J Wood Sci (2006)
DOI 10.1007/s10086-005-0755-2

NOTE

**Loïc Brancheriau · Henri Baillères · Pierre Détienne
Joseph Gril · Richard Kronland**

Key signal and wood anatomy parameters related to the acoustic quality of wood for xylophone-type percussion instruments

Received: June 17, 2005 / Accepted: August 3, 2005

Abstract Wood percussion instruments have been part of culture since the earliest human societies. In making an instrument, the practical experience of musical instrument makers ensures its acoustic quality, especially with respect to selecting the most suitable wood species. The aim of this study was thus to gain further insight into the relationship between the physical properties and the perceptual classification of woods to be used in xylophone-type percussion instruments. A xylophone maker perceptually classified 58 tropical wood species, most of which are not usually used for musical instruments. Dynamic tests were then performed to record radiated signals. Key signal parameters pertaining to the acoustic quality of the material were extracted. Relationships between perceptual classifications, signal parameters, and wood anatomical characteristics were thus analyzed. It has been shown that percussive acoustic quality of wood, as determined empirically by the xylophone maker, can first be related to the temporal damping of the fundamental frequency. The samples tested in this study were not musically tuned; this could explain why no frequency descriptor was relevant. However, a draft anatomical portrait of a good acoustic wood could be drawn up. The organization of wood components in the tested species highlighted the importance of the regularity and homogeneity of the anatomical structures. The axial parenchyma seems to be the key trait. It should be paratracheal, and not very abundant if possible. The rays are another important feature; they should be short, structurally homogeneous, and not very numerous.

Key words Wood musical quality · Acoustic properties · Vibration · Wood anatomy

Introduction

Wood is used in making many musical instruments because of the indispensable physical and mechanical properties of this material. The sound quality of wood is perceptually assessed by musical instrument makers and musicians. It is essential to know what musical instrument or component is involved when assessing the "acoustic quality" of a wood specimen. Our study was thus designed to gain further insight into the relationship between the physical properties, anatomical characteristics, and the perceptual classification of woods to be used in xylophone- and marimba-type percussion instruments. Hence, a xylophone maker perceptually classified 58 tropical wood species, and, based on this classification, key signal parameters pertaining to the acoustic quality of the material were identified. These parameters were then correlated with the physical and anatomical properties of each wood. This article presents complementary results with those of "Classifying xylophone bar materials by perceptual, signal processing and wood anatomy analysis," to be published in *Annals of Forest Science*.

Materials and methods

Materials

Fifty-eight tropical hardwood species were selected within a wide range of density (from 210 to 1280 kg/m^3), without consideration of their known musical quality. For each species, a sample was cut with dimensions: 350 (L) × 45 (R) × 20 mm (T). The specimens were stabilized in a climatic chamber at 65% relative humidity and 20°C.

L. Brancheriau (✉) · H. Baillères · P. Détienne
CIRAD – Forêt, 34398 Montpellier Cedex 5, France
Tel. +33-467-616-517; Fax +33-467-616-560
e-mail: loic.brancheriau@cirad.fr

