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Investigation of Modal Behaviour of Resonance Spruce Wood Samples (*Picea abies* L.)

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Results of experimental modal analysis of a resonance and non-resonance spruce wood (*Picea abies* L.) are presented. The resonance wood came from a tree from Poland and Bosnia and Herzegovina, while the non-resonance wood came from the vicinity of Olsztyn from the north-eastern Poland. The modal parameters (modal frequency, modal damping and mode shapes) of the wood samples were determined for the samples of 8 mm in thickness. Modal analysis was made by pulse excitation. The resonance and non-resonance wood differ in the fundamental modal parameters as well as in the number of potential modes. Additionally, calculated values of damping factor are presented. The values are much bigger for a non-resonance wood than for good quality resonance spruce.

Keywords: resonance wood; spruce wood; modal analysis.

1. Introduction

A general definition of wood quality is difficult as different applications like pulp and paper industry, manufacturing of structural elements, production of wood-base materials, or manufacturing of musical instruments require different wood features.

Violins are constructed of about 80 different wood components. Generally, the elements can be divided into those that form resonant body, and those that complement the exterior and interior of the instrument. The top plates of resonance body are usually made of resonant spruce. Spruce wood is characterized by uniform and narrow annual rings. When compared to pine or larch wood, spruce wood is described by lower density, higher tensile strength and a higher modulus of elasticity along fibre. Small gradient of density and modulus of elasticity within individual annual rings in mature spruce wood positively affects the basic parameters characterizing resonance wood.

In string musical instruments, wood is used for construction of the resonant body which enhances sound of strings thanks to the phenomenon of resonance. The smaller a logarithmic decrement of vibrating system damping the bigger gain of sound. Although the logarithmic decrement is a parameter of a given vibrating system and not of a material (Bucur, 2006), according to many reports the decrement is very important because it describes the suitability of wood for the manufacture of musical instruments. It is more important than often used sound propagation velocity in wood (Ono, Norimoto, 1984; Yano *et al.*, 1993). The authors describing the decrement pointed out that for a good-quality resonant wood the decrement should have values as low as possible (Zieger, 1960; Bariska, 1978; Holz, 1984; Bucur, Böhnke, 1994; Gough, 2000). Additionally, wood for musical instruments should be characterised by high radiation damping, small inner damping, high elasticity but low density (Bucur, 2006).

Acoustic parameters considered in evaluation of resonance wood for string instrument making include: sound propagation velocity, acoustic impedance and acoustic constant. These parameters depend on structural features of wood. Although the values of wood density and elasticity modulus permit calculation of certain acoustic parameters, they are insufficient for evaluation of a quality of resonance wood. Acoustic properties of vibrating systems are often described in terms of the so-called modal parameters, i.e. modal frequencies and damping and mode shapes (Ono, Norimoto, 1984; Spycher *et al.*, 2008; Skrodzka *et al.*, 2009; 2013; 2014; Duerinck *et al.*, 2014). A mode shape is a specific form of vibration corresponding to a particular (modal) frequency. It is characterized by nodal lines or areas (where there is no motion or its amplitudes are very small minimal) and anti-nodal areas/lines (where the vibrational motion is maximal) as well as by modal frequency and damping. If a system vibrates with the frequency of its basic resonance, all its points move in the same phase. For increasing modal frequencies mode shapes become more complicated with increasing number of nodal lines. The complex vibrations of the linear system excited by broadband signal can be described by a sum of vibrational modes, i.e. by the sum of "elementary" vibrations (Ewins, 1995).

Each mode is characterized by the modal frequency, damping factor, and mode shape. These parameters depend on wood inhomogeneity and are important for evaluation and choice of wood for manufacturing of musical instruments. It should be added that due to the inhomogeneity that is not always possible to achieve good correlation between mechanical and acoustic parameters for unambiguous evaluation of the resonance wood quality (Hori *et al.,* 2002).

