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Dense and hard woods in musical instrument making: comparison of mechanical properties and perceptual "quality" grading

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Musical instruments are composed of parts which have different functions, and call for particular wood characteristics. Besides the lightweight "resonance wood" for soundboards, dense hardwoods appear in many parts: xylophone keys, drum barrels, woodwinds, bows, back, sides and necks of string instruments, and their fittings : bridges, tail-pieces and pegs, etc...Can the mechanical/acoustical properties of these woods be correlated to the perceptual "quality" choice made by instrument makers? The study is based on a sampling of 214 wood pieces from 60 species, classified in 3 groups : (i) tropical woods used in classical/modern making, such as ebonies and rosewoods ; (ii) European hardwoods with historical and/or traditional uses ; (iii) potential alternative woods, which might overcome current shortage in the supply of appropriate quality of preferred woods. Density and dynamic mechanical properties (modulus of elasticity and "quality factor" or damping) are measured by vibrational and ultrasonic methods, at the scale of the laboratory or of the workshop. We compare choices made by three makers, one of xylophones, one of violin accessories, and one of flutes, first between these three empirical grading, then by confronting them with measured mechanical properties. It appears that the "perceptual" selections by these three makers are different.

1 Introduction

In a long term research project on the acoustic of cello tailpieces, we are considering now the question of the choice of materials for making them. Historically, tailpieces have been made of European hard woods such as maple (supposedly at the end of the 17th century), ebony veneered maple (first half of the 18th century), solid ebony tailpiece (1766). On all instruments which have been modernized in the 19th c., and for instruments made from then, museum collections own numerous solid ebony tailpieces from the 1780's onwards, of slightly different shapes from 1800 to 1960's, when plastic and metal started being used. Boxwood and rosewood have also been employed for violin tailpieces in the 20th c., but seldom for cellos. Cheaper tailpieces made of softer European woods, colored in black or with ebony veneer. Here we explore other species of wood to find alternative materials with appropriate qualities, given the scarcity of good ebony, and the risk of using wood coming from illegal logging, for instance from Madagascar National Park, as it was shown that this practice is a real problem since the crisis in that country in 2009, although the protection law had been applied since 2000 [1].

The main criteria for makers to choose wood can be stability, homogeneity of the grain, hardness, flexibility, plasticity. Other than the obvious problem of commercial availability, the instrument makers need the wood to be chosen in order to be stable [2]. Dried and seasoned wood is critical, but the way the wood has been dried is generally not well known. The homogeneity of the grain gives makers two advantages, even with the anisotropic characteristic of wood: Plasticity and workmanship under the cutting tools (as opposed to abrasive tools) makes it quicker to work it, and a better chance to predict the reaction of the wood, with a part of repeatability, but only partial because not two pieces of wood are alike. Hardness, flexibility and elasticity, are chosen from studying the grain direction. [3]

Makers know they have to adapt to the wood they choose, and that resonance may be achieved differently depending on the quality of the wood they bought. A heavy wood can be thinned down, while a soft wood must stay thick. A heavy and soft wood may be bad news, while a light springy piece can give better results. Compromises are necessary to achieve the best possible instruments, or part of instruments.

We will study here physical parameters of samples of wood that will be used to make cello tailpieces and we will compare them with the choice of wood by three makers, in order to see if there are any correlation between what makers feel and think, and the physical parameters chosen.

2 Characterization of various woods in laboratory or workshop conditions

2.1 Studied material and selection criteria

A group of 214 samples of 60 different woods species was gathered:

- 19 different species of precious and semi-precious European hard woods: boxwood, hollywood, zyzyphus, Sorb, Dogwood, Plum tree, Pistachia),
- 14 species of tropical hardwoods traditionally used in musical instrument making today: diverse types of ebony, rosewoods, padouk and pernambucco.
- 27 species of alternative tropical hardwoods to replace endangered species: Purpleheart, Tabebuia (Trumpet tree, Ipe), Mussutaiba , Massaranduba, Ferreol, Cumaru, etc.

