What do we know on ” resonance wood ” properties? Selective review and ongoing research

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Amongst the many different wood species used in musical instrument making, the term "resonance wood" usually refers to material for soundboards of strings (in Western classical instruments, principally softwoods and mostly spruce: *Picea abies* or spp.). As material properties of soundboards are believed to play a significant role in the acoustic behaviour of a completed instrument, many references have dealt with "resonance wood" for nearly one century. This paper aims at depicting this landscape, focusing on wood vibrational properties, their natural variability and microstructural determinants, and how they are influenced by external factors. Some characteristics of "resonance wood" are quite well known (range of density, of specific dynamic modulus of elasticity and viscoelastic damping along the grain), whereas others are still not fully characterised (anisotropy and frequency dependence). The interactions with hygrometry or various "treatments" (biological, chemical, thermal or "ageing") are also the object of ongoing research. Finally, the essential definition of "resonance wood" is the fact that it is selected by makers and effectively used for building an instrument's soundboard. However, this has been little studied. It calls for interdisciplinary approaches connecting the empirical criteria of evaluation used by luthiers, with wood mechanics, material perception studies, and (psycho-) acoustics.

1 Introduction

Wood is the main constitutive material of many kinds of musical instruments and as such it plays a major role in their design and construction process. The repercussion of wood properties in the behaviour of a completed instrument may be primarily acoustical, or mechanical, aesthetical, or a combination, depending on the families and parts of instruments. Although several hundred of wood species are employed in various instruments and geo-cultural ensembles [1], in the collective mind the first thought would probably be "wood for violins", due to the cultural importance of strings in the Western classical music. The soundboards of violins, but also of pianos, most guitars, etc, is essentially made from spruce (*Picea abies* or sometimes other *Picea* species). The material "quality" selected for this use is usually referred to as "resonance wood" [2, 3].

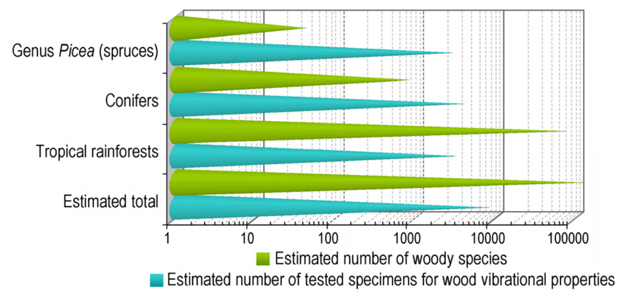

Figure 1: Comparison of estimated number of wood species of different origins, with number of data for viscoelastic vibrational properties (as collected in the database presented in [1]). Only 5 to 10% of existing species have been characterised and spruce (*Picea*) species account for more than 1/3 of available data.

"Resonance spruce" has drawn since a long time the interested of many researchers into musical acoustics, wood mechanics and forestry alike, resulting in the widest existing corpus on mechanical/acoustical properties for a single species (Figure 1). This makes it a good "model" for understanding wood acoustical behaviour and its multi-scale determinism [4]. Furthermore, the notion of "instrument making wood" involves many interactions between disciplines, and the wealth of cultural knowledge on this wood makes it, here again, an excellent model for studying the "tree to music" system.

The general aim of this study is to review the different aspects involved in the notion of "resonance wood", focusing mainly on the mechanical/acoustical features and their multiple dependences (biological variability, physical conditions, treatments…) and consequences for instrument making. An attempt is also made at placing the subject in the wider context of current knowledge in wood science or of other instrument making woods. Given the impossibility of detailing an important corpus of literature within a very short paper, the accent will be put on trying to identify the questions which remain lesser-studied or even un-solved.

2 Collection of references and information

During a more than 10 years research on wood viscoelastic properties and uses in musical instruments, more than 350 references have been collected by various means, including scientific publications, technical sources and ethnographic or historical materials. A significant part of the collected information was gathered in a relational database specially developed on the topic [1], which notably includes most of published data on viscoelastic vibrational properties of wood. The priority goal was to explore the diversity (both biological and cultural) of wood used or usable in instruments.

