# Simultaneous non-destructive identification of multiple elastic and damping properties of spruce tonewood to improve grading

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## Abstract

The tonewoods used in musical instruments are finely selected and are subject to current and upcoming availability issues. Wood grading assesses the quality of the tonewood and depends on both subjective and objective criteria. Traditionally, grading criteria based on mechanical properties consider mainly the longitudinal direction. This paper investigates the elastic and damping properties of spruce wood used in the making of acoustical guitars and violins. In this context, the mechanical grading properties will be studied in multiple directions. A non-destructive vibrational characterization method is used to simultaneously identify at least six mechanical properties of wood and leads to the determination of the elastic and damping parameters of wood along the different material directions. The main objective is to quantify the variability of the mechanical properties in different material directions as a function of the grading attributed by the wood seller. The results show that material anisotropy decreases as the grade decreases. This is attributed to strong increase of the specific elastic modulus in the radial direction and the specific shear modulus in longitudinal and radial plane. Moreover, grading seems to be assigned as a function of specific elasticity and loss factor in the longitudinal direction, which is tied in with the preferences of instrument makers. Following the assumption that high specific modulus is desirable, the classification based on instrument makers choices can be improved for new grading criteria that consider directions than longitudinal. Moreover, the substitution of wood species and the proposal of new materials exhibiting equivalent elastic and damping properties can be proposed.

## Highlights

- Simultaneous non-destructive determination of at least six elastic and damping properties of tonewood.
- Description of elastic and damping properties as a function of tonewood grades.
- Decrease of specific longitudinal modulus and increase of longitudinal loss factor for decreasing grades.
- Increase of specific elastic modulus in radial direction and specific shear modulus in longitudinal and radial plane for decreasing grades.

*Keywords:* Tonewood grading, Non-destructive testing, Identification, Wood variability, Finite element model updating, Modal analysis, Violin and guitar making

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## Research aim

It is a common belief of musicians, instrument makers and audiophiles that the finely selected wood that is used to construct musical instruments plays a dominant role in the sound quality and timbre of the instrument. The availability of woods considered to be the most effective for guitars, cellos and double bass making is becoming a concern, and a better understanding of the wood selection criteria and wood seller grading becomes necessary. Generally, instrument makers attribute a pri-

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mary importance to the longitudinal direction of tonewood. Nevertheless, recent studies [1], [2] based on simulations of the structural dynamics of musical instruments showed that other directions also influence the dynamic behaviour of musical instruments, in particular the radial elastic modulus and the longitudinal-radial shear modulus. However, data is less abundant along the non longitudinal directions and thus are rarely used for tonewood grading. Meanwhile, previous work suggests that the current selection criteria might be improved to account for a wider range of material properties. By considering the other material directions, the choice of wood species used can be broadened and new materials can be proposed. The objective of this study is to simultaneously evaluate multiple elastic and damping parameters of spruce tonewood samples in a non-destructive way at the scale of the full sample and to discuss the link between tonewood grading and elastic and damping material parameters.

## Nomenclature

- L : longitudinal direction.
- R : radial direction.
- T : tangential direction.
- $\rho$ : density.
- $\frac{E_L}{\rho}$ : specific modulus in L direction.
- $\frac{E_R}{\rho}$ : specific modulus in R direction.
- $\frac{G_{LR}}{\rho}$ : specific shear modulus in LR plane.
- $\eta_L$ : loss factor in L direction.
- $\eta_R$ : loss factor in R direction.
- $\eta_{LR}$ : loss factor in LR plane.
- T : temperature
- RH : relative humidity
- MC : moisture content
- MFA : micro-fibril angle.

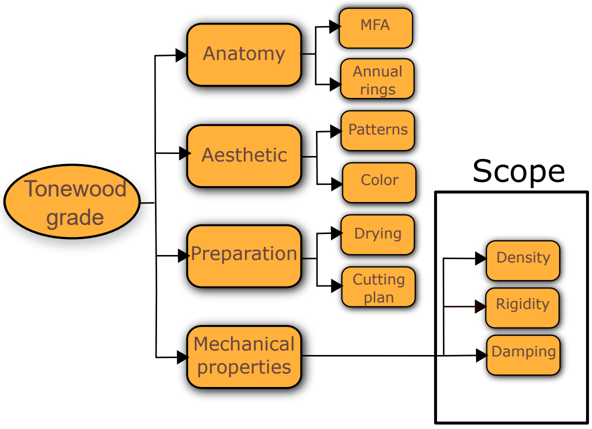
## 1. Introduction

Chordophones such as acoustic guitars and quartet instruments are mainly constructed of resonant boxes that amplify and transmit string vibrations to the air. The resonant boxes are primarily made of wood parts that are assembled with glue. Instrument makers sculpt and assemble the wood parts according to traditional and empirical methods. In the early stages of making an instrument, instrument makers choose the wood species and samples that will be assembled according to their own techniques and tastes that may be different from those of tonewood sellers.

