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Assessment of resonance wood quality by comparing its physical and histological properties

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Abstract The quality of wood used for music instrument making (resonance wood) is determined by assessing six physical properties: density, modulus of elasticity, sound velocity, radiation ratio, emission ratio, and loudness index. This can easily be done by means of measurements of the resonance frequency and the corresponding damping factor. The method described here is based on vibrational analyses, adapted from standard non-destructive testing of solid material, so as to provide information both for scientific studies and for violin making. The above six properties were assessed in samples of resonance wood of different quality and in normal (control) wood of Norway spruce and sycamore. The differences observed between the samples correlated with anatomical or histological characteristics of the wood. A sample of best-quality Norway spruce resonance wood showed a high radiation ratio in the axial direction, which correlated with the presence of small wood cells with thin cell walls. In "curly maple", a high sound velocity in the radial direction correlated with the presence of broad xylem rays. The influence of external factors like wood moisture content or the geometry of the system is discussed within the context of the present study.

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Introduction

The selection of resonance wood for violin making is often biased and entirely based on the empirical knowledge of the maker and the gross appearance of the wood. At the beginning of the nineteenth century, scientists realized that wood properties influence the sonority of the violin and they tried to classify resonance wood on this basis (Bucur 1980; Dunlop 1978; Schleske 1990; Schwalbe 1925). Later, Blossfeld et al. (1962) proposed a range of criteria related to the visual appearance of the wood. The main criteria by which violin makers, as well as most materials scientists, continue to recognize first-quality resonance wood are the regularity of the annual rings and an absence of defects, together with a high modulus of elasticity.

Young's modulus of elasticity (MOE) is one of several properties that have been assessed as indicators of resonance wood quality (Ono and Norimoto 1984). Most of the studies up to the present have proved this to be of key importance together with sound velocity (c) and the radiation ratio (R) (Haines 1979), which is the ratio between the sound velocity and density ρ (Müller 1986; Rajcan 1998).

Additional properties used to evaluate resonance wood are the loudness index (L) (Haines 1979) and the figure of merit (U) (Meyer 1995), which combine the damping properties with the radiation ratio and the modulus of elasticity. Unlike the preceding authors, Ono and Norimoto (1984) as well as Yano et al. (1994) emphasize the significance of the damping factor δ. They stress that this factor, in combination with the radiation ratio, is more important than the velocity of sound as a single parameter. The damping factor, which can be related to the other acoustic properties mentioned above, is defined by a coefficient (K) as follows: $\delta = K\frac{\Delta f}{f_{\mathrm{r}}}$, where f_{r} is the resonance frequency and Δf the associated damping. The value of K varies between $K = \frac{1}{\pi}$ (Meyer 1995), $K = 1$ (Ono and Norimoto 1984) and $K = \frac{\pi}{\sqrt{3}}$ (Rajcan 1998). A summary of the properties used to characterize the resonance wood quality is presented in Table 1. These properties correlate with the propagation of sound waves in the top and bottom plates of a violin and allow the best possible selection of wood specimens for violin making (Schelleng 1963).

Unfortunately, most systems for measuring technical properties are generally not accessible to the majority of violin makers. The dynamic modulus of elasticity (E_{dyn}) is, however, a useful indicator of wood quality and can be readily derived from measurements of dynamic resonance frequency. Such measurements, originally described by Goens (1931), are successfully used for assessing the quality of

Table 1 Principal parameters used for the assessment of tone wood quality for axial (L) and radial (R) directions

Young's modulus of elasticity E (MPa) and density ρ (kg/m^3)	E for L and R directions and ρ
Sound velocity c (m/s)	$c = \left(\frac{E}{\rho}\right)^{1/2}$ for L and R directions
Radiation ratio R (m^4/kg s)	$R = \frac{c}{\rho} = \left(\frac{E}{\rho^3}\right)^{\frac{1}{2}}$ for L and R directions
Emission ratio H (m^4/kg s)	$H_L = \frac{R_L}{\delta_L}$ or $H_R = \frac{R_R}{\delta_R}$ for L and R directions
Loudness index L (m^8/kg^2 s^2)	$L = \frac{R_L \cdot R_R}{\delta_L \cdot \delta_R} = H_L \cdot H_R$

constructional timber (Hearmon 1966; Kollmann and Krech 1960) and can also greatly facilitate the estimation of E_{dyn}, for a range of other purposes: e.g. assessment of resonance wood by music instrument makers. The simplicity of the measurement system is one of its greatest advantages, together with the facility of adjusting it to the desired specimen size.

The objective of this study was to evaluate a system for measuring resonance frequency in order to assess resonance wood comprehensively and objectively and thus to serve the requirements both of scientific research and violin making. The value E_{dyn} and the damping factor δ were measured in samples of Norway spruce and sycamore resonance wood and normal wood. Tested specimens were then microscopically assessed so as to determine whether the above acoustic properties were correlated with anatomical and histological properties.