In the attempt of getting a more exhaustive survey for the special case of spruce resonance wood, systematic searches were recently done with main bibliographic databases, with Boolean query terms (["wood*" OR "timber" OR "spruce"] AND ["resonan*" OR "music*" OR "violin" OR "string*"] NOT ["wood"=Author]). Raw outputs differed widely both in number and in focus between searched databases. Overall, after sorting out all irrelevant references and eliminating duplicate entries, the searches with ISI Web of Science and Scopus yielded 305 references with at least a slight link to the topic of material properties in musical instruments. Further sorting is in progress to extract entries directly linked to "resonance wood" itself. However, one first observation is that, amongst these search results, many very relevant references (that we knew of by more manual "old-fashioned" means of bibliographic search) were not retrieved. This mostly applies to references published prior to 1990 or so and/or in non-English journals, which is a serious drawback of consulted databases, given that a lot of relevant early research came notably from Japan, Germany or Eastern Europe. More logically, several of the references bringing important insights into the general topic are fundamental studies on wood behaviour which were not directly identified by the above search terms.

The two sets of references are currently being merged together, with the aim of producing (i) a quantitative "bibliometric" analysis of the different disciplines and topics addressed in the "resonance wood" system; (ii) a classified and annotated table of references, which we hope could be useful to other researchers or craftsmen. In the present paper, we survey the different subjects which are directly related to wood mechanics/acoustics, focusing on issues which would need further research.

3 Mechanical/acoustical properties of "resonance wood" as compared to biodiversity

3.1 Properties along the grain

Basic properties relevant for soundboards are the density (ρ); specific modulus of elasticity (E'/ρ, proportional to resonance frequencies and to sound velocity) and the viscoelastic damping coefficient (or internal friction) tanδ. As response seldom involves one single property, various "material performance indexes" have been designed to describe the contribution of wood in a soundboard [5], such as the *characteristic impedance* $z=(E\rho)^{1/2}$ ("difficulty of transmission from one media to another"); the *radiation ratio* $R=(E/\rho^3)^{1/2}$ ("average loudness"); or the *acoustic converting efficiency* $ACE=([E/\rho^3]^{1/2})/\tan\delta$ ("peak response").

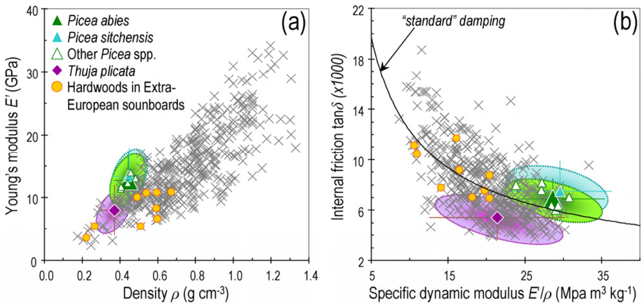

Figure 2: Average density and Young's modulus (a) and vibrational properties (b) along the grain for soundboard woods, compared to 450 woody species (crosses[1]). Ranges are indicated for "resonance wood" of Norway and Sitka spruce and Western red cedar (*Thuja plicata*).

Resonance wood of spruce has rather, but not extremely, low density (≈0.43 g cm^{-3} in average) and damping (≈6.9 10^{-3} in average), whereas it has very high values of E'/ρ (up to 36 MPa m^3 kg^{-1}, leading to sound velocities of about 6000 m s^{-1}). Other woods with such high E'/ρ are mostly other species of *Picea*, or some rare tropical hardwoods with very high densities. As a result, the "radiation ratio" of resonance spruce is much higher than most other woods; however, lighter species have much higher values of this index (some light hardwoods in extra-European instruments, or balsa). In terms of ACE, spruce is exceeded by western red cedar used in guitars, which is "softer" but also lighter and with a lower damping. Other *Picea* species, including Sitka which is also used for soundboards, have properties closely related to resonance Norway spruce. On the contrary, woods used in extra-European chordophones are very notably different.