The blocks were cut as blanks of 24 x 7 x 1, 8 cm. These dimensions are not what would usually be chosen for dynamic mechanical analysis, whose lengths need to be much longer than the width in order to measure essentially the bending motion of the samples and to minimize the torsion modes in lower frequencies [5]. The ratio Length/width is here 3.4. So it is not fully possible here to compare the modal analysis with that of a beam model, as some twisting modes operate here at lower frequencies and are stacked over or in between bending modes.

Certain species with interlocked, wavy or crossed grain, or with accidents such as knots, will add difficulty for studying this anisotropic material.

2.2 Mechanical/acoustical methods

Conditions of study:

After the wood was cut, it was left for seasoning for more than six months in a workshop, and 22 samples have been measured three times between October 2010 and July 2011 in the workshop, in different hygrometric conditions.

Then, the blanks were measured by three different methods: The BING® analysis system for testing the quality of wood (CIRAD, Montpellier), the Stoppani Software (Manchester), and the Lucchi ultrasound elasticity Tester (Cremona) which is often used in violin and bow makers workshops.

Methods

The BING® apparatus and method, developed by the CIRAD in Montpellier is a measurement device that calculates the elasticity and the damping factors of beam like wood samples.

The test was made on 178 pieces resting on elastic bands, such as to be considered as vibrating freely, each test being repeated three times. A marble falls on the end of the wood block, and a laser sensor registers the displacement. The spectra of the flexing wave is registered as a Fourier transform, then the modes are extracted by calculations in order to find the lengthwise (axial) elastic modulus E, as well as the quality factor Q, and its inverse the damping coefficient (or internal friction) *tanδ*.

The FRF (frequency response function) calculations done with the violin maker George Stoppani's Software by impact hammer/accelerometer measurements of samples, also lying on elastic bands, give a dynamic mechanical analysis [4]. A specific application allows finding and simulating the modal shapes and movements of plates, originally designed to do modal analysis of violin bodies in violin makers' workshop. Another series of measurements on 8 specimens was hammered in 18 points in order to visualise the repartition of the modes, which are more complex than a beam deformation, as we have already mentioned, because of the larger width of our samples.

Each of the 214 samples, lying in similar conditions than for the BING® test [5], was hammered 10 times, with a PCB hammer weighing 2 grams. The acquisition was measured in one point of the piece by an accelerometer weighing 0.6gramms.

The resulting FRF curve permits to extract then the modes, to get the lengthwise elastic modulus E, as well as the quality factor Q.

The Lucchi elasticity tester was developed by the Cremonese bow maker Giovanni Lucchi, in order for him to sort out wood qualities at the saw mill or in the workshops. This apparatus measures the ultrasound velocity between two electrodes pressed against the two end grain sides of a piece of wood. Here, it is the analysis of the compression wave that allows the calculation of the speed of the ultrasound, and then the calculation of an elasticity modulus. This test has been done with two different apparatus for 21 test pieces, and then only one times on the 135 other specimen.

2.2.1 Comparison of values obtained by the different methods

Measurement of uncertainty of the FRF method was assessed by running 40 repetitions on two specimens, one with homogeneous structure and response, and one with interlocked grain and giving double peaks. Uncertainty, calculated as (1.96×standard deviation/mean) was ≤0.1% for the 1st Eigen frequency, and of 3% in average (4.5% in the « worst » conditions) for the quality factor Q. This is smaller than previous estimations for BING (≈7% on damping in Brancheriau et al. 2010) [6]. On 167 specimens, the variation in Q between 3 BING repetitions was of 7% in average; however, variations exceeded 16% for nearly one third of tested specimens. Repeatability of the Lucchi-meter was not evaluated as above, however, it showed a good reproducibility between tests run on 21 specimens in two different workshops with their own equipments (the ratio between measured velocities was close to unity: 0.98, with a R^2 of 97%).