Materials and methods

Specimen preparation

For comparison of the acoustic properties of normal wood and resonance wood of Norway spruce (*Picea abies*) and sycamore (*Acer pseudoplatanus*), 120 heartwood specimens of each species were tested. Of the 120 specimens, 80 were categorised as resonance wood and the remaining 40 as normal wood. The 80 resonance wood specimens of each species comprised two 'samples' (A and B), having been collected from two different sites (Tables 4, 5). The remaining 40 specimens were of normal wood (of unknown provenance). The resonance wood specimens were selected initially on the basis of having narrow annual rings and being free from visible defects or knots. The 40 normal specimens of each species (the 'control' sample) were selected only on the basis of having homogeneous annual rings. The selection was then verified independently by a violin maker and a resonance wood retailer, who also categorised the quality of the resonance wood as 'good' (sample A) or 'very good' (sample B). The resonance wood specimens ranged in density between 360–490 and 530–630 kg/m^3 in Norway spruce and sycamore, respectively (Tables 2, 3).

In order to determine acoustic properties in the axial as well as in the radial direction, half of the 40 specimens in each sample were cut with their longest sides axially orientated ('axial specimens'), while the other half were cut with their longest sides radially orientated ('radial specimens'). The dimensions of the axial specimens were: 3 (tangential) × 25 (radial) × 150 mm^3 (longitudinal) and those of the radial specimens were 3 (tangential) × 25 (longitudinal) × 100 mm^3 (radial). Prior to each measurement, wood specimens were preconditioned at 23°C and 50% RH until a constant weight was reached; i.e. the moisture content of the specimens was 10.5 ± 0.5%.

In order to determine the influence of moisture content on the resonance frequency, additional resonance wood specimens of each species; ten radial and ten axial, were tested. For each species, these specimens were of the same provenance as 'sample A' (Tables 4, 5). They were stored for two weeks at

Table 2 Averages of the principal properties calculated for Norway spruce specimens in axial (upper value) and radial (bottom) directions (Absolute values ± SD)

	Quality	Density ρ (kg/m^3)	Dynamic modulus of elasticity E_{dyn} (MPa)	Sound velocity c (m/s)	Radiation ratio R [m^4/kg s]	Emission ratio H [m^4/kg s]	Loudness index L
Norway spruce sample A	Good	495 ± 17	14784 ± 2814	5449 ± 346	11.1 ± 0.4	4.86 ± 0.54	1.04 ± 0.17
			363 ± 46	851 ± 54	1.7 ± 0.1	0.21 ± 0.03	
Norway spruce sample B	Very good	382 ± 14	9979 ± 1186	5103 ± 280	13.4 ± 0.8	6.07 ± 0.68	3.78 ± 0.87
			731 ± 223	1365 ± 201	3.6 ± 0.5	0.62 ± 0.14	
Norway spruce control sample	–	360 ± 16	10464 ± 1004	5388 ± 134	15.0 ± 0.8	5.34 ± 1.77	2.10 ± 1.12
			458 ± 77	1124 ± 93	3.1 ± 0.3	0.39 ± 0.16	

Table 3 Averages of the principal properties calculated for sycamore specimens in axial (upper value) and radial (bottom) directions (Absolute values ± SD)

	Quality	Density ρ (kg/m^3)	Dynamic modulus of elasticity E_{dyn} (MPa)	Sound velocity c (m/s)	Radiation ratio R (m^4/kg s)	Emission ratio H (m^4/kg s)	Loudness index L
Sycamore sample A	Good	579 ± 17	7315 ± 1363	3533 ± 291	6.1 ± 0.4	1.71 ± 0.29	0.54 ± 0.10
			1050 ± 51	1348 ± 30	2.3 ± 0.1	0.31 ± 0.02	
Sycamore sample B	Very good	625 ± 22	9707 ± 1345	3894 ± 310	6.1 ± 0.7	1.85 ± 0.40	0.76 ± 0.16
			1703 ± 236	1662 ± 97	2.7 ± 0.1	0.41 ± 0.03	
Sycamore control sample	–	569 ± 15	9974 ± 769	4180 ± 143	7.3 ± 0.4	2.52 ± 0.46	1.30 ± 0.27
			1645 ± 66	1703 ± 24	3.0 ± 0.0	0.51 ± 0.03	

Table 4 Microscopic and macroscopic characteristics of Norway spruce specimens (Absolute values ± SD)

	Number of specimens	Maximal thickness of the cell walls (μm)	Diameter of late wood tracheids (μm)	Diameter of early wood tracheids (μm)	Annual ring width (mm)	Proportion of latewood (%)	Colour and aspect	Provenance
Norway Spruce sample A	20	6.3 ± 1.2	25.3 ± 9.6	38.7 ± 6.0	1.0 ± 0.5	20 ± 2%	yellow-white	France Jura
Norway Spruce sample B	20	3.7 ± 0.9	22.8 ± 8.5	33.9 ± 8.7	1.2 ± 0.5	15 ± 2%	white	Switzerland Grisons
Norway Spruce control sample	20	5.6 ± 1.0	24.1 ± 10.2	38.6 ± 9.5	3.5 ± 0.5	25 ± 2%	brown-white	Unknown

Table 5 Microscopic and macroscopic characteristics of sycamore specimens (Absolute values ± SD)

	Number of specimens	Height (*L*) of the rays (μm)	Width (*B*) of the rays (μm)	Average distance between two rays (μm)	Annual ring width (mm)	Colour and aspect	Provenance
Sycamore sample A	20	–	–	–	4	Strongly curled, dull red	Bosnia
Sycamore sample B	20	318 ± 114	61 ± 12	294 ± 82	3.5	Slightly curled, bright colour	Germany Mittenwald
Sycamore control sample	20	224 ± 89	20 ± 4	133 ± 50	5	No curly motif, brown-white	Unknown

constant temperature and different relative humidity (RH) following a cycle in five phases: 50, 70, 50% RH, then dried for 24 h at 103°C and finally stored at 50% RH. The corresponding moisture content was determined after each phase. The resonance frequency was measured after each phase and compared with the dried specimens.