3.2 Anisotropy and frequency dependence

Wood in general is highly anisotropic, following a cylindrical orthotropy. Axial-to-transverse anisotropy is important in determining vibrating modes of plates. Furthermore, most of the apparent frequency dependence of wood vibrational properties in bending vibration is due to the contribution (increasing with mode order) of shear properties, so that the axial to in-plane-shear anisotropy of both E'/ρ and tanδ plays a strong role in defining spectral features and timbre [4]. Softwoods have higher ratios of anisotropy than hardwoods, and resonance spruce in particular is amongst the most highly anisotropic woods. However, if quite many data exist on the elastic anisotropy [2], much less is known on the viscoelastic (i.e. including damping) anisotropy. Although data on at least some of the anisotropic ratios (mostly axial to radial and axial to in-plane-shear) for both storage moduli and internal friction could be collected for circa 100 wood species [6], full sets of viscoelastic anisotropic properties – i.e. 3 Young's moduli (R,T,L) and 3 shear moduli (LR, LT, RT) and associated damping factors – are extremely scarce or non-existent on a single sample. Even in the case of spruce. Moreover, it seems that virtually no sets of reliable experimental data on Poisson's loss factors are available for wood in the audio range. Although they might in some cases be neglected in mechanical/acoustical models, getting at least realistic approximations might be interesting.

3.3 Hygro-mechanical couplings

As is well known, wood is a quite hygroscopic material, and its mechanical properties are strongly affected by its moisture content. However, relatively few works have addressed the conditions relevant for musical instruments. A reference work [7] details the effects of moisture content (in equilibrium state) on dynamic mechanical properties of "resonance wood quality" Sitka spruce.

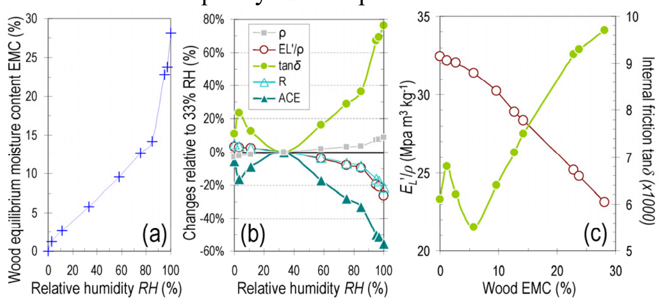

Figure 3: Relation between humidity and "acoustic" properties of Sitka spruce at equilibrium state, redrawn from [7]. (a) sorption isotherm; (b) changes in properties with surrounding relative humidity RH, normalised to values at 33%RH; (c) evolution of E'/ρ and tanδ depending on wood equilibrium moisture content.

Moisture dependence has a much higher amplitude and less "linear" profile for damping coefficient than for elastic properties, and as a consequence in "performance indexes" ACE is much more affected than R. tanδ exhibits a minimum (and ACE a maximum) around 6% EMC – 33% RH. Additionally, the profile of the dependence of E'/ρ, and especially of tanδ on wood equilibrium moisture content can vary with:

- Directions of anisotropy (stronger moisture dependence across than along the grain [8])
- Differences in chemical composition. Little relevant in natural "resonance spruce", but applied treatments can strongly modify its moisture dependency.

Furthermore, results above concern wood in equilibrium state (i.e. kept for at least 2 weeks in given regulated conditions). Studies on non-equilibrium moisture dependence of vibrational properties show that tanδ increases much faster than wood moisture content does (in adsorption) and that it also increases suddenly in the first stages of *desorption*, before diminishing again along with MC [9]. This effect of transitional destabilisation has an obvious relevance for musical instruments, which undergo climate changes in playing context. However, it has been studied only over quite extreme variations in RH (35 to 81%), and little is known on its amplitude for smaller differences in RH. Additionally, the repeated application of vibrations can accelerate the "stabilisation" and reduce tanδ of a few %, which may be related to the "playing in" effect often evocated by luthiers.