### 1.1. *Instrument maker's point of view*

The term “tonewood” or “resonance wood” refers to wood used for acoustic guitars and instruments from the violin family [3]. Instrument makers carefully select the wood used for musical instrument making based on both objective or subjective criteria, such as physical, mechanical, aesthetic, workability, and availability as seen in figure 1. It has to be pointed out that some idealizations and folklore may have skewed assertions about tonewood quality [4]. The importance given each of these classification criteria vary according to each instrument maker [5] as do the different types of evaluations considered (auditive, tactile, visual). There is no clear trend for a preferred evaluation method, and a majority of instrument makers use mainly subjective selection criteria, and moderately scientific approaches, despite their interest for studies on tonewoods [6]. According to the studies [5] and [6], instrument makers consider the wood to be one of the most determining factors for sound quality, especially the wood used for back and top plates, prior to the geometrical making choices. Instrument makers also insist that the prior acoustical properties of wood evolve differently if the instrument is played or not.

Figure 1: Summary of the criteria for tonewood grading.



From the pragmatic viewpoint of the instrument maker, a straight fibre and grain is preferred due to wood workability issues. Indeed, the lack of defects such as nodes is directly related to structural integrity. Aesthetic considerations are involved for the final appearance of the instrument, based on the tastes of musicians and instrument makers. Special patterns like flames for maple or indented rings for spruce are selected for aesthetic as well as mechanical considerations. Indeed, a recent study pointed out that flames in maple changed the mechanical properties of the wood [7]. Moreover, the indented rings of spruce, also known as bear claw, reduce anisotropy in the wood [8].

As with most biological materials, wood shows a high variability in mechanical properties between the different species, subspecies, individuals and the same individual. Tonewood is previously selected by the specialised vendor through a dedicated selection process different than for wood used in other applications. Instrument makers mainly buy tonewood from these sellers [6], and their selection is mostly based on their own defined quality and the prices given by the seller. For musical instruments, the average price of spruce tonewood, as purchased by the wood seller, is close to 500 € per $m^3$. Thanks to the selection process, the variability is reduced. Most of the time samples showing nodes and twisted grain are rejected. At the end of the sorting process, tonewood is graded according to a nomenclature that depends on the logger, who adapts the selection as a function of market choices and evolution.

### 1.2. Tonewood seller criteria

Following a discussion with a local speciality wood seller[1], tonewood grading follows the set of guidelines summarized in table 1. It should be pointed out that the guidelines and classification criteria are not systematic, and the attribution of a grade may vary. The main criteria are the cutting orientation (with medullary rays clearly visible due to quarter sawing), the density, the percentage of latewood, the uniformity of the annual growth rings and their width. The seller pointed out that the selection process differs between plates (for guitar making) and quarters (for violin making). For plates, it is very important that the grain be not twisted at the full scale of the sample. Moreover he adapts the grades as a function of request, market and availability. During the sorting process, he also favours the homogeneity of the annual rings to avoid strong expansion, and a gradual narrowing from the center of the tree to the bark.

The seller also remarked that since the 1980's, instrument makers are more demanding, especially about the longitudinal stiffness and density for the soundboard, and the prices can now range between 10 € and 300 € per pair [6]. At the same time, studies have shown that an important quality for resonance wood plates was a high radiation ratio associated with a low density [9]. The best grades generally exhibit a low density, the absence of defects and compression wood, and homogeneous annual ring growth. The lower grades tend to exhibit one of the previous defects or inhomogeneous annual rings, and the different grades in lower qualities exhibit these features with different amplitudes and frequency of occurrence. If violin quarters are light in weight, exhibit a straight grain in longitudinal direction, show narrow and constant annual ring width and no compression wood, they are likely to be sorted to the best quality category. Generally, 2nd choice and 1.B may also show some blue stained fungal attacks or compression wood.

The density is an important factor in the selection and grading process. The type of tonewood may differ depending on the growth location, and the seller reported that the spruce wood sold by Italian sellers was generally lighter. The position along the height of the tree may vary and he indicated that tonewood is generally selected from the first five meters of the log. Meanwhile, some loggers select tonewood from up to eight to twelve meters. Hence individual loggers may have preferences for selecting wood, above and below the center of gravity of the tree, close to eight meters for a thirty meters height tree. In the case of plates, the sound velocity in the radial direction is one of the criteria for the selection, where a high speed, and so a high specific modulus, is favoured in the radial direction. This last feature suggests that the mechanical properties are also taken into account for plates.

### 1.3. Material properties

In terms of materials properties, the “quality” of tonewood is associated first and foremost with physical (density) and mechanical properties (elasticity and damping), but also to sound velocity, radiation ratio and loudness, which are described in [10]. Among the different ways to evaluate the choices

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[1] Bernard Michaud from *Le bois de lutherie, Fertans, France*

Table 1: Spruce tonewood grading key and price as a function of the gradings for both plates (guitars) and quarters (violins), according to a personal communication with tonewood seller.