Resonance frequency measurements and calculation of the dynamic modulus of elasticity as well as the damping factor

Figure 1 illustrates the principle of the measurement system used to determine the resonance frequency according to Hearmon (1966). At one end of the specimen, a magnetic field excited the attached magnet. The sound waves propagated along the specimen and the response was recorded with a microphone at the other end of the specimen.

In the present study, the amplitude of the stress wave and its frequency were preset with the support of a computer program made with the help of LABVIEW®. This program also determined the appropriate frequency range and the number of resonance peaks that were recorded during measurement. By combining the data obtained from the applied vibration with the data from the response of the specimen, it analysed the resonance frequency and calculated the modulus of elasticity. Each peak was first identified by locating its frequency range approximately and then accurate measurements of its resonance frequency were made. The width of its peak was measured at half the peak height and was used to calculate the damping factor δ.

First, in order to assess the acoustic quality of wood, the density (ρ) had to be measured with gravimetry (Table 1). Secondly, the dynamic modulus of elasticity

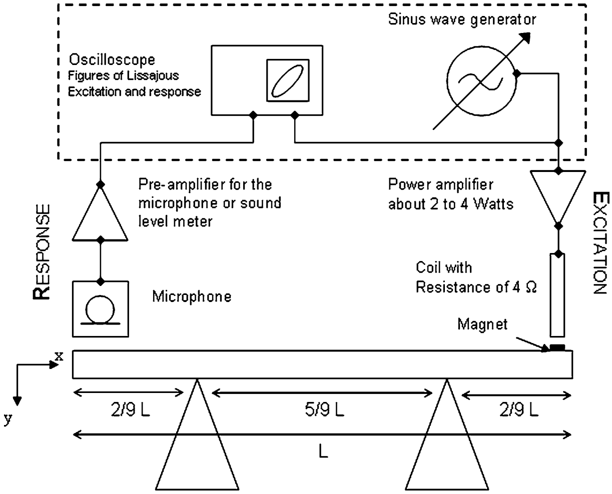

Fig. 1 Schematic drawing of the device used for resonance frequency measurements. The steps outlined by a *dashed line* were undertaken with the aid of a computer program

E_{dyn} was calculated on the basis of Eq. (1), which describes the free transverse vibration of a beam, including shear deformation and rotational inertia (Craig and Kurdila 2006) with regard to the test set-up shown in Fig. 1:

$$\rho \cdot A \cdot \frac{\partial^2 y}{\partial t^2} + E_{\mathrm{dyn}} \cdot J \cdot \frac{\partial^4 y}{\partial x^4} - \rho \cdot J \cdot \left(1 + \frac{E_{\mathrm{dyn}}}{\kappa \cdot G_{\mathrm{dyn}}}\right) \cdot \frac{\partial^4 y}{\partial x^2 \partial t^2} = 0 \tag{1}$$

where ρ is the density of the specimens, A the area of their cross-section, J is the areal moment of inertia and G_{dyn} the dynamic shear modulus. The third term accounts for rotational inertia and shear deformation, the shear coefficient κ is set to 0.833 for rectangular cross-sections. t stands for time, y for the lateral deflection and x is the distance along the beam as indicated in Fig. 1.

Equation (1) is solved using the function described in (2):

$$y(x,t) = (A_0 \cdot \sin(k \cdot x) + B_0 \cdot \cos(k \cdot x) + C_0 \cdot \sinh(k \cdot x) + D_0 \cdot \cosh(k \cdot x)) \cdot \mathrm{e}^{\mathrm{i}\omega \mathrm{t}} \tag{2}$$

where k is the wave number and $\omega = 2 \cdot \pi \cdot f_r$ is the circular frequency. Inserting Eq. (2) into (1) yields the relation (3) between wave number and circular frequency.

$$\omega^2 = \frac{E_{\mathrm{dyn}} \cdot J \cdot k^4}{\rho \cdot A \cdot \left(1 + \frac{J}{A} \cdot k^2 \cdot \left(1 + \frac{E_{\mathrm{dyn}}}{\kappa \cdot G_{\mathrm{dyn}}}\right)\right)} \tag{3}$$

Additionally, the boundary conditions have to be fulfilled. In contrast to the configuration used by Görlacher (1984) the mass m_0 of the magnet, although amounting only to 0.0523 g, had to be taken into account.

$$\begin{array}{ll} \text{for } x = 0 & M = 0 \text{ and } V = 0 \\ \text{for } x = L & M = 0 \text{ and } V = m_0 \cdot \frac{\partial^2 y}{\partial t^2} \end{array}$$

where M is the bending moment and V is the shear force:

$$M = E \cdot J \cdot \left(\frac{\partial^2 y}{\partial x^2} - \frac{\rho}{\kappa \cdot G_{\mathrm{dyn}}} \cdot \frac{\partial^2 y}{\partial t^2}\right)$$

and

$$V = -E \cdot J \cdot \frac{\partial^2 y}{\partial x^3} + \rho \cdot J \cdot \left(1 + \frac{E_{\mathrm{dyn}}}{\kappa \cdot G_{\mathrm{dyn}}}\right) \cdot \frac{\partial^3 y}{\partial x \partial t^2}.$$

Inserting Eqs. (2) and (3) into the boundary conditions yields a linear, algebraic homogeneous system of four equations. This set has only a nontrivial solution, if the determinant of the coefficients vanishes. A relation between resonance frequency f_r and Young's modulus E_{dyn} is found which is solved numerically to determinate the value of E_{dyn}.