4 Structure-properties relationships and natural variability

As a biological material with a complex hierarchical structuration, the macroscopic behaviour of wood derives from the nested contributions of the different scales. This is of course a topic much more general than the present case of "resonance wood", but is essential for the understanding or prediction of changes in acoustic properties due to biological variability and/or to applied treatments. Luckily, spruce has often been taken as the study material for such fundamental researches, given that its structure is relatively homogeneous and "simple" as compared to wood species diversity. However, several of the questions of importance in the case of instrument making, such as factors affecting viscoelasticity in the audio-frequency range, have been far less (or not) addressed in multi-scale approaches, than static properties.

4.1 Nano scale, chemistry and hygro-viscoelasticity

Fundamentally, wood can be considered as a hetero-polymeric composite material. Its constitutive matter is composed of two types of sugar-based polymers (cellulose and hemicelluloses) and one phenolic polymer (lignins). Cellulose forms highly crystalline microfibrils which are very stiff (axial Young's modulus ≥100GPa), elastic, and little accessible to water. They are "embedded" in a relatively amorphous, softer matrix (E≈4GPa) formed by hemicelluloses (highly hygroscopic) and lignins (highly viscoelastic).

At this scale, features that mostly influence the macroscopic viscoelastic vibrational properties are (i) the degree of cristallinity of cellulose [10] and (ii) the nature and properties of the "matrix" [4]. They affect most strongly tanδ of wood. Unfortunately, there are no reliable experimental data on the loss factor of the matrix at audio-frequencies. However, viscoelasticity in this domain is mostly attributed to lignin, and appears to be modulated by the different compositions in monomers and degree of condensation that can be found in lignins from different wood types or species [11]. However, it is not known if such differences can have a detectable influence within normal wood of a single species, such as between different "qualities" of resonance spruce.

Furthermore, additional compounds of low molecular weight can be naturally "incrusted" in the polymeric material ("extractives" deposited during the formation of heartwood) and some of these are able to modify tanδ by up to a factor 2 [4,12]. Such phenomenon does not appear in resonance spruce which contains little extractives, however, it can be applied as a "natural chemical treatment" and has been tested with some success in spruce soundboards.

This scale has the biggest influence on macroscopic damping, and is also the one most affected by hygro-mechanical couplings or different types of wood treatments.

4.2 Micro scale: the prime importance of cell wall organisation

Wood is formed by "tubular" cells which are empty, very slender (length to diameter ratio >100 in spruce) and mostly arranged in parallel along the axial direction. Therefore, along the grain, E'/ρ and tanδ of wood are proportional to those of the cell walls. These are organised as a multilayer, fiber-reinforced composite. Crystalline microfibrils of cellulose are deposited, parallel to each other, forming a helix around the cell. When the "microfibril angle" (MFA) with respect to the cell axis is small, the axial behaviour is dominated by the stiff and elastic microfibrils; when this angle is wider, the contribution of the soft and viscoelastic matrix increases. That is, with increasing MFA, E'/ρ decreases and tanδ increases. This co-dependence on MFA generally results in a strong correlation between tanδ and E'/ρ [4,13]. Only differences in matrix chemistry/viscosity can shift this relation to lower or higher values of tanδ, as illustrated in Figure 4.

This scale has the biggest influence on macroscopic specific modulus of elasticity and sound velocity along the grain, and also affects axial-to-shear anisotropy to a great extent [4]. Microfibril angle is determined during wood formation, that is, it is essentially related to natural variability, but could hardly be affected by treatments. On the other hand it would be interesting to better understand how it is related to environmental conditions of growth.