As could be expected, there was a very good concordance between bending modes frequencies measured with BING or FRF in close hydrothermal conditions (Figure 1 left), with the exception of some specimens with inhomogeneous structure giving double-peaks. For the quality factor Q, although dispersion was higher, both measurements were well correlated for the 1st bending mode (R^2=88% after eliminating the biggest discrepancies which are due to the presence of double peaks). There was, however, a systematic bias: Q values were in average 12% lower by FRF than by BING, leading to values of internal friction tanδ 16% higher in average by FRF (Figure 2). It should be noted that for the 2nd bending mode, Q values were inconsistent, for both methods, and will not be used hereafter.

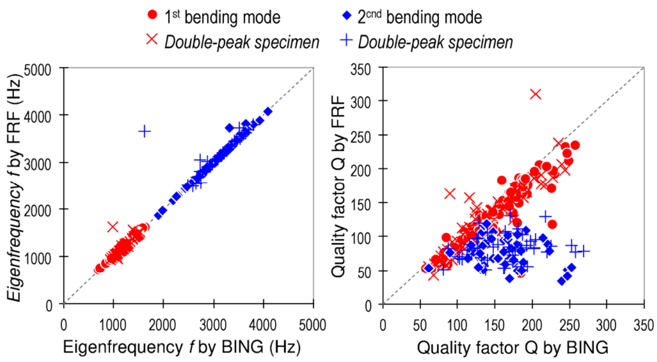

Figure 1: Comparison of raw data (eigenfrequencies and quality factors of the 1st and 2nd bending modes) obtained on 179 specimens by "BING" and "FRF" methods, before any data sorting.

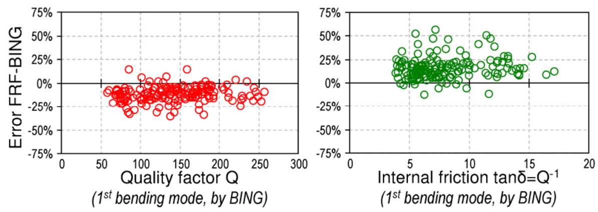

Figure 2: Error in values of damping parameters Q and tanδ between FRF and BING tests.

The different resulting evaluations of specific dynamic modulus (E'/ρ, modulus of elasticity divided by density) are compared in Figure 3. The calculation according to Timoshenko theory (i.e. taking into account the effect of shear in bending vibrations) with BING method is taken as reference. Calculations by Bernouilli theory (neglecting shear) are very consistent between BING and FRF, as measured frequencies are. They are well correlated (R^2=93% for FRF) to "reference" values, but the error increases with increasing E'/ρ (i.e. Bernouilli estimation gets much lower than Timoshenko), as high E'/ρ is usually correlated to high axial-to-shear anisotropy. Estimations of E'/ρ by ultrasonic velocity are generally higher than in the audio range, as is usually observed. However, the difference decreases, in a non-linear way, with increasing specific modulus of tested woods.

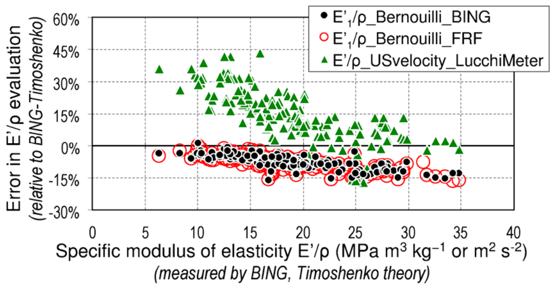

Figure 3: Error in values of specific dynamic modulus of elasticity calculated from 1st bending frequency (by Bernouilli theory, BING or FRF) or ultrasonic velocity (Lucchi-meter) relative to values according to Timoshenko theory (BING), after elimination of outsiders.