Determining Young's MOE requires an estimate of the shear modulus G_{dyn}. According to Niemz (1993) the shear modulus parallel to the grain was taken as 500 MPa for Norway spruce and 1,000 MPa for sycamore. The respective values perpendicular to the grain were assumed to be 10% (DIN 1052 2004) of the parallel to the grain values. Calculations showed that the estimated Young's modulus is not very sensitive to the value of the assumed shear modulus. In the present configuration, a variation of 20% in G_{dyn} results in a deviation of less than 0.5% in E_{dyn}.

The third property of importance is the sound velocity $c = \left(\frac{E}{\rho}\right)^{\frac{1}{2}}$, which was calculated using the value obtained for the dynamic modulus of elasticity. Additionally, a high radiation ratio (R) in the axial direction, combined with a low wood density, has been described as being of the utmost significance for first-quality resonance wood (Müller 1986; Ono and Norimoto 1983). On the other hand, it has been demonstrated that the significance of the radiation ratio concept is sometimes overrated and that in some circumstances the sound velocity should be preferred as the decisive property (Holz 1973).

The damping factor (δ) was then defined according to the theory of electric circuits as the ratio of the width (Δf) of the resonance curve at half of the maximum amplitude or at half-power level to the resonance frequency (Bucur 1995; Haines 1979). The relationship (4) defines the damping factor δ for axial or radial directions (Bucur 1995).

$$\delta_{L/R} = \pi \frac{\Delta f}{f_{\mathrm{r}}} \tag{4}$$

where f_{r} is the resonance frequency and Δf the width of the peak at the amplitude 3 dB below the resonance frequency amplitude or at half-power level.

In addition, the emission ratio (H) and the loudness index (L) of the wood specimens were calculated (Table 1). These properties, which represent the damping factor, are an essential consideration for hit and plucked string instruments (e.g. harpsichord, guitar), which require a very low damping of sound waves (Norimoto et al. 1984). For bowed string instruments like violins, these factors are less critical because the string is continuously excited.

Measurement of static modulus of elasticity: static flexure test

In order to assess the accuracy of the calculated value of the dynamic modulus of elasticity (E_{dyn}), the 120 specimens of Norway spruce and of sycamore, were subjected to a three-point bending test, so as to measure the static modulus of elasticity (E_{stat}) and to determine whether the relationship between E_{dyn} and E_{stat} was consistent with published data. The tests were conducted by applying a central load both to the axial and the radial specimens with a span (L) of 100 mm using a universal 100 kN test machine with a load rate of 2.5 mm/min. The load was measured using a 1,000 N force sensing device with a maximum error of 2% and a mid-span deflection w with a maximal error of 1%. The values of E_{stat} were calculated according to Eq. (5) as a secant modulus between a lower load (F_1) and an upper load (F_2). The corresponding mid-span deflections were w_1 and w_2. When specimens were tested parallel to the grain, the values of F_1 and F_2 were 20 and 40 N, respectively. Perpendicular to the grain, specimens were tested with a lower load F_1 of 2.5 N and an upper load F_2 of 4 N.

$$E_{\mathrm{stat}} = \frac{(F_2 - F_1) \cdot L^3}{4 \cdot (w_2 - w_1) \cdot b \cdot h^3} \quad (5)$$

where b and h are the width and thickness of the specimens, respectively.

Light microscopy

For light microscopy, test specimens were cut into smaller specimens of approx. 10 × 5 × 5 mm^3. The specimens, with transverse, radial, and tangential faces exposed for examination, were fixed in 2 vol.% glutaraldehyde buffered at pH 7.2–7.4, dehydrated with acetone and embedded in a methacrylate medium. The embedded specimens were sectioned at approx. 2 and 4 μm using a rotary microtome (Leica® 2040 Supercut) fitted with a diamond knife. For general observation of wood anatomy and histology, sections were stained for 12 h in safranin and then counter-stained for 3 min in methylene blue and for 30 min in auramin. Micrographs were taken, using a colour film (Kodak® EPY 64T), with a Leitz® Orthoplan microscope fitted with a Leitz-Vario-Orthomat® camera system.

Results and discussion

Reliability of the measurement system and relationship between E_{dyn} and E_{stat}

Repeated measurement of the resonance frequency on the same specimens indicated that the system created only very small errors, within the range of approx. ±0.1 to ±0.6%. The configuration of the system was considered as a possible source of variation but it was found that the distances between the magnet and the coil, as well as between the microphone and the test specimen, had no noteworthy affect on the measured value of resonance frequency. Moreover, the precision with which the distance between the supports was set did not significantly affect the final value of E_{dyn}. This result is confirmed by Haines et al. (1996). Irregularities in wood density, ranging between 0 and 1%, were an additional source of variation of E_{dyn}, the calculated value of which diverged by 0.5–3.5%. Consequently, the error on the radiation ratio value induced by the measurement method ranged between ±0.5 and ±4.0%.