As modal analysis is widely used to describe dynamic properties of vibrating structures, we decided to describe modal parameters of two types of the material qualified as good and very good resonance wood. For comparison the same modal test was performed on the material which does not meet requirements posed for wood used for the manufacturing of musical instruments. Thus, the main aim of the paper is to describe in an objective (experimental) way the most characteristic and well pronounced modal features of samples of resonance spruce wood and compare them to modal parameters of non-resonance spruce wood. Contrary to our previous paper (Mania *et al.*, 2015), thickness of our samples is 8 mm. Wood pieces of such thickness are usually an original material for manufacturing of top and back plates of violins

2. Material and methods

Resonance spruce wood (*Picea* sp.) coming from Poland and Bosnia-Herzegovina and non-resonance wood from Poland were selected for a modal test. The test was performed for a spruce wedges subjectively classified as good resonance wood. The first tested wedge was classified as very high quality wood, having a regular width of annual rings, a minor contribution of the late wood and straight course of fibre. It was obtained from the eastern mountainous areas of Bosnia and Herzegovina, from Mazoče. At the width of the sample from Mazoče there were 120 annual rings. The second spruce tree from which the sample was taken grew near Istebna, a village in Beskid Śląski. It had 86 annual rings along sample width. The wedges were 450 mm long, its radial width was 130 mm and the tangential width at the thicker end was 50 mm, while at the thinner end it was 27 mm. The wood density was 360 kg/m^3 and 380 kg/m^3, respectively. The control wood from a tree grown near Olsztyn, a town in north-eastern Poland, did not show the features of resonance wood. At the breast height of the tree trunk, a 50-cm-long block was cut out front the tree, from which then a central balk of 50 mm in width was cut. The study was performed on a sample of the experimental balk mature part containing 77 annual rings. The widths of its annual rings were irregular and it was characterised by a great contribution of latewood. Its density was 490 kg/m^3. Thus, the control sample (Olsztyn) was denser than resonance samples (Mazoče and Istebna) and its pattern of annular rings was significantly less regular than the pattern of resonance samples.

Modal analysis was performed on samples of the size 240 (in longitudinal direction) $\times$120 (in radial direction) $\times$ 8 mm (in tangential direction). On the surface of the wood samples 171 measuring points, distant 14 mm from each other in longitudinal and radial directions were chosen. They formed uniform, square-shaped measuring mesh. Moisture content of all samples was 9%. For modal experiment samples were mounted in a box of significant mass by clamping longer sides in a direction perpendicular to the main surface.

An experimental modal analysis with a fixed response point and varied point of excitation was made. An excitation signal was delivered from an impact hammer with a piezoelectric force transducer (PCB Piezoelectronics Impact Hammer Model 086C05). The impact of the hammer delivered a signal of a wide spectrum to the studied samples. Such type of excitation, offers a fast and convenient way to determine the normal modes of a structure. The response signal of the sample was measured by an accelerometer NP – 2910 (Ono Sokki, Tokio), 2 g in mass, attached to the sample on bee wax. The accelerometer was mounted on the sample surface. It was 30 mm distant from the long edge and 58 mm distant from the short edge of the sample, similarly to situation described in our previous paper (Mania *et al.*, 2015). Position of the accelerometer has been chosen in preliminary studies as the point through which no nodal or symmetry lines passed. Signals from both transducers (acceleration and excitation force) were delivered to dual channel FFT analyser ONO SOKKI CF 5210. Measurements were made in the frequency range of 0–6400 Hz with the spectral resolution of 3 Hz. At a single measuring point ten impacts were executed to enable spectral averaging of both, excitation and response signal. The force hammer was moved from point to point in a grid. Thus, from each pair of the excitation signal (measured in successive point on the grid) and the response signal (measured always at the same point of accelerometer mounting) it was possible to measure a corresponding frequency response function (FRF). The resulting FRFs were processed by a computer and modal parameters were calculated using the SMS STAR Modal software package. Each FRF measurement was controlled by the coherence function.