| Grade | Anatomic features | Aesthetic features | Density | Defaults | Price (€) | Mechanical parameters |
|---|---|---|---|---|---|---|
| Plates ($600 \times 200 \times 5$ mm, pair) | | | | | | |
| 1.S | Low MFA, homogeneous | Medullary rays | Lightest | No | 65 | High radial modulus |
| 1.A | Homogeneous | Medullary rays | - | No | 45 | - |
| 1.B | Irregular growth rings | Compression wood | - | No | 30 | - |
| 2nd | Irregular growth rings | Small blue stain fungi/compression wood | Possibly heavy | Resin pockets accepted | 18 | - |
| Quarters ($450 \times 150 \times 28$ mm, pair) | | | | | | |
| 1.S | Low MFA, homogeneous | Medullary rays | - | No | 43 | High longitudinal modulus |
| 1.A | Homogeneous | Medullary rays | - | No | 30 | - |
| 1.B | Irregular growth rings | Some compression wood | - | No | 20 | - |
| 2nd | Irregular growth rings | Small blue stain fungi/compression wood | Possibly heavy | Resin pockets accepted | 12 | - |

of instrument makers when selecting tonewood, the mechanical behavior can potentially provide objective and quantifiable criteria. The different parameters used to quantify the material properties are the elastic moduli (both specific and non specific), the loss factors and the density. Generally, mechanical studies of tonewood consider the density, the longitudinal specific modulus $\frac{E_L}{\rho}$ and the corresponding loss factor $\eta_L$. The work presented here focuses on the species used for the making of guitar and violin soundboards, namely European spruce, *Picea abies*. It is usually considered that spruce tonewood exhibits specific properties, such as high specific modulus in longitudinal direction.

Generally, lower densities are observed for the best ranked woods [11]. In this study the material properties of the wood are compared as a function of the grading and hence price. The specific studies, dedicated mostly to spruce, are based on a wide variety of experimental methods [12]. These studies have highlighted an intra and inter individual variability. The different sources of variability in spruce wood are generally well-known and correspond to both macroscopic and mesoscopic structure [13]. Moreover microscopic features are also at the source of the wood variability. The orientation of the cellulose microfibrils which constitute the $S_2$ layer of the cell wall of the tracheid, named microfibril angle (MFA) is a soruce of variability. Moreover the degree of cristallinity of the cellulose is also a source of variability. It has been higlighted in [14] that spruce tonewood exhibits a microfibril angle (MFA) that is two times lower than regular spruce. This study also showed that the MFA is smaller in latewood than in earlywood.

The different studies have led to the mean and standard deviation of spruce properties in all directions as reported in the table 2. Spruce tonewood, in comparison to other softwoods, exhibits higher $E_L$, lower $\eta_L$, and higher anisotropy ratio [15]. In [16], it was observed that the stiffness of tonewoods is generally higher than the values reported for general woods, which instrument makers assume indicated good quality. A higher specific modulus has been associated with a higher loudness of musical instruments, based on a higher acoustic conversion efficiency value [17]. It is generally alleged that these characteristics are favourable for instrument dynamics and acoustics, but no objective studies have clearly associated the quality of an instrument with its material properties. Moreover, from a structural dynamics point of view, it has been emphasized that the longitudinal stiffness of the wood used for soundboards and violin backs in the longitudinal direction was not the most influential parameter in comparison to the radial elasticity and longitudinal-radial shear stiffness [1].

Meanwhile, data for the properties of tonewood along the non longitudinal directions is lacking. At this point, two main propositions are raised. It is generally supposed that high specific modulus is better for instruments dynamics, hence $\frac{E_R}{\rho}$ and $\frac{G_{LR}}{\rho}$ should be higher for high grades. In the other cases, high $\frac{E_R}{\rho}$ and $\frac{G_{LR}}{\rho}$ are not associated with good quality woods. So, the tonewood mechanical properties may not be considered as the most influential properties on the dynamics or acoustics of instruments. The last proposition is not in adequation with violin maker criteria for wood choice [18].

### *1.4. Objectives*

In this paper, a methodology is proposed to simultaneously identify several mechanical tonewood properties, in particular $E_R$ and $G_{LR}$. The objective is to provide a means for monitoring the mechanical behaviour of the material from the raw material to the instrument where traditional destructive methods are not applicable. In this work, the mechanical properties of tonewood will be studied using a non-destructive method enabling the measurement of several elastic and damping parameters in different directions simulaneously in contrast to other techniques which evaluate one direction at a time and require calibrated specimens ([12], [19], [20]).

In the present study, we propose to use a non-destructive inverse method based on finite element model updating (FEMU) and 3D vibratory field measurements (3DVF). This approach is motivated by the fact that wood samples used for instrument making are generally plate or quarter shaped. Traditional mechanical tests usually need to cut specimens in raw material which may preclude the future utilisation for instrument making. Moreover, the rarity and the cost of the sample may also be arguments for the use of non-destructive testing. The value of musical instruments, both old and new, is also an obstacle for performing mechanical studies that is alleviated by a non-destructive technique. The proposed approach is non-invasive, fast, easy to set-up, and requires reduced preparation time for samples. In addition, dynamic responses such as the vibratory modes are more representative of the global behaviour of the material in contrast to static properties that are generally driven by local phenomena. These benefits have led to the development of numerically based identification methods over the last thirty years ([21], [22]) to estimate both anisotropic loss factors and stiffnesses of composite plates [23] or arbitrarily shaped parts [24]. It has been noted that the measured elastic modulus $E_{dynamical}$ is generally close to 1.1 times $E_{static}$ in the longitudinal direction [25] and 1.2 times larger in the radial direction, thus leading to discrepancies in the trends obtained which each method.

In 2016, a review paper [26] made a list of the works relating to the identification of material properties using vibrational approaches. This paper highlights the fact that, despite its potential, this method has mostly been applied to flat plate specimens and not more complex shape parts, which is covered in this study by the application to violin quarters.

