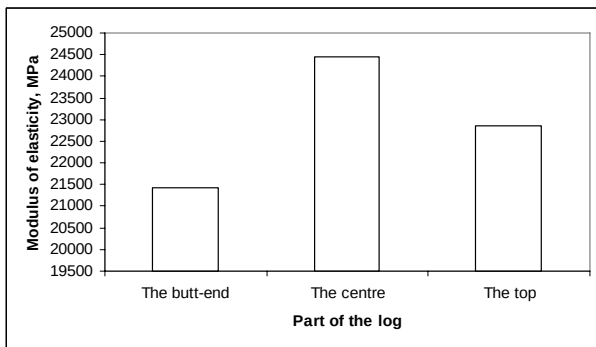


Fig. 7. The dynamic modulus of elasticity distribution along the log

Corresponding results were obtained also studying distribution laws of the dynamic modulus of elasticity and coefficient of damping in other places of the log.

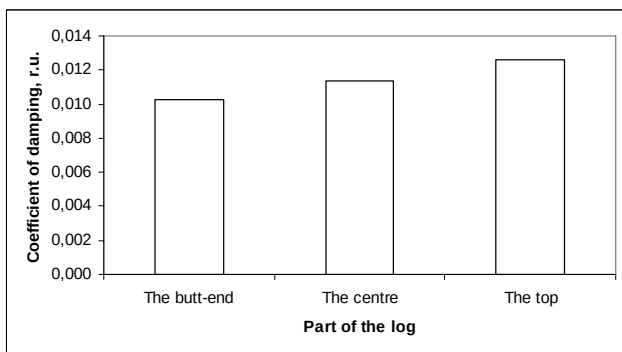


Fig. 8. The coefficient of damping distribution along the log

The change of dynamic modulus of elasticity directly corresponds to the change of density. Density and modulus of elasticity respectively acquire the highest value in the central (655 kg/m³) part of the log, while in the butt end (623 kg/m³) and at the top their values decrease.

Analyzing in general the change of dynamic modulus of elasticity and coefficient of damping moving from the pith to the bark (in radial direction), it is seen, that modulus of elasticity acquires the least value in the centre of the log (V1 – 15000 MPa), while moving outwards the value increases (Fig. 9, a).

From Fig. 9, b, it can be seen, that coefficient of damping changes contrary to modulus of elasticity: the least values coefficient of damping acquires in outer specimens (1V4, V3 – 0.011). Analogous situation prevails both in the butt end and in the central part of the log. However, this regularity sometimes changes due to shifts of the pith position and arrangement of annual rings.

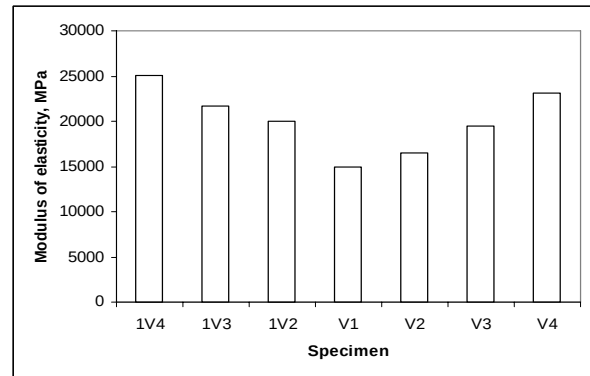
The change of dynamic modulus of elasticity and coefficient of damping at the top, moving around the log with outer specimens, is presented in Figs. 10 and 11.

Analyzing the distribution of annual rings it can be observed, that small values of modulus of elasticity are related to the size of annual rings.

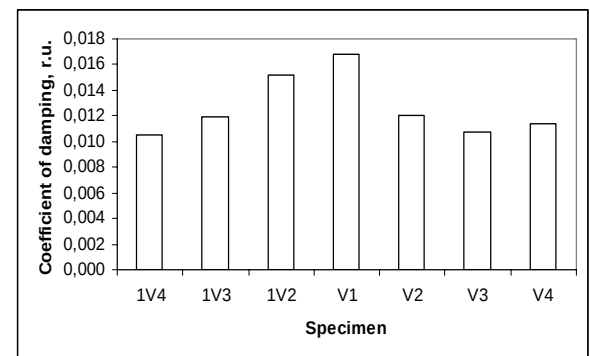
In specimens, where annual rings are wider (in the specimen V4 ring width is about 3.5 mm) (at the same time

their number per specimen is less), modulus of elasticity is less, while in specimens, where there are more annual rings, modulus of elasticity increases.

In wider annual rings early wood prevails. It is comprised of thin-walled and larger elements. Its density differs from the late wood. Early wood is much more porous.



a



b

Fig. 9. Change of the dynamic modulus of elasticity (a) and coefficient of damping (b) moving from the pith outwards – in radial direction

Analyzing the change of coefficient of damping on log perimeter (Fig. 11), it can be seen, that a reverse relationship exists between it and modulus of elasticity. In both diagrams are revealed points (5V4 and 3V4), where coefficient of damping values are the highest.