Ten spectral averages were used to reduce the variance of accidental noise in measured signals and to improve the quality of measured FRFs. Examples of measured FRFs are presented in Fig. 1.

The damping factor (δ) is defined according to the theory of electric circuits as the ratio of the frequency difference (Δf) of the resonance curve at half maximum amplitude or at half-power level to the resonance frequency (Haines, 1979; Bucur, 2006). In this study, this parameter is defined as

$$\delta = \frac{\Pi \Delta f}{\sqrt{3} f_0},$$

where f_0 – resonance frequency [Hz], Δf – the width of the peak at the amplitude 3 dB below the modal (resonance) frequency [Hz].

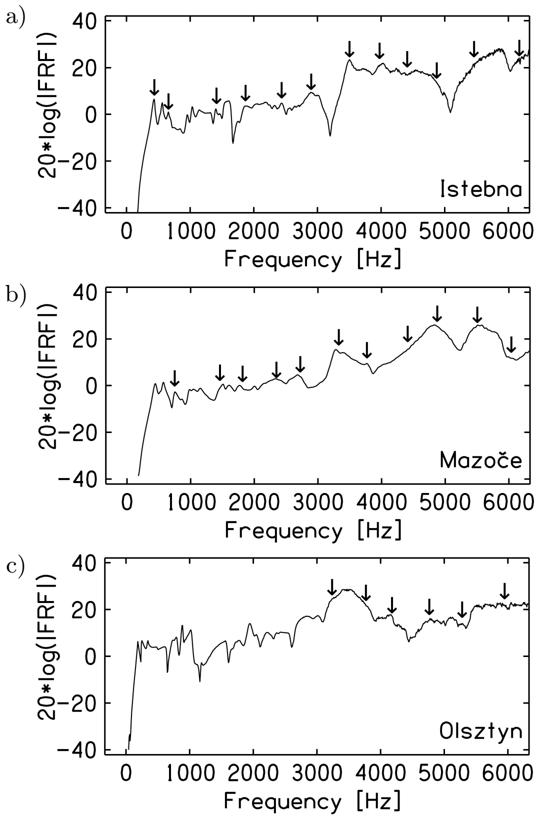


Fig. 1. Examples of the FRFs measured on spruce samples of: a) subjectively evaluated as a good quality resonance wood (Istebna), b) subjectively evaluated as a high quality resonance wood (Mazoče), c) non-resonance wood (Olsztyn). Arrows indicate frequencies of modes described in the text.

3. Results and discussion

In Table 1 results of modal analysis of spruce wood samples are presented, i.e. number of mode, modal fre-

Table 1. Modal frequencies and damping obtained from impact modal testing for spruce wood of different quality.

Number of mode	Istebna	Mazoče	Olsztyn	Istebna	Mazoče	Olsztyn	Istebna	Mazoče	Olsztyn
	f [Hz]			d [%]			D [Hz]		
1	397	–	*308*	6.97	–	*30.09*	5.1	–	*20.8*
2	782	739	*714*	7.42	6.19	*12.13*	10.8	15.9	*42.7*
3	1417	1330	–	5.61	4.17	–	24.2	29.1	–
4	1862	1817	–	3.38	3.58	–	31.3	38.1	–
5	2435	2461	–	4.76	5.84	–	44.1	59.6	–
6	2891	2794	–	3.86	3.23	–	61.6	76.8	–
7	3456	3372	3274	5.27	4.10	7.97	84.1	96.3	132.9
8	3899	3761	3777	4.81	6.05	4.43	90.1	106.3	157.8
9	4422	4354	4228	3.94	6.60	4.81	98.4	116.7	174.3
10	4875	4846	4752	3.81	4.19	4.14	124.8	148.8	211.5
11	5474	5337	5280	3.86	7.43	8.55	144.2	165.9	242.6
12	6157	6032	5973	2.75	3.10	2.21	160.9	179.7	257.4