J. Gril
LMGC, Université Montpellier II, 34090 Montpellier, France

R. Kronland
CNRS – LMA, 13402 Marseille Cedex 20, France

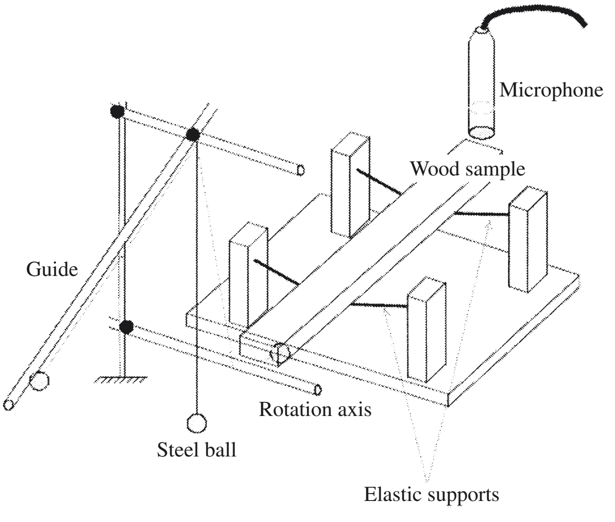

Fig. 1. Experimental setup for dynamic tests

Methods

Flexural vibration tests

The prismatic-shaped wood samples were set on two elastic supports (Fig. 1). A pendulum, consisting of a nylon cord (30 cm long) and a metal ball (diameter 14 mm, mass 12 g), was set in motion to trigger a vibration in the longitudinal direction of the wood specimen by hitting the end with the metal ball. An omnidirectional microphone was placed at the other end of the specimen to measure the acoustic pressure radiated at impact. Each signal measured by the microphone was recorded to allow an acoustic classification and a signal-processing analysis.

Perceptual classification

A xylophone maker conducted acoustic classification of the wood specimens on the basis of recorded sounds. He had no direct access to the wood specimens to avoid interactions with other perceptual senses (multisensory classification). A computer interface was designed and all sounds, represented by identical icons, were randomly distributed on the computer screen. The xylophone maker could click on an icon to listen to a sound as many times as he wished, and then he classified the sounds by sorting the icons in order of acoustic quality on the screen. The wood specimens were classified in terms of their "musical suitability" for xylophone bar material.

Key signal parameters

To extract relevant parameters from acoustic sounds, the concept of additive synthesis, described by Ystad,[1] was applied. Each temporal signal $s(t)$ was then considered as a sum of exponentially damped sinusoids:

$$s(t) = \sum_{i=1}^{\infty} \beta_i \exp(-\alpha_i t) \sin(2\pi f_i t + \varphi_i) \tag{1}$$

where s is the radiated signal as a function of time t, fi is the resonance frequency of the order i, and φ_i is the phase shift. The parametric method of Steiglitz and McBride[2] was used to simultaneously determine the first resonance frequency f_1, the amplitude β_1, and the temporal damping α_1 associated with f_1. Only the first frequency was considered because of its high energy; the determination error was then reduced to less than 0.1% for f_1, to 4.3% for α_1, and to 8.2% for β_1.

These parameters characterized real acoustic sounds but were not intrinsic parameters of wood material. The specific longitudinal modulus of elasticity E_L/ρ was calculated using the Bernoulli model.[3] The first vibration frequency depends notably on the specific modulus (Eq. 2) so this parameter appeared to be an appropriate descriptor. The wavelength corresponding to this frequency is about 40 cm.

$$f_1 = \frac{3.56}{L^2}\sqrt{\frac{I}{A}\frac{E_L}{\rho}} \tag{2}$$

A is the cross-sectional area, I is the moment of inertia, and L is the length. The combined use of additive synthesis models and waveguide synthesis also allowed the computation of the internal friction $\tan(\delta)$ using Eq. 3 associated with the complex modulus concept[4] with respect to transverse vibrations:[5]

$$\tan\delta = \frac{2}{\pi}\frac{\alpha_1}{f_1} \tag{3}$$

Results

Relationship between key signal parameters and acoustic classification

Eight samples that were outliers due to defects or cutting problems were excluded from the analyses so that the total number of samples was 50. A unitary distance between 2 samples in the acoustic classification was arbitrarily attributed in order to make the acoustic classification variable quantitative (with the best quality represented by number 1 to the worst quality represented by number 50).