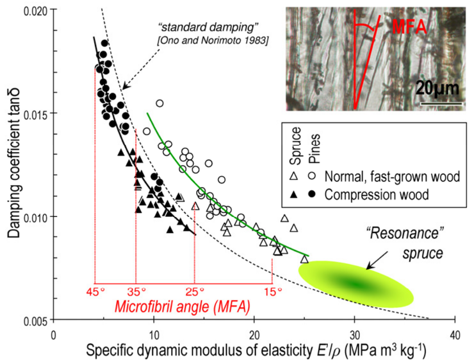

Figure 4: Relationship between axial tanδ and E'/ρ and principal affecting factors: slow-growth "resonance spruce" has a very low microfibril angle leading to very high E'/ρ and relatively low tanδ. Compression wood has a very high MFA and therefore low E'/ρ, but its more condensed lignin reduces its tanδ. Redrawn from [11].

4.3 Meso scale and the question of growth rings

In conifers (softwoods) and particularly in spruce, the vast majority of axial cellular elements consists of a single type of cells, the tracheids, which evolve during the season of growth, from a function of conduction (thin cell walls giving a very low density material) in spring, to a function of mechanical support in summer-autumn (thick walls and high density material). The micro features also evolve, although their seasonal trends are less generally known.

Generally, in softwoods, faster growth rate is associated to higher early (spring) wood proportion, so that wider annual rings are associated with lower-density material, and inversely. However, "resonance wood" is paradoxical in this respect, as it is usually chosen for having both narrow rings *and* as low a density as possible [2,3]. This involves a small proportion of late (summer) wood, which can only happen in cold climates with reduced growing seasons, i.e., generally in altitude forests.

However, despite the importance given to annual rings in the selection of resonance wood by makers (as is attested by sections in technical treatises, or even by official norms for resonance wood in ex-RDA), no correlations, or very weak ones, could be found between macroscopically measurable features of growth rings and axial vibrational properties E'/ρ and tanδ [10,14]. This reflects the fact that these properties are determined at the cell wall scale: very significant correlations were found with cellulose cristallinity and microfibril angle in the same samples [10,14]. However, there are very probably some biologically-driven correlations between the "meso" (ring width and latewood proportion) and "micro" (cristallinity, MFA and their seasonal variations) features, and this would need to be further studied on a very wide sampling of resonance wood in order to get representative information in relation to acoustical properties.

Another "meso" structural feature often cited for resonance wood is the occasional presence of "indented rings" ("hazelfichte" in German). Results on this type of wood suggests it has a slightly higher density, smaller anisotropy, and, apart from the visual aspect, may not be a strong indicator of "exceptional acoustical quality" [3].

4.4 Macro scale heterogeneities: wood types

The different structural scales of wood strongly vary between species and between trees of course, due to genetics, but also within a given tree during its life. This results in different mechanical/acoustical properties within a trunk, which are defined by different "wood types":

Juvenile wood: inner part of the trunk, formed when the tree was young, this wood usually has higher MFA and lower properties and is generally removed for instrument making.

Heartwood/sapwood: In most species, the whitish sapwood is only a few cm wide and is removed for instrument making, which can be related to the fact that, in species which have very low damping due to particular extractives, sapwood has much higher tanδ [15]. In spruce, however, sapwood is not visible but can remain for about 60 years (≥6 cm), and its chemistry and acoustical properties are not significantly different, so that it is not always removed from soundboards [16]. As sapwood is more permeable, however, this may have consequences for varnishing or hygro-mechanical couplings.

Compression wood: formed by the tree to keep or restore verticality, this type of wood has very high MFA and density and low E'/ρ (Figure 4) and is never used as such in instruments. However, compression wood can appear in only one or a few rings and in this case has limited impact on a soundboard's properties, but is nevertheless rejected for more visual reasons.

Spiral grain: very often, the "grain" (= orientation of cells) is not strictly aligned with the trunk axis, but forms an angle with it which increases with tree age. Given the very high anisotropy of resonance spruce, this should be detected and avoided, as an angle of only 5° decreases E'/ρ of at least 10% [6].