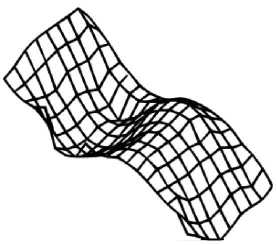
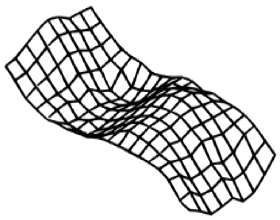
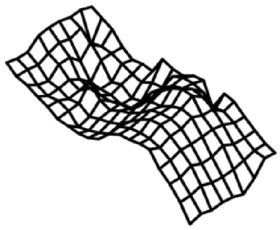
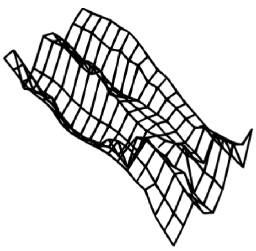
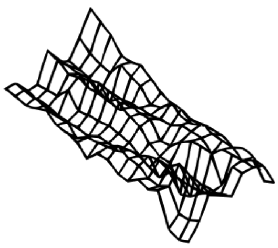
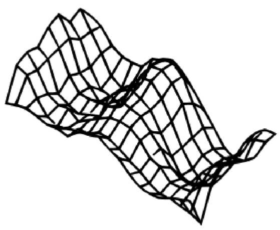
quencies f, percentage of critical modal damping d and the width of the resonance maximum D. Results were obtained by the impact excitation of the resonance spruce wood from Istebna and Mazoče and non-resonance wood from the vicinity of Olsztyn. Table 1 gathers the most distinct and characteristic modes obtained in the studied frequency range, with small damping values, i.e., less than 10% of critical damping. Systems or materials with the percentage of critical damping lower than 10% can be classified as linear (Ewins, 1995; Skrodzka *et al.*, 2009; 2013). Only linear materials can be subjected to modal analysis, i.e. those which obey the principle of mode superposition. The modes with critical damping higher than 10% were marked by italic fonts in Table 1.

Further analysis was performed for the modes number 8, 10 and 12. For both samples of the resonance wood and the control sample of the non-resonance wood chosen above modes had well pronounced envelopes of very similar shapes and small values of d.

In Table 2 mode envelopes with corresponding modal frequencies and critical damping d are shown. The first mode, labelled by the number 8, had two nodal lines perpendicular to the longer axis of the sample.

The modal frequencies of mode 8 were 3456 ± 3 Hz and 3372 ± 3 Hz for the resonance wood from Istebna and Mazoče, respectively. The frequency of mode 8 of the control wood (Olsztyn) was 3274 ± 3 Hz. The second mode labelled by 10, of a higher frequency, was characterised by three nodal lines along the longer axis of the sample. For all samples of wood studied the frequencies of this mode were similar and close to 4.3 kHz. Mode 12 occurred at the high frequency of almost 6000 Hz. The envelope of this mode had three nodal lines perpendicular to the longer axis of the sample. For all three modes (number 8, 10 and 12) modal frequencies of the resonance wood were higher than those of the control wood sample. The average value of the logarithmic damping decrement for resonant wood from Istebna was 0.0412 ± 0.007 and had the lowest value among all analyzed samples of wood. For the sample from Bosnia-Herzegovina (Mazoče) analyzed property reached the value 0.0494 ± 0.006. The highest values were observed in the control wood, which was characterized by the lowest value of the damping. The average value of the logarithmic damping decrement for this wood was 0.0785 ± 0.003. Krüger and Rohloff (1938) for frequency 860 Hz obtained values of damping factor δ equal to 0.024 for Norway spruce wood. In comparison and for a similar frequency range Spycher *et al.* (2008) received the value of this parameter equal 0.032 for Norway spruce. However, the choice of measuring frequency 860 Hz was not clearly explained.