Figure 2 shows a comparison of the static modulus of elasticity (E_{stat}) and dynamic modulus of elasticity (E_{dyn}) for Norway spruce and sycamore wood specimens in the axial direction. The data points are shown separately for the specimens of resonance wood and of normal (control) wood. Compared to the value of E_{stat}, the numerical value of E_{dyn} measured with this method was on average 10.1% higher in Norway spruce and 5.3% higher in sycamore.

The relationship between E_{stat} and E_{dyn} in the wood of Norway spruce was originally described by Holz (1968). Schletter (cited in Holz (1968)), using a similar

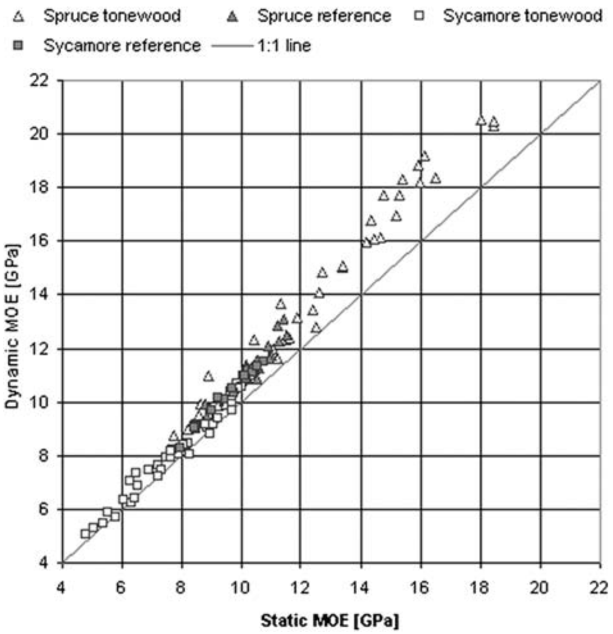

Fig. 2 Static MOE as a function of dynamic MOE for Norway spruce (*triangle*) and sycamore wood specimens (*square*) in the axial direction

testing device to the one in this study, found that the value of E_{dyn} was approx. 11.1% higher than E_{stat}. Haines et al. (1996) and Sinclair and Farshad (1987) obtained values of E_{dyn} which were respectively 6 and 10% higher than E_{stat} by inducing vibration with a hammer blow. The consistency between these previous results and those obtained in the present study provides additional evidence that our measurement system is sufficiently reliable.

In the radial direction, the relationship between E_{stat} and E_{dyn} was broadly similar to that found in the axial direction (Fig. 3). Compared to the value of E_{stat}, the numerical value of E_{dyn} was on average 20.2% higher for Norway spruce and 16.5% higher for sycamore. Moreover, it has also been observed that, in both Figs. 2 and 3, the difference between E_{dyn} and E_{stat} increases with the absolute value of E_{dyn}.

Resonance frequency measurements on wood logs show that E_{dyn} varies with the frequency (Ouis 2002). In fact, E_{stat} is generally the lower value for the modulus of elasticity, which is measured by the static flexure test and corresponds to a frequency of zero. For solid materials in general, E_{dyn} increases proportionally with increasing frequency, up to a finite limit (Pritz 1998). This increase is the consequence of the duration of the excitation and the non-causal response of the material, which is related to the dissipation of energy (Marra et al. 1966).

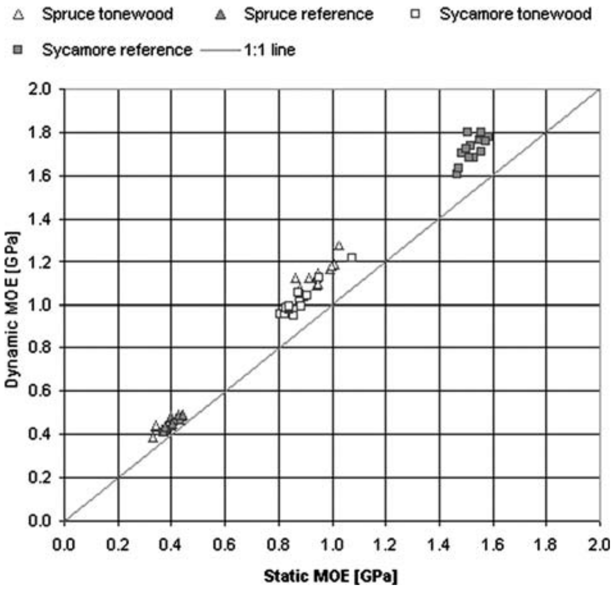

Fig. 3 Relationship of static and dynamic MOE in the radial direction for specimens of Norway spruce (*triangle*) and sycamore (*square*)

Influence of the resonance frequency on the damping factor

The damping factor (δ) in the axial direction was found to be 0.032 for Norway spruce and 0.043 for sycamore wood for a frequency of respectively 860 and 540 Hz. In comparison and for a similar frequency range, Krüger and Rohloff (1938) obtained values of damping factor δ equal to 0.028 for sycamore and to 0.024 for Norway spruce wood. Furthermore, Fig. 4, which represents δ as a