The proposed method is described in detail in [27] and applied to a violin soundboard made of bio-based composite. The FEMU-3DVF method deals with a finite element model and and experimental set-up comprising an acoustic exciter (speaker) and a Doppler effect laser 3D vibrometer. This allows the determination, through the measurement of velocities at the surface of the specimen in the three material directions, of the experimental modal basis. The identification process consists in the minimisation of the discrepancies between the frequencies of the matched test-analysis modes. In what follows, specimens will be tested using the FEMU-3DVF method and the mechanical parameters are reported as a function of the grading of each sample in the results section. Finally, conclusions are drawn based on the results and perspective studies are proposed.

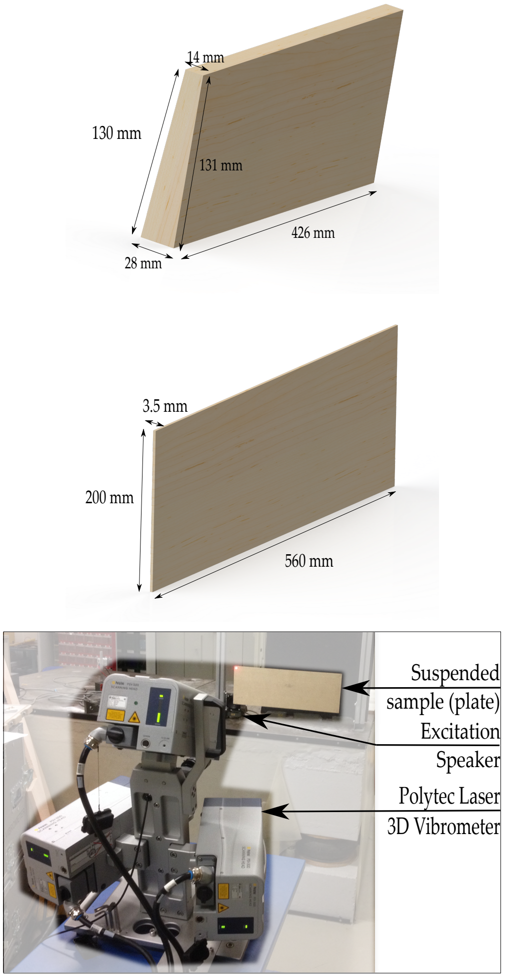
## 2. Material and methods

### 2.1. Materials

The tonewood species studied is European spruce, *Picea abies*. The samples have been provided by a local sawmill specialised in tonewood, *Le bois de lutherie*, *Fertans*, *France* in the form of plates and quarters. The plates are used for guitar making and are flat. The quarters are bulk pieces with trapezoidal cross sections and are used for the back and the top of the violin where they are carved to create an arch. The dimensions of the quarters vary, and figure 2 (a) reports the average values. For all the quarters, the dimensions are measured with a rule and a calliper. The precision of the length measured with the rule is ± 0.5 mm and the precision of the trapezoidal shape, measured with a calliper is ± 0.1 mm. The samples are weighed with a KERN® weighing machine whose precision is ± 0.1 g. The average relative error on the evaluation of the mass is equal to ± 0.02 %. The volume is evaluated from the dimensions of the parts. The relative error on the estimation of the volume is estimated to ± 1.4 %. The density is evaluated as the ratio between the mass and the volume. The relative error in the evaluation of the density of the quarters is close to 1.5 %. The impact of measurement errors on the identification of material parameters is detailed in the section 6 of the *data in brief* document. Ten spruce quarters have been studied and are labelled $i$ with i varying from 1 to 10. Table 4 in the results section indicates for each quarter the label, references, and harvest year given by the first two digits. Their density and their "grading rank" as sold by the sawmill are also given. Note that some spruce quarters exhibit indented rings patters, known as bear-claw wood, described in [28].

The wood used for guitar soundboards is sold in the form of plates. Figure 2 (b) shows a sample plate and its dimensions. The dimensions of the plates vary, and the figure only indicates an average value. The dimensions of the plates are measured with the same apparatus as the quarters while a thickness calliper is used to evaluate their thickness with

Figure 2: Dimensions of the quarters (a) and plates (b), (c), experimental setup of the FEMU-3DVF method applied to wooden plates.



(a)

(b)

(c)

a precision of ± 0.05 mm. The relative error for the plate volumes is estimated to be ± 1.5 %. The relative error on the densities of the quarters is close to 1.6 %. Twenty spruce plates have been studied. The spruce plates are labelled in Roman numerals, from I to XX. The table 3 gives the label of the plates, their references, their density and their grading. The year of logging is given with the first two numbers of the reference. The samples are grouped into sets of a given quality, yielding : 9 samples of fourth quality ($2^{nd}$), 9 samples of third quality ($1.B$), 8 samples of second quality ($1.A$) and 4 samples of first (best) quality ($1.S$). The logging years vary from 1996 to 2015. The specimens have been conditioned in a climatic chamber at $50 \pm 2.5\%$ RH and $21 \pm 1°$C during several weeks and tested outside the climatic chamber with the protocol described below. The measurements of each specimen last less than 30 minutes and are performed in a room where RH and T are measured with LOGTAG® HAXO-8. During the measurements, the temperature is equal to $23 \pm 2°$C. The relative humidity is equal to $45 \pm 5\%$. Considering the conditioning values, and using sorption isotherms [29], the moisture content MC is comprised between 9 and 11 %.