Table 2. Mode shapes with the corresponding modal frequencies and critical damping d for wood of different origin (Istebna, Mazoče and Olsztyn).

Istebna	Mazoče	Olsztyn
3456 Hz 5.3% mode 8 	3372 Hz 4.1% mode 8 	3274 Hz 8.0% mode 8 
4422 Hz 3.9% mode 10 	4354 Hz 6.6% mode 10 	4228 Hz 4.8% mode 10 
6157 Hz 2.7% mode 12 	6032 Hz 3.1% mode 12 	5973 Hz 2.2% mode 12 

The relationship between the logarithmic decrement of the damping and modal frequency in the analyzed samples of wood is shown in Fig. 2. For comparison results of Krüger and Rohloff (1938) and Spycher *et al.* (2008) are also presented in Fig. 2. It is clear that the relation is distinct and in the range of experimental data it can be approximated by a straight line ($0.88 < r < 0.99$). Figure 2 shows that the logarithmic damping decrement constantly increases with increasing modal frequency for the resonance wood coming from Istebna and Mazoče and almost constant for non-resonance wood. This observation is consistent with findings of Ouis (2002). In his paper Ouis (2002) shown that in case of resonant frequency ranging from 0.2 kHz to 1.5 kHz, the value of decrement changed slightly. In the range from 1.5 kHz to 7 kHz, the value of the decrement increased 2 to 4 times. In our case, the increase of damping factor was not so rapid. In resonance wood from Mazoče and Istebna, in the full frequency range, changes in the decrement values were smaller, i.e. the decrement value increased about 1.4 times. This may indicate the specific properties of resonance spruce wood. From Fig. 2 it is also evident that changes in logarithmic decrement of damping were very similar for both resonance wood samples and they were far away from the decrement values of non-resonance spruce. Our values of the decrement for resonance samples were consistent with limited data of Krüger and Rohloff (1938) and Spycher *et al.* (2008).

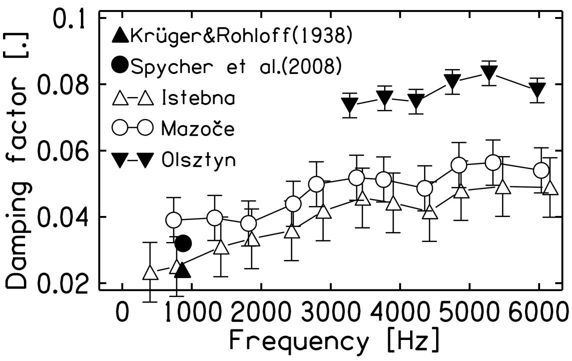


Fig. 2. Relation between the damping factor and modal frequencies of spruce wood samples of resonance (Istebna and Mazoče) and non-resonance spruce wood (Olsztyn). Vertical bars indicate single standard deviation. Data of Krüger and Rohloff (1938) and Spycher *et al.* (2008) are shown for comparison.

4. Conclusions

The results of modal analysis of resonance and non-resonance spruce wood samples of small thickness lead to the following conclusions.

1. In the measured frequency range the number of modes was not the equal for all three samples.
2. In the control sample (Olsztyn) no modes were found in the range of low frequencies (1000–3000 Hz), while in samples of resonance wood (Istebna and Mazoče) in the same range, four characteristic modes were observed. Thus, the resonance wood is more apt to free vibrations.
3. Modal frequencies found for the resonance and control woods did not coincide. Modal frequencies of the wood from Istebna and Mazoče were higher than those of the control sample.
4. The average value of the damping factor in resonant woods had lower values (0.0453 on average) compared to non-resonance wood (0.0785 on average).
5. These objective results may be an useful and promising tool for the choice of wood used for violin manufacturing. Proper choice of wood is a crucial factor determining sound quality of a violin.

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