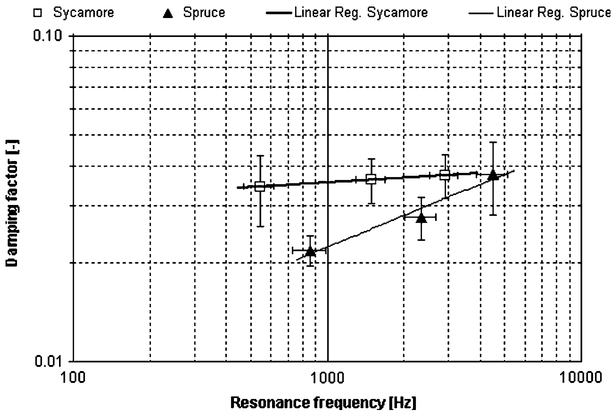

Fig. 4 Development of the damping factor in relation to the logarithm of the resonance frequency for specimens of Norway spruce (*triangle*) and sycamore (*square*)

function of the resonance frequency, shows that the measurements were less accurate when the damping factor was greater. It was also apparent that the damping factor δ increased exponentially with increasing resonance frequency. The coefficients of determination R^2 were 0.93 in spruce and 1.0 in sycamore. The increase in exponential form is in good agreement with the model for wood developed by Ouis (2002). In the frequency range between 10^2 and 10^5 Hz, Holz (1973) observed a similar increase of the damping factor, using two different measurement systems.

Another finding shown in Fig. 4 is that the damping factor (δ) increased more steeply with increasing resonance frequency in Norway spruce than in sycamore. The model of Ouis (2002) describes this very well with adapted values of the parameters. A chemical explanation has been proposed by Pritz (1998), who stated that the frequency dependence of dynamic properties is particularly strong in organic polymers with an amorphous structure. Over the frequency range of 10^2 to 10^5 Hz, the attenuation of sound waves and the corresponding relaxation mechanisms in polymers are usually associated with cooperative movements of large segments of the molecular structure (Dunlop 1978). The content of lignin, which is the principal amorphous polymer in wood, is higher in Norway spruce wood (25–29%) than in sycamore (21–24%) (Rowell 1984). Consequently, the lignin content, the crystallinity of the cell wall material and the structure of the amorphous zones of the cell wall are likely to be the most important factors influencing the frequency dependence of the damping of sound waves.

Influence of moisture content on the measured resonance frequency

When the resonance frequency of dried wood was compared with that of wood at different percentages of moisture-content, an inverse linear relationship was found (Fig. 5); the coefficient of determination R^2 ranged between 0.95 and 0.99 for the two species and the two directions of sound propagation. This effect was greater in the radial than in the axial direction and it was also greater in sycamore than in Norway spruce. Small differences between measurements of resonance frequency should, however, be considered in the context of the precision of the equipment, which was in the range of ±0.6% in the present study.

According to Akitsu et al. (1993), water acts as a plasticizer above 8% moisture content. The cohesive forces between molecules are decreased and the molecular movement is facilitated. The plasticizing effect of water is greater in the radial direction and in hardwoods, as exemplified by the radial specimens of sycamore wood in the present study.

Six relevant properties used to evaluate the quality of resonance wood

For Norway spruce wood, the results presented in Table 2 are in good agreement with those of Ono and Norimoto (1983). Specimens of normal (control) wood had a superior radiation ratio (R) but their annual rings were too wide, a feature that is

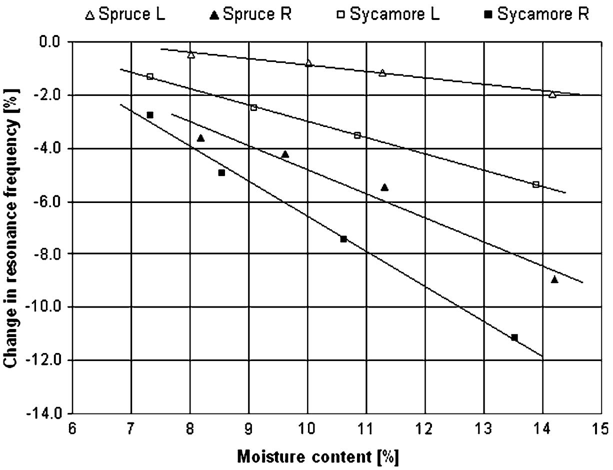

Fig. 5 Resonance frequency in relation to moisture content: percentage diminution compared with the resonance frequency of dried specimens/Axial (L) and radial (R) directions for specimens of Norway spruce (*triangle*) and sycamore (*square*)

considered by violin makers to be aesthetically disadvantageous. Of the two samples of resonance wood (A = good quality and B = very good quality), sample B had the lower density and the higher radiation ratio. Also, the overall value of E_{dyn} met the stiffness and strength requirements for a music instrument. Moreover, its radial value of E_{dyn} and its radial radiation ratio were very high. This characteristic is considered as decisive by Holz (1984) who defined "resonance wood" as wood having a radial MOE exceeding 500 MPa and with a latewood content lower than 20%.

For sycamore, the selection of resonance wood is first and foremost governed by its aesthetic appearance (violin makers prefer "curly maple"). Of the two samples of curly sycamore wood compared in Table 5, sample B (very good quality) showed a slightly distorted fibre alignment, whereas the distortion in sample A was strong and visible as axial "waves". This distortion represents an extended pathway for the axial propagation of sound waves, leading to greater attenuation than in sycamore wood with a regular structure. It was therefore not surprising that the values of modulus of elasticity, sound velocity and radiation ratio of resonance wood were approximately 10% higher in the control specimens (Table 3).