No significant correlation was found between specific modulus E_L/ρ and acoustic classification (Table 1, $r = 0.04$). The samples tested were not musically tuned; this could explain why E_L/ρ (frequency descriptor) was not relevant. Another explanation was the sufficient narrow variability of the first frequency (with a mean value of 1008 Hz and a standard deviation of 96 Hz). The same result was found for the first frequency f_1 (Table 1, $r = 0.02$). The amplitude β_1, related to the sound intensity, was found to be irrelevant (Table 1, $r = -0.04$). However, a significant correlation was found between temporal damping α_1 and acoustic classification (Table 1, $r = 0.77$). Figure 2 shows the linear relationship between temporal damping α_1 and acoustic classification. The same linear relationship was found

Table 1. Pearson correlation coefficients for signal parameters and acoustic classification

	Classification	Amplitude β_1	Damping α_1	Frequency f_1	Specific modulus E_L/ρ
Amplitude β_1	–0.04				
Damping α_1	0.77*	0.08			
Frequency f_1	0.02	0.58*	0.25		
Specific modulus E_L/ρ	0.04	0.45*	0.29	0.95*	
Internal friction $\tan(\delta)$	0.77*	–0.17	0.89*	–0.21	–0.15

* Significant correlation at $P = 0.05$

Table 2. Species ranked at both extremes of the acoustic classification

Good acoustic quality			Poor acoustic quality		
Species	Temporal damping α_1 (s^{-1})	Internal friction $\tan(\delta)$ (s.Hz)$^{-1}$	Species	Temporal damping α_1 (s^{-1})	Internal friction $\tan(\delta)$ (s.Hz)$^{-1}$
Dalbergia sp.	12.17	0.0082	*Coula edulis* Baill.	24.95	0.0176
Hymenolobium sp.	14.74	0.0109	*Ongokea gore* Pierre	24.90	0.0176
Commiphora sp.	14.97	0.0091	*Manilkara huberi* Standl.	32.16	0.0221
Calophyllum caledonicum Vieill.	17.05	0.0115	*Pyriluma sphaerocarpum* Aubrev.	33.48	0.0208
Swietenia mocrophylla King	19.39	0.0123	*Letestua durissima* H.Lec.	26.19	0.0154
Pseudopiptadenia suaveolens Brenan	21.29	0.0125	*Manilkara mabokeensis* Anbrev.	26.16	0.0152
Simarouba amara Aubl.	20.90	0.0126	*Cunonia austrocaledonica* Brong. & Cris.	25.34	0.0192

Determination accuracy on α_1 = 4.3%, $\tan(\delta)$ = 4.4%

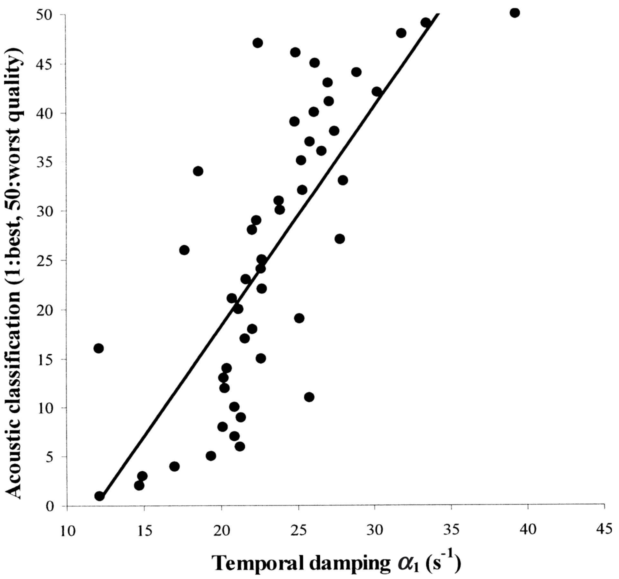

Fig. 2. Linear regression between temporal damping α_1 and acoustic classification ($R^2 = 0.60$ with $n = 50$)

between internal friction $\tan(\delta)$ and acoustic classification (Table 1, $r = 0.77$). We can explain these similar results by a sufficient narrow variability of frequency f_1, which leads to a low influence of f_1 in Eq. 3 regarding the acoustic classification.