2.3 Variations in workshop-based measurements with seasons and hygrometry

A sub-sample of 22 specimens, representative of the range in properties observed over the general sampling, has been measured successively three times during a year, using the FRF method, in workshop conditions (i.e. not regulated in hygro-thermy). Compared to measurements made in February (17°C and 40% relative humidity RH), tests conducted in summer (July then early September, with conditions of circa 21°C and 70%RH) gave values of E'/ρ slightly lower (-4%) and of internal friction (tan*δ*) clearly higher (at least + 13% in average). These trends are consistent with known general effects of moisture content on dynamic properties (Obataya et al. 1998) [7]. Measurements of E'/ρ were strongly correlated between summer and winter (R^2=98%), whereas there was more dispersion for tanδ (R^2=86%).

2.4 Synthesis of assessed properties on all studied wood samples

The mean values of basic properties (ρ, E', E'/ρ and tanδ) of the wood species under study are compared in Figure 4. BING data were used, as their values of damping were previously found to be consistent with other well-established methods (Brancheriau et al. 2010)[6], which thus allows to compare our woods with the collection of data on 450 species by Brémaud (2012)[8].

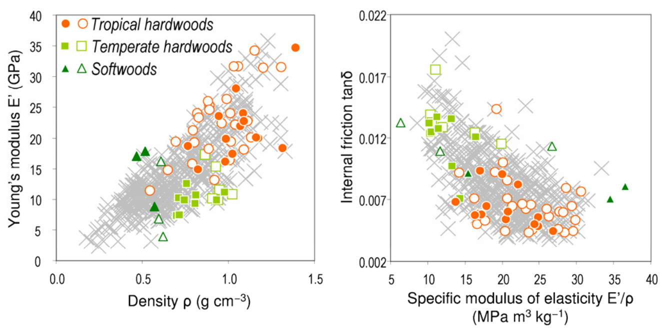

Figure 4: Mean values of density, Young's and specific modulus and damping coefficient tan*δ* for the studied species, compared to 450 species from Brémaud 2012 (grey crosses). Filled symbols: woods used in different types of instrument making; open symbols: species lesser-known for this use.

The hardwood species studied in our work are indeed mostly denser than the global average for woods (≈0.75g cm^{-3}), with some in extreme values. Previously reported trends in properties between categories are also observed between the studied temperate (lower rigidity and higher damping) and tropical hardwoods. Present data support previous observations that very low damping is a characteristic of tropical hardwoods. Some of the lesser-known temperate hardwoods sampled in this study show, however, densities quite "extreme" for this category.

3 Qualification by different makers on a sample of studied wood parts

3.1 Methodology of the perceptual grading

Three professional instrument makers have contributed to a rank-order association test. Claire Soubeyran (CS) is a baroque, classical and romantic period flute maker, and restores old wooden flutes. She chooses her wood on sensation of weight, colour, smoothness of touch, and doesn't really take into account the sound of the wood samples stroked I any manner. Nikolaus Warneke (NW), originally a classical organ builder, has evolved, following his interest for Western Africa language and music, towards *Balafon* making, an African xylophone. Eric Fouilhé (EF), a maker, searcher and copyist of modern and period fittings and accessories for violins and cellos, has made quantity of high quality tailpieces and pegs.

NW and EF have first sorted out by eye and by ear 213 wood samples, and eliminated 131 they found not as good (to short, too thin or not interesting for the xylophone) and rated the 76 resting left in order of preference.

From these 76 pieces rated from 1 to 76, the first rated 1 to 30 were chosen, and the worst 30 rated from rank 47 to 76 also.

Class I is made of 10 pieces that were taken out of the 30 better, (but one of the 30 better pieces broke during the test, leaving us with 29 pieces) on the criteria of wood diversity.

Class II is composed of 10 pieces of the lot n°47 to 76, also chosen for a good diversity of wood species.

Class III, is a choice of diverse pieces from the 131 eliminated, the "worse" blanks, chosen for species diversity.

Each maker had his personal taste for different uses of the wood, but all three are used to the same species of wood in their workshop practice. The unusual situation was that of the shape of the blocks, much larger than the blocks used for flutes, and shorter than the dimension of xylophones blades. The samples lying in a line on a table were freely examined and ringed near the ear by NW and EF. Then they were ordered by each maker from 1 to 29 from the piece judged best to the worst.