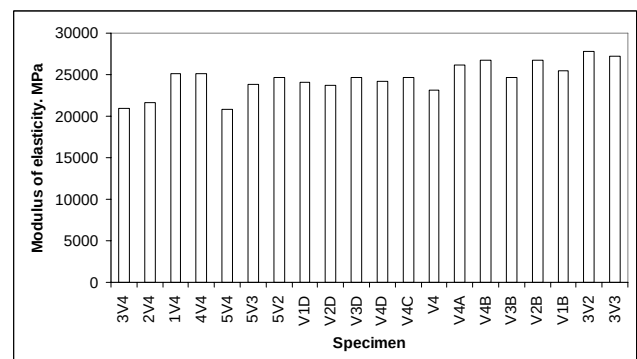


Fig. 10. The change of dynamic modulus of elasticity at the top, observing outer specimens of the log

The values of these parameters are affected by defects – the bark. Besides, it can be seen, that in this part of the

log on one of its sides modulus of elasticity is higher (coefficient of damping is less) and vice versa.

Observing distribution of these properties on log perimeter, a conclusion can be drawn, that the least value of modulus of elasticity and damping is in the butt end (20990.97 MPa and 0.01044), while the highest value of modulus of elasticity is in the central part (25332.10 MPa), and that of coefficient of damping – at the top (0.01288).

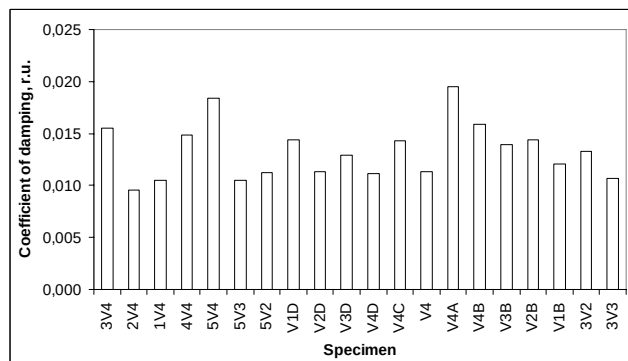


Fig. 11. The change of coefficient of damping at the top, observing outer specimens

Thus, it was ascertained, that elasticity properties of birch wood are interrelated. Damping (viscous) properties in various places of the log are exchanged by elastic properties.

CONCLUSIONS

The presented method and equipment allowed to evaluate dynamic birch wood modulus of elasticity and coefficient of damping. Mean modulus of elasticity in the butt end comprises 20990.97 MPa, in the centre – 25332.10 MPa, at the top – 23693 MPa. Coefficient of damping in the butt end – 0.01044, in the centre – 0.012, at the top – 0.01288.

It was found, that mean log modulus of elasticity is 22686 MPa and coefficient of damping 0.012. The range of changes of these parameters is 13500 MPa – 28000 MPa and 0.0049 – 0.0183, respectively.

It was ascertained, that the highest value of modulus of elasticity in most cases is obtained when specimen bending direction is perpendicular to annual rings, while the least,

when the direction of rings is leaning at an angle of 45° in the butt end and in the centre, and when the direction of rings is perpendicular to bend direction at the top.

It was found, that in general moving from the butt end towards the top the values of modulus of elasticity increase, while those of coefficient of damping decrease.

It has been ascertained, that there exists a reverse relationship between coefficient of damping and dynamic modulus of elasticity with the increase of one parameter, another decreases, i.e. elastic properties of wood are exchanged by damping properties.

REFERENCES

1. **Cai, Z., Ross, R. J., Hunt, M. O., Soltis, L. A.** Pilot Study to Examine Use of Transverse Vibration Nondestructive Evaluation for Assessing Floor Systems *Forest Products Journal* 52 (1) 2002: pp. 89 – 93.
2. **Wang, X., Ross, R. J., Mattson, J. A., Ericson, J.R., Forsman J. W., Geske E. A., Wher M. A.** Nondestructive Evaluation Techniques for Assessing Modulus of Elasticity and Stiffness of Small – Diameter Logs *Forest Production Journal* 52 (2) 2002: pp. 79 – 85.
3. **Cai, Zhiyong, Hunt, M. O., Ross, R. J., Soltis, L. A.** Static and Vibration Modulus of Elasticity of Salvaged and New Joints *Forest Products Journal* 50 (2) 2000: pp 35 – 40.
4. **Xoji, H., Masaharu, O., Hiroshi, T., Kiyoharu, F.** Effect of Board Density on Bending Properties and Dimensional Stabilities of MDF – Reinforced Corrugated Particle Board *Journal of Wood Science ISSN 1435-0211* 49 2003: pp. 398 – 404.
5. **Boren, H., Barnard, G.** Analysis of Strenght and Stiffness Properties of Small Diameter Round Scots Pine Timber Tests Bending and Compression Parallel to the Grain *Paper and Timber ISSN 0031-1243* 1 2000: pp. 343 – 349.
6. **Malkin, A. Ya, Askadski, A. A., Kovriga, V. V.** Experimental Methods of Polymer Physics. Moscow, Mir Publishers, 1983.
7. **Molin, N. E., Lindgren, L. E.** Parameters of Violin Plates and their Influence on Plates Modes *J. Acoustic. Soc. Am.* 83(1) 1988: pp 281 – 291.
8. **Vobolis, J., Aleksiejūnas, M.** Investigation of Wood Mechanical Properties by the Resonance Vibrations Method *Material Science (Medžiagotyra) ISSN 1392-1320* 9 (1) 2003: pp. 139 – 143.