Focusing on the internal friction, similar results were found in previous works. Ono and Norimoto[6] demonstrated that samples of spruce wood (*Picea excelsa*, *Picea glehnii*, *Picea sitchensis*), which is considered to be a suitable material for soundboards, had a high sound velocity and low longitudinal damping coefficient when compared with other softwoods. The cell wall structure could account for this phenomenon. Internal friction and the longitudinal modulus of elasticity are markedly affected by the microfibril angle in the S2 tracheid cell layer, but this general trend does not apply to all species. For instance, pernambuco (*Guilandina echinata* Spreng.), which is traditionally used for making violin bows, has an exceptionally low damping coefficient relative to other hardwoods and softwoods with the same specific modulus.[7,8] This feature has been explained by the abundance of extractives in this species.[9] Obataya et al.[10] confirmed the importance of extractives for the rigidity and damping qualities of reed materials. Matsunaga et al.[11] reduced the damping coefficient of spruce wood by impregnating samples with extractives of pernambuco (*Guilandina echinata* Spreng.).

Relationship between wood anatomy and acoustic classification

Anatomical study focused on species ranked at both extremes of the acoustic classification (seven samples with a good quality and seven with a poor acoustic quality, see Table 2).

The organization of wood components in the tested species highlighted the importance of the regularity and homogeneity of the anatomical structures, as remarked by Bucur.[12] It was notably observed that, in the range of frequencies used in this experiment:

Acoustic quality could not be explained by any vessel characteristics.

Fiber morphology did not seem to have a major impact on acoustic quality.

Axial parenchyma seemed to be the key trait (paratracheal, and not very abundant for good quality).

Rays were also an important feature (short, structurally homogeneous but not very numerous for good quality).

Acknowledgments The authors are extremely grateful to Robert Hébrard, musical instrument designer and xylophone maker, who gave useful advice and performed the acoustic classification of the wood specimens.

References

1. Ystad S (1998) Sound modeling using a combination of physical and signal models. PhD Thesis, Ecole supérieure de mécanique de Marseille, pp 7–12
2. Steiglitz K, McBride LE (1965) A technique for the identification of linear systems. IEEE Trans Automat Contr 10:461–464
3. Brancheriau L, Baillères H (2002) Natural vibration analysis of clear wooden beams: a theoretical review. Wood Sci Technol 36:347–365
4. Ouis D (2002) On the frequency dependence of the modulus of elasticity of wood. Wood Sci Technol 36:335–346
5. Brancheriau L (2002) Expertise mécanique des sciages par analyses des vibrations dans le domaine acoustique. PhD Thesis, Ecole supérieure de mécanique de Marseille, pp 97–125
6. Ono T, Norimoto M (1983) Study on Young's modulus and internal friction of wood in relation to the evaluation of wood for musical instruments. Jpn J Appl Phys 22:611–614
7. Sugiyama M, Matsunaga M, Minato K, Norimoto M (1994) Physical and mechanical properties of pernambuco (*Guilandina echinata* Spreng.) used for violin bows. Mokuzai Gakkaishi 40:905–910
8. Matsunaga M, Sugiyama M, Minato K, Norimoto M (1996) Physical and mechanical properties required for violin bow materials. Holzforschung 50:511–517
9. Matsunaga M, Minato K (1998) Physical and mechanical properties required for violin bow materials II: comparison of the processing properties and durability between pernambuco and substitutable wood species. J Wood Sci 44:142–146
10. Obataya E, Umezawa T, Nakatsubo F, Norimoto M (1999) The effects of water soluble extractives on the acoustic properties of reed (*Arundo donax* L.). Holzforschung 53:63–67
11. Matsunaga M, Minato K, Nakatsubo F (1999) Vibrational property changes of spruce wood by impregnating with water-soluble extractives of pernambuco (*Guilandina echinata* Spreng.). J Wood Sci 45:470–474
12. Bucur V (1995) Acoustics of wood. CRC, NY, pp 135–143

The publication of this article was made possible by an Emachu Research Fund. The authors are greatful for the fund.