Test A was done twice by NW, who chose "good wood for a xylophone", which he thinks has to have a "good attack", and "easy development ". He chose primarily with the ear, by hitting the piece with a xylophone hammer in the center, while holding it between two fingers laterally on the edges at the node level of the bending first mode.

Test B was done by NW again, twice: The criterion was “a long ring”, chosen with the ear. The maker thinks this choice is different from the first one.

Test C, was done twice by EF, violin fittings maker, his criteria was “good wood for a nice and good tailpiece”. He chose by eye and touch (weight, fineness of the grain) as well as by ear, in striking the wood by the same method as NW.

Test D was done once by CS, her criterion was “wood to make a good and beautiful flute”. She chose nearly exclusively by touch and did’nt stike the wood with the xylophone hammer, but sometimes tapped it gently with her fingers.

3.2 Repeatability of the grading done by two makers

For the 30 rated samples the repeatability is 91% and 93% for the A and B test done by NW, and 89% for the C test by EF.
It is interesting to note the ranking repeatability of the makers shows their empirical ability in their wood grading choices.

3.3 Similarities and differences in the choice made by makers of different parts and families of instruments

The sound seems to be the criteria for NW. The two other makers are more sensitive to the weight, the texture, the colour and the regularity of the grain.

For vibration blades, such as xylophones’ blades, the link between physical parameters and sound perception seems to be more obvious: the Q factor is directly linked, and the position in the frequency domain of modes 2 and 4 are specific for the distinctive sounds of Marimbas and Xylophones.

For cello tailpieces however, more complex in their geometry and because they will be used on the stringed instrument under tension, the possibility of making a direct relationship between the ringing wood and the finished instrument is inexistent for the time being.

The two ratings A and B by NW were, for him of a different nature: in test A he classified wood for xylophones, while in test B, he privileged the duration of resonance after ringing. But it appears that the correlation between A and B is superior to the repeatability intra-class in A and in B: the result gives a sorting of pieces which is not significantly different between A and B.

The correlations AC and BC between the classification of NW and EF are inferior to 68%, showing a significant difference in the choice of the two makers.

3.4 Relationships between sensorial qualification and mechanical/acoustical properties

In order to better understand the selection made by the three makers involved in this study, we searched for correlations between their respective grading (A, B, C, D, from 1= best to 30=worst) and wood descriptors. These included:

- Material properties (ρ, E’, E’/ρ, tanδ)
- Material “performance indexes” (“characteristic impedance” z ; “radiation ratio” R; “acoustic converting efficiency” *ACE*), see e.g. Wegst 2006[11]:

$$z = \sqrt{E\rho} \quad (1)$$

$$R = \sqrt{E/\rho^3} \quad (2)$$

$$ACE = \frac{\sqrt{E/\rho^3}}{\tan\delta} \quad (3)$$

- Simple signal descriptors: frequency of the 1st bending mode *f1*; ratio between 2nd and 1st frequency (*f2/f1*); bandwidth (=quality factor Q) of the 1st mode and its temporal damping ($\alpha=\tan\delta\times f\times\pi$); presence of double peaks (*dp*, coded as 0-1-2).
- Basic descriptors of wood grain: fineness (*fg*, 0=very fine; 1=medium; 2=coarse) and orientation (*sg*, from 1=straight to 4= interlocked and 5=wavy).

Several of these indicators are correlated between them (Figure 5) and this should be taken into account when observing their correlations with the perceptual gradings done by the 3 instrument makers (Figure 6).

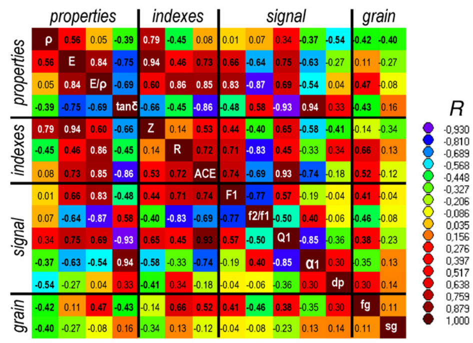

Figure 5: matrix of correlation between the different wood descriptors used.