### *2.2. Mixed numerical-experimental method description*

The numerical-experimental method used is fully described in [27]. The measurement of the velocity field is made with a Polytec PSV-500 vibrometer as shown in the figure 2 (c). The excitation is produced by a loudspeaker, between 10 and 2000 Hz for the plates and 100 to 5000 Hz for the quarters. The acoustic excitation on the sample leads to strain levels close to $150.10^{-9}$ (flexural strain) and $200.10^{-9}$ (torsional strain). A modal analysis using the Polymax method is performed on the non-normalized frequency response functions using an in-house numerical tool called MODAN developed using MATLAB®. The measured and synthesized frequency response functions are provided in the *data in brief* document. The modal dampings of each modes are evaluated with the modal analysis. The modal damping of the purely torsion and flexural modes are used for the loss factors estimation. The loss factors $\eta_L$, $\eta_R$ and $\eta_{LR}$ are estimated as the double of the modal damping $\xi$ of the modes 2, 4 and 1 (shown in the figure 4 and 6 of the *data in brief* document), respectively.

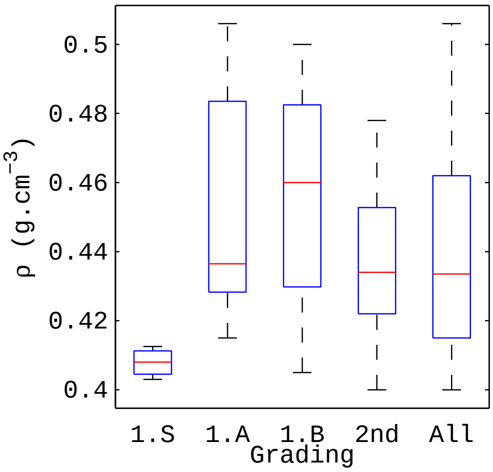
In the identification process, the eigenmodes computed using a finite element model of the structures are compared to the experimentally evaluated modes. The identifiability of the elastic and damping parameters is based on the sensitivity analysis of each mode. The error in the matched frequencies [30] is reduced using a first order sensitivity algorithm. At the end of the process, the discrepancies between experimental modal basis and computed ones are reduced (as shown in the *data in brief* document) and the elastic parameters are identified. The error in the estimation is based on algorithm convergence and the evaluation of the geometry and density of the samples. The FEMU-3DVF method has been applied to thirty spruce samples, divided in twenty plates and ten quarters. Preliminary results like sensitivity analyses and identification errors due to measurement and method errors are given in the *data in brief* document.

## 3. Results

### 3.1. Density evaluation

The values of the densities of the samples (quarters and plates) are given as box and whiskers plots in the figure 3. The mean value (0.45 $g.cm^{-3}$) is in accordance with the usual values for spruce (0.43 $g.cm^{-3}$) from [12]. The density of all the samples are given as a function of the grading in the figure 3. It is shown that high grade spruce is lighter than the other grades, as observed in [6], and its dispersion is at least 5 times smaller, as expected [11], but it should be pointed out that the number of high grade samples is lower and the samples are only plates. Nevertheless, the number of samples is very small for the first grading and this needs to be taken into account when interpreting the results.

FIGURE 3: Box and whiskers plots of the density as a function of gradings. The horizontal line inside the boxes corresponds to the median. The lower and upper boundaries of the boxes correspond to the lower and upper quartiles respectively. The lower and upper limits of the dashed lines correspond to the 9 and 91 % percentiles respectively.



### 3.2. Identified material properties for spruce quarters and plates

The matched eigenfrequency errors are given before and after finite element updating process in the *data in brief* document for each specimen. The average absolute error of matched eigenfrequencies is very low and implies a good correlation between the experimental and numerical modal bases thus validating the underlying assumptions for the material's mechanical behaviour, and especially the identifiability of the elastic parameters. Once the finite element model updating is performed, the values that minimize the error of each elastic parameters are used in the following paragraph that lists the material properties.
The identification errors attributed to geometrical measures and method algorithm are given in the section 6 of the *data in brief* document. Depending on the sample type studied, the sum of each type of error is close to 4 and 5 % for plates and quarters, respectively.
Initially, the average values of the identified properties on the spruce wood are given in the table 2. The results for each sample and specimen type are also provided. The global results, given in the table 2 are in adequation with the standard values of spruce available in literature [12]. The standard deviation of each parameter is high, even for a highly selected material such as spruce tonewood. Generally, spruce tonewood is more rigid in the longitudinal direction and more anisotropic than standard softwoods. The shear modulus, $G_{RT}$ is much lower than the one predicted by [31], and in accordance with the one usually measured for spruce woods. Figure 4 gives the dispersion in the elastic and damping values for all the gradings and specimen type mixed in the results cases "all". It should be pointed out that the variability covers a wide span of values depending on the parameter. In the longitudinal direction, the covariance of $\frac{E_L}{\rho}$ and $\eta_L$ are equal to 10 and 13 %, respectively. In the radial direction, the covariance is equal to 20 % for $\frac{E_R}{\rho}$ and 10 % for $\eta_R$. In the LR plane, the specific shear modulus covariance is equal to 14 %, and, for the corresponding loss factor $\eta_L R$, equal to 16 %. Finally, the covariance of the density is smaller and equal to 6 %.