5 Beyond natural variability? Wood treatments

May it be driven by "historical" (searching for a "lost secret") or "engineering" (seeking to "improve raw material") viewpoints, several types of treatments have been proposed for application to resonance wood. They might be classified into:

Chemical: several compounds or reactions have been tried for improving hygroscopic stability and modifying vibrational properties [8]. A typology of the involved mechanisms and effects on vibrational properties is given in [4].

"Natural chemical": extractives able to modify damping were extracted from tropical hardwoods and re-injected into spruce, reducing its hygroscopy and damping [12]. This could be an eco-friendly process as extractives can be recycled from instrument production wastes. However, they often also colour the wood, which may be appreciated or not depending on the considered instrument.

Hygrothermal: in other domains that instrument making, many industrial processes are based on this general principle. "Milder" processes have also been tried for resonance wood, including in the viewpoint of a possible temperature-time equivalency (see below).

Natural ageing: this cannot really be "applied" in a realistic sense, as time scales involved are over 100years. However, recent results indicate that wood acoustical properties "improve" in a way that cannot really be reproduced by artificial heat treatments [17].

Biotechnological: some species of wood-degrading fungi have a high selectivity towards certain lignin structures and cellular locations and can be used to diminish wood density without altering its strength [18]. We are currently working at optimizing the process and assessing the kinetics of changes in acoustical properties, which amplitude and direction depend on the different stages of the treatment.

These various "technologies" result in different profiles of modifications in physical, mechanical, acoustical and even aesthetical properties. They also involve different mechanisms of action; however, the main phenomena concern the "nano scale" and chemical composition. The biotechnological treatment also has the ability to modify cellular structure. Nevertheless, up to our knowledge, microfibril angle cannot be much altered.

6 How do wood properties relate to instrument makers' qualification and/or to instrument "quality"?

From an engineering sciences viewpoint, one can emit rather firm statements: "resonance wood" of spruce is naturally characterised by a very high axial E'/ρ and anisotropy, and low (but not extremely so) density and tanδ. This has evident consequences on the vibrational behaviour of beams and plates; however, one cannot easily "jump" directly from there to a notion of "musical quality". In the case of xylophones, clear correlations could be found between material properties and sound perception [19], whereas the complexity of the construction and structure of string instruments makes it more difficult. A few playing or listening tests of instruments with varying wood properties have been conducted, however, some studies did not give conclusive results, while some did but their conclusions were not always comparable with other results. This suggests that the question should be addressed "by steps".

It seems that a first step would be to assess the relation between material properties, and wood evaluation by instrument makers. Although "resonance wood" properties are clearly differentiated from "general supplies", "good" and "medium" qualities were often found to have overlapping ranges in properties [8]. A recent study even suggested that classification (of pre-selected wood however) by violin makers was mostly related to density and visual parameters but little so to acoustical properties [3]. Given the complexity of the system and of the interactions between cultural and mechanical parameters, however, it sounds that a re-apraisal of this question through fine psychosensorial methodologies [19] may be quite enlightening.

7 Conclusion and some ongoing questions

"Resonance wood" of spruce (mainly *Picea abies*) is the principal wood used for soundboards of violins and other Western classical string instruments and as such, it has benefited from much more research than other instrument making woods, both in terms of the number of studies, and of the different aspects involved in this interdisciplinary topic. This relatively wide corpus of referenced information on a single species makes it an excellent "model" for furthering research into fine and precise aspects that are still not well understood, both from the point of view of fundamental wood mechanics/acoustics, and of the global "tree to music" system. Anisotropy, hygromechanical couplings, multiscale modelling in connection to biological parameters, and finally material perception by luthiers and musicians are amongst the topics which would deserve further research. Other remaining questions that were not addressed here concern the wood properties in historical instruments. Several hypotheses have been put forward in this domain but, although dendrochronological and related studies have brought some valuable information, the difficulty in accessing to often priceless heritage instruments and the lack of non-destructive methods able to access to the relevant scales still preclude any conclusion concerning the acoustical properties of their wood.

Acknowledgements

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