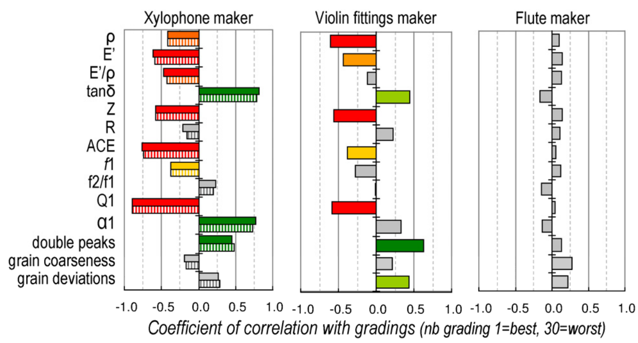

Figure 6: Coefficients of correlation between indicators (material properties and indexes, signal descriptors, wood grain) and grading by the 3 makers. N=30. NB: for

xylophones, filled bars=overall quality, hatched bars: "length of resonance".

The first observation is that the number and significance of correlations with wood descriptors decreases between the grading for xylophones, cello tailpieces, and flutes. This sounds consistent with the expected respective influence of wood vibrational properties in these different parts/families (e.g. Wegst 2006[9]). No significant correlation appear for the "flute" grading, however finer descriptors of wood grain/porosity and surface properties might be needed in this case. Grading done by the xylophone and violin fittings makers show some common trends but also some dissimilarities. Damping-related descriptors (tanδ, ACE, Q, α) account for all the highest significant correlations for xylophone choices. This seems consistent with previous findings (e.g. Aramaki et al. 2007[10]). By comparison, for tailpieces, density and "double peaks" appear as being as much, or even more, correlated to the grading.

Frequency parameters are not or very weakly related to grading. Even for the xylophone maker where a significant (at a level of 5%) correlation appears with $f1$, this is weaker than the related material property E'/ρ, and temporal damping ($\alpha=\tan\delta\times f\times\pi$) has a less strong correlation to grading than tanδ or Q. The presence of double peaks, on the other hand, is negatively correlated with the grading by the xylophone or quatuor fittings makers. This is particularly true for the later maker, where the presence of double peaks has the highest absolute value of correlation with grading, which is most probably related (cause or effect?) to the fact that this maker's grading is the only one to be correlated to grain deviations (material in-homogeneities that can cause double peaks).

In all cases, frequency parameters are not or very weakly related to grading.

The variety of wood species measured and used in the sorting tests will allow us to propose alternative wood for instrument making in a future analysis.

4 Conclusion

In the three methods that were compared, BING and FRF are very consistent, as the measured frequencies are. They are well correlated (R^2=93% for FRF) to "reference" values, but the error increases with increasing E'/ρ probably due to high axial-to-shear anisotropy. The Lucchi meter shows higher values but this difference decreases with increasing specific modulus of tested woods.

The different climate, in workshop's conditions, due to dryer climate in February (40% HR), and wetter conditions in July and early September (70% HR) gave two latest values of E'/ρ slightly lower (-4%) and of internal friction (tanδ) clearly higher (at least + 13% in average) as could be expected. Measurements of E'/ρ were strongly correlated between summer and winter (R^2=98%), whereas there was more dispersion for tanδ (R^2=86%).

Choice of wood by three makers showed significant differences between them. The xylophone maker NW has a mean repeatability 92% in choosing his wood, which he does clearly by ear, with a good correlation with the acoustical properties, specially damping-related descriptors (tanδ, ACE, Q, α) and temporal damping ($\alpha=\tan\delta\times f\times\pi$). The violin fittings maker EF chose his wood with criteria more closely associated to material property such as density, lack of grain deviations and homogeneity (no double peak). The flute maker CS 's choice had practically no correlation with mechanical/acoustical properties, and more descriptors on porosity and surface properties may be needed.

Acknowledgments

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