#### 3.2.1. Plate specimens

Based on the results of the table 3, the longitudinal modulus of spruce plate specimens ranges from 8.7 to 17.6 GPa, for densities ranging between 0.4 and 0.5 $g.cm^{-3}$ which is in accordance with what was expected based on Guitard's models [31]. Nevertheless, these relations are not systematically verified. The loss factor in the L direction ranges from 0.6 to 1.0 %, and in R direction from 1.4 to 2.2 %. It has to be highlighted that a high $\eta_L$ is often correlated with low $\eta_R$, which can be explained by the MF orientation. It is shown that the specific rigidity in the L direction covers a broad range, from 20 to 35

TABLE 2: Summary of the mechanical parameters of spruce, and comparison with bibliography values [12], [6] (labelled as Ref.). For the presented results, the value of the MC is comprised between 9 and 11 %.

| **Parameter** | **Mean** | **RSD** (%) | **Range** | **Ref. mean** | **Ref. RSD** (%) | **Ref. range** |
|---|---|---|---|---|---|---|
| Density $\rho$ $(g.cm^{-3})$ | 0.45 | 7 | 0.39-0.51 | 0.42 | 13 | 0.32-0.55 |
| $E_L$ $(GPa)$ | 12.8 | 12 | 8.7-17.6 | 13.5 | 21 | 9-16.2 |
| $E_R$ $(GPa)$ | 1.01 | 22 | 0.6-1.93 | 0.92 | 21 | 0.54-1.12 |
| $G_{LR}$ $(GPa)$ | 0.81 | 15 | 0.57-1.2 | 0.93 | 17 | 0.7-1.2 |
| $\frac{E_L}{\rho}$ $(GPa.g^{-1}.cm^3)$ | 29.0 | 10 | 21-35 | 29.7 | 11 | 18-36 |
| $\frac{E_R}{\rho}$ $(GPa.g^{-1}.cm^3)$ | 2.28 | 20 | 1.46-3.82 | 2.2 | 18 | 1.7-3.6 |
| $\frac{G_{LR}}{\rho}$ $(GPa.g^{-1}.cm^3)$ | 1.85 | 14 | 1.3-2.4 | 2.2 | - | - |
| $\eta_L$ (%) | 0.73 | 12 | 0.55-1 | 0.68 | 11 | 0.6-1.0 |
| $\eta_R$ (%) | 1.7 | 10 | 1.35-2.2 | 2.0 | 19 | 1.55-2.7 |
| $\eta_{LR}$(%) | 1.2 | 17 | 0.7-1.6 | 1.8 | 6 | 1.6-2.0 |
| $G_{RT}$ $(GPa)$ | 0.046 | 22 | 0.031-0.073 | 0.035 [32] | - | 0.03-0.045 |
| $G_{TL}$ $(GPa)$ | 0.79 | 21 | 0.5-1.2 | 0.8 | - | 0.48-1.12 |

$GPa.g^{-1}.cm^3$. In the radial direction, the values of the specific elastic modulus range from 1.46 to 2.78 $GPa.g^{-1}.cm^3$ between the minimal and maximal values. In the longitudinal radial plane, the values of the specific shear modulus range from 1.48 to 2.44 $GPa.g^{-1}.cm^3$.

### *3.2.2. Quarter specimens*

The properties identified on the quarters are reported in the table 4. The mean density is equal to 0.46 $g.cm^{-3}$. The average values of the Young's moduli in L and R directions are equal to 13.8 and 1.2 GPa, respectively. The loss factors in the same directions are equal to 0.75 and 1.75 %, respectively. In the LR plane the average value of the shear modulus is equal to 0.8 GPa, and the loss factor in this plane is equal to 1.3 %. The averaged values of the shear moduli in the RT and TL planes are equal to 47 MPa and 0.85 GPa, respectively. As a reminder, the usual values are given in the table 2. The averaged values of the specific Young's moduli in L and R directions are equal to 29.4 and 2.8 GPa, respectively. In the LR plane the specific shear modulus averaged value is equal to 1.8 GPa. The usual values of the specific parameters are also given in the table 2.

### *3.3. Comparison of the mechanical parameters as a function of grading*

This subsection compares the mechanical properties with respect to the grading levels. In order to evaluate the correlation between instrument maker choices (and/or price grading) and mechanical properties, the specific elastic and damping properties are regrouped in box and whiskers plots, shown in the figure 4. It is observed that the loss factor in the L direction tends to increase when the grading decreases, as observed in [6], which is not observed in the other material directions. Moreover, in the radial direction, the loss factor tends to decrease when the grading decreases. In the LR plane and R direction, the loss factors increase when the grading decreases, but surprisingly are also low for the "lowest" grade. It is shown that, depending on the grading, the evolution of the rigidities and loss factors in the L and R directions and the LR plane vary.
Considering the specific mechanical parameters, trends for specific moduli in R direction and LR plane are observed. The specific longitudinal modulus mean value decreases when the grading decreases but the variaiblity remains very high to exhibit clear trends, it is nevertheless lower for lower quality, as observed in [6]. The contrary is observed for $E_R$ and $G_{LR}$. These observations tend to contradict the commonly suggested criteria guiding instrument makers choices, namely that choosing the best wood for instrument making implies a lower specific rigidity in R and LR directions. Nevertheless, it has been shown in [1] that these moduli are particularly influential on the dynamical behaviour of the musical instruments. The clear dispersion of the material properties indicate that it is possible to find in lower qualities woods that exhibits mechnaical properties close the the best one, which was also pointed out in [6].