The results showed also that the radiation ratio in the axial direction was similar for sample A and B. The radiation ratio should therefore not be used as single parameter for an objective selection of curly maple wood for instrument making. On the other hand, the higher values of sound velocity and MOE that sample B showed in the radial direction were specific characteristics for high quality "curly maple". Additionally, sample B had a higher emission ratio in the axial direction than sample A and therefore did not damp the sound waves as much as sample A. In summary, a high value of emission ratio, particularly in the radial direction, and a high loudness index were decisive factors in characterizing resonance wood. In this study, these properties clearly explain the superior quality of specimens of sample B when compared to those of sample A.

Influence of macrostructure of wood

The width of the annual rings and the proportion of latewood are both regarded as important in the selection of resonance wood (Tables 4, 5). Wood with broad annual rings is rarely selected for resonance wood, mainly because of aesthetic requirements. Also, ring width can affect the density of the wood but the results of the present study showed no such relationship in Norway spruce wood, provided that the ring width was below 2.5 mm; this finding was consistent with that of Holz (1984). The density was however lower in specimens with an annual ring width higher than 2.5 mm and they showed a slightly higher radiation ratio (Fig. 6).

Latewood content is regarded as more significant than ring width for the characterization of resonance wood. In the present study, sample B of Norway spruce wood had a very low latewood content. This, combined with narrow annual rings, was typical of first-quality resonance wood. For sycamore wood, latewood content was less important but the overall density was crucial for resonance wood quality.

Light microscopy findings in relation to the calculated properties

The two samples of Norway spruce wood differed anatomically and histologically in a number of ways, which were consistent with their values of radiation ratio and sound velocity (Fig. 7). The wood cells in sample B, i.e. tracheids, had a smaller mean diameter (22.8 μm in the latewood, compared with 25.3 μm). Also, their walls were thinner (3.7 μm, compared with 6.3 μm) and the latewood was only 4–6 cell rows wide, as compared with 10–15 rows in sample A. Also, the structural

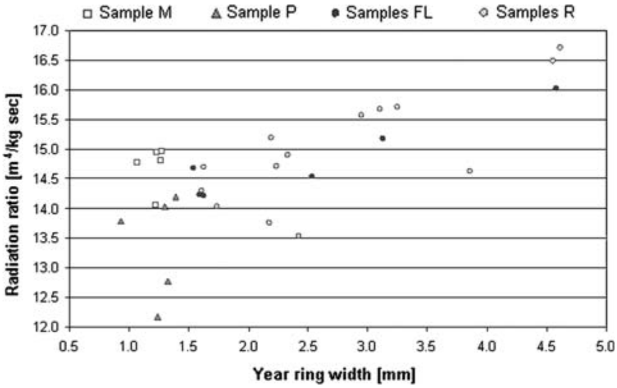

Fig. 6 Radiation ratio versus annual ring width. Norway spruce samples with identical letters were extracted from the same wood block

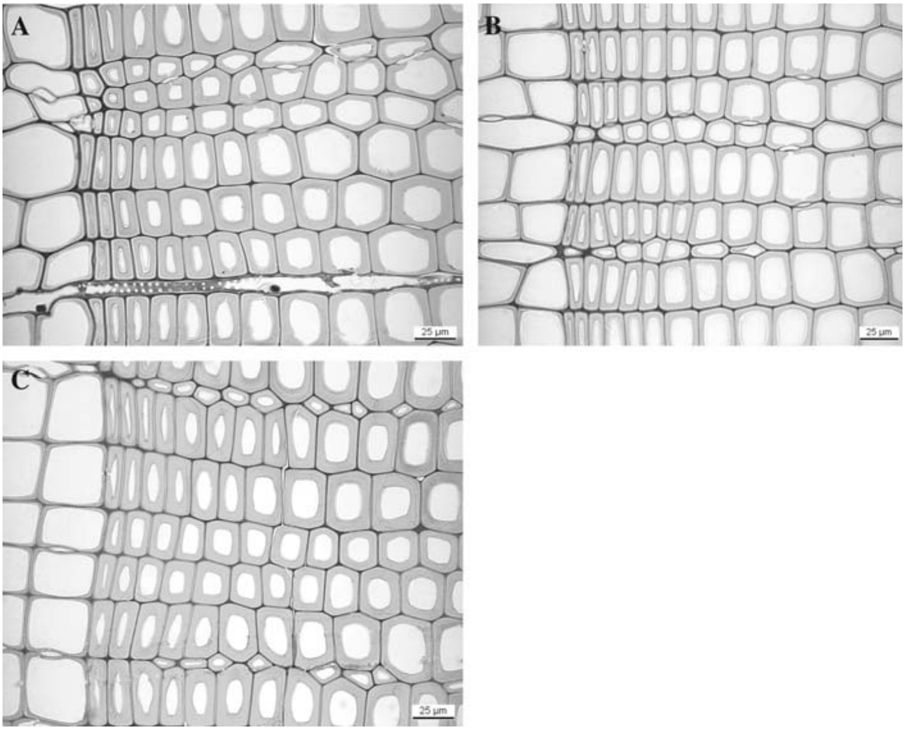

Fig. 7 Transverse sections of Norway spruce wood: (A) sample A from France/(B) sample B from Switzerland/(C) control sample

differences between the late- and earlywood were less marked in sample B than in sample A. These characteristics of sample B are typical for first quality resonance wood with a high sound velocity (Buksnowitz 2006). Also, the narrowness of its latewood seems consistent with its superior emission ratio, since Bucur (1995) found that the propagation of sound waves was hampered by a wide latewood zone.

The control sample of Norway spruce was similar to sample A with regard to the lumen diameter and the cell wall thickness of the tracheids. It had a wider latewood zone (12–18 cell rows) but also a considerably wider earlywood zone. As a result, the damping induced by the latewood zone was reduced, so that the emission ratio was higher than in sample A.

The samples of sycamore wood (Figs. 8, 9) differed mainly with regard to their xylem rays. Sample B had wider rays (6–8 cells wide) than sample A or the control sample (3–4 cells wide). The greater width of its xylem rays explains its high radial values of MOE and velocity of sound (Bucur 1995). Another difference was that the distance between two xylem rays was greater in sample B than in the control sample (Fig. 8). This can be directly related to the low emission ratio of sample B.

The proportion of latewood and the overall ring width was similar in all three samples and so showed no relationship with their acoustic differences.

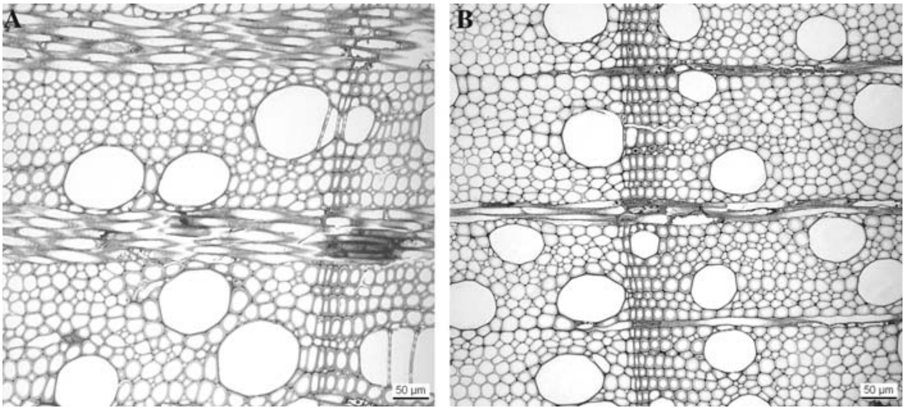

Fig. 8 Transverse sections of sycamore showing typical features of diffuse porous wood. (A) Sample B from Switzerland/(B) control sample

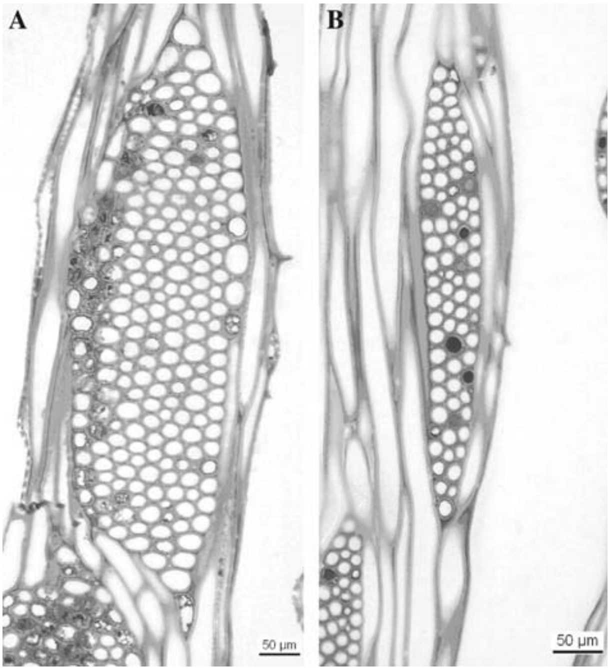

Fig. 9 Tangential sections of sycamore showing broad (A) and narrow xylem rays (B). (A) Sample B from Switzerland/(B) control sample

Conclusions

In this study, a method to assess resonance wood quality with improved objectivity was introduced, evaluated and critically discussed. Resonance frequency derived from vibration testing allows calculation of six important properties. Generally, a low density and high radiation ratio in the axial and radial directions are crucial properties for first-quality Norway spruce resonance wood. In addition, emission ratios and loudness index are valuable properties for estimating general resonance wood quality.

Comparison of the resonance wood quality of different wood specimens requires some precautions. Firstly, the resonance frequency measurements should always be conducted with the same apparatus under standard conditions. Secondly, the measurements should be taken over the same frequency range. Finally, the moisture content of the specimens should be strictly controlled.

Evidence is also provided that the wood structure and the size of the wood cells influence the value of some of the calculated properties. In Norway spruce, first-quality resonance wood has a homogeneous arrangement of small-dimensioned cells with thin walls, while in sycamore, high quality of resonance wood is associated with wide xylem rays. For future studies, it would be interesting to relate the acoustic quality of the wood to the chemical composition of the cell walls, particularly of the lignin content and its composition. Furthermore it would be of interest to develop a method for assessing all relevant elastic properties of tone wood specimens in real shapes and dimensions.

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