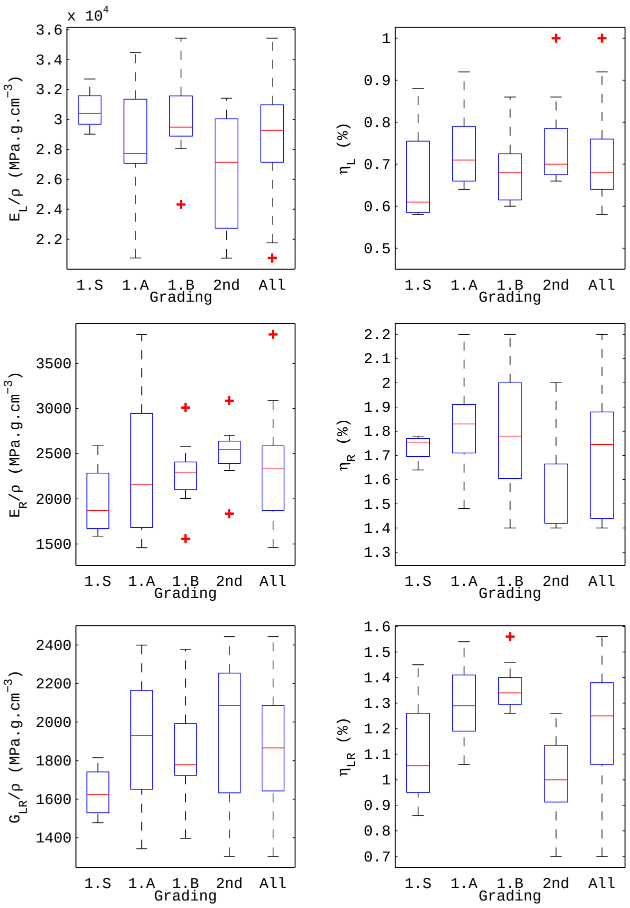
Table 3: Identifed mechanical properties for spruce plate samples.

| **Sample** | **Grading** | **Reference** | **Density** | $\frac{E_L}{\rho}$ $(GPa.g^{-1}.cm^3)$ | $\frac{E_R}{\rho}$ $(GPa.g^{-1}.cm^3)$ | $\frac{G_{LR}}{\rho}$ $(GPa.g^{-1}.cm^3)$ | $\eta_L$ (%) | $\eta_R$ (%) | $\eta_{LR}$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| I | 1.A | 13C100 | 0.415 | 27.2 | 1.53 | 1.96 | 0.65 | 1.9 | 1.05 |
| II | 1.A | 13I81 | 0.44 | 27.3 | 1.46 | 1.82 | 0.65 | 1.9 | 1.25 |
| III | 1.A | 13F286 | 0.43 | 20.7 | 1.87 | 2.4 | 0.85 | 1.80 | 1.25 |
| IV | 1.B | 9J75 | 0.425 | 29.4 | 1.56 | 1.78 | 0.60 | 2.2 | 1.40 |
| V | 1.B | 13F247 | 0.46 | 28.0 | 2.29 | 2.06 | 0.7 | 2 | 1.55 |
| VI | 1.B | 9H356 | 0.46 | 29.2 | 2.0 | 1.73 | 0.6 | 1.72 | 1.28 |
| VII | 2nd | 10J256 | 0.48 | 23.1 | 2.3 | 2.09 | 0.85 | 1.4 | 1.1 |
| VIII | 2nd | 10H322 | 0.4 | 21.7 | 2.62 | 2.44 | 1 | 1.40 | 0.95 |
| IX | 2nd | 10N447 | 0.41 | 24.5 | 2.57 | 2.23 | 0.65 | 1.45 | 0.8 |
| X | 1.S | 14A257 | 0.41 | 30.5 | 1.75 | 1.67 | 0.6 | 1.75 | 1.05 |
| XI | 1.S | 14A155 | 0.40 | 29 | 1.98 | 1.48 | 0.6 | 1.65 | 0.85 |
| XII | 1.S | 14A87 | 0.41 | 30.35 | 1.59 | 1.58 | 0.65 | 1.80 | 1.05 |
| XIII | 1.A | 14C69 | 0.43 | 30.7 | 1.74 | 1.94 | 0.65 | 1.65 | 1.15 |
| XIV | 1.B | 12F23 | 0.455 | 31 | 2.13 | 1.97 | 0.6 | 1.4 | 1.3 |
| XV | 1.B | 15E238 | 0.50 | 35.4 | 2.35 | 1.74 | 0.6 | 1.8 | 1.45 |
| XVI | 1.B | 13J27 | 0.405 | 23.5 | 2.78 | 2.44 | 0.85 | 1.45 | 1.45 |
| XVII | 2nd | 08 | 0.47 | 31 | 2.52 | 1.30 | 0.7 | 2 | - |
| XVIII | 2nd | 08 | 0.45 | 29.7 | 2.41 | 1.64 | 0.65 | 1.65 | - |
| XIX | 2nd | 08 | 0.43 | 27.7 | 2.54 | 2.32 | 0.9 | 1.40 | 0.65 |
| XX | 1.S | 12 | 0.41 | 32.7 | 2.59 | 1.81 | 0.9 | 1.75 | 1.45 |
| **Average** | - | - | **0.435** | **28.1** | **2.1** | **1.9** | **0.7** | **1.7** | **1.2** |

Table 4: Identified material properties for spruce quarter samples.

| **Sample** | **Grade** | **Ref.** | **Density** | $\frac{E_L}{\rho}$ $(GPa.g^{-1}.cm^3)$ | $\frac{E_R}{\rho}$ $(GPa.g^{-1}.cm^3)$ | $\frac{G_{LR}}{\rho}$ $(GPa.g^{-1}.cm^3)$ | $\eta_L$ (%) | $\eta_R$ (%) | $\eta_{LR}$ (%) | $G_{RT}$ (MPa) | $G_{TL}$ (GPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1a | 1.A | 10Z120 | 0.51 | 32.0 | 3.06 | 1.49 | 0.9 | 1.90 | 1.55 | 49 | 0.83 |
| 2a | 1.A | 11K5 | 0.505 | 26.9 | 3.82 | 2.37 | 0.75 | 1.5 | 1.4 | 73 | 1.12 |
| 3a | 1.A | 110131 | 0.43 | 28.2 | 2.45 | 1.34 | 0.75 | 1.75 | 1.45 | 30 | 0.63 |
| 4a | 1.A | 13A360 | 0.46 | 34.5 | 2.94 | 1.92 | 0.7 | 2.2 | 1.35 | 36 | 0.68 |
| 5a | 1.B | 10Q89 | 0.43 | 31.0 | 2.24 | 1.40 | 0.75 | 1.8 | 1.4 | 42 | 0.575 |
| 6a | 1.B | 13C58 | 0.48 | 33.2 | 2.58 | 1.71 | 0.7 | 2.0 | 1.35 | 44 | 0.76 |
| 7a | 1.B | 13C38 | 0.49 | 29.5 | 2.33 | 2.7 | 0.7 | 1.65 | 1.30 | 47 | 0.87 |
| 8a | 2nd | 96WG46 | 0.43 | 20.7 | 3.09 | 2.10 | 0.75 | 1.4 | 1.1 | 65 | 1.2 |
| 9a | 2nd | 98WI40 | 0.45 | 31.4 | 1.84 | 1.60 | 0.70 | 1.75 | 1.25 | 54 | 0.93 |
| 10a | 2nd | 96WG67 | 0.44 | 26.9 | 3.5 | 1.99 | 0.75 | 1.4 | 1.25 | 48 | 0.85 |
| **Average** | - | **0.46** | - | **29.4** | **2.8** | **1.8** | **0.75** | **1.75** | **1.35** | **47** | **0.85** |

FIGURE 4: Average rigidities and loss factors as a function of the grading. The horizontal line inside the boxes corresponds to the median. The lower and upper boundaries of the boxes correspond to the lower and upper quartiles respectively. The lower and upper limits of the dashed lines correspond to the 9 and 91 % percentiles respectively. The out of bounds crosses correspond to extreme values out of 9 % percentiles.



## 4. Conclusions

The main objective of this work was to simultaneously identify the material properties of spruce tonewood for different gradings at the scale of the raw material. For this purpose, plate and quarter specimens were tested using the FEMU-3DVF method. The results show that at least three rigidities, $E_L$, $E_R$ and $G_{LR}$ as well as the damping properties in these corresponding directions can be determined successfully at once. The identified parameters using this type of metohds were comparable to the properties determined on the same specie by numerous previous studies, using dynamic and static direct methods. Moreover, the method used provides a global evaluation, that prevents from intra specimen high variability pointed out in [6], which is equivalent to inter specimen variability

It has been shown that the assumption that high specific modulus and low damping is a key choice for instrument acoustics is verified in the longitudinal direction. However, this hypothesis is shown to be invalid in the radial and longitudinal directions which can even exhibit inverse trends. As these directions are also influential on the dynamics of the violin and guitars, the usual selection criteria are controversial and a fine description of the impact of these directions on the dynamics and acoustics of the full instrument is required to provide an objective assessment of the impact of wood choices, which is still considered to play a prime role in the perceived overall “quality” of a musical instrument.

This study highlights the fact that a previously selected biological material may exhibit high variability and the identified parameters exhibited variations depending on the directions, ranging from 10 % (longitudinal direction) and 20 % (radial direction). The covariance of the density for the considered samples is equal to 6 %. Hence, a wood selection based uniquely on a single objective property like density is not sufficient to ensure a small variability of elastic and damping parameters. The high variability in material properties can be considered as an opportunity for substitution materials, either biological or manufactured, that exhibit elastic and damping parameters comprised within the intrinsic variability of tonewood.

In conclusion, this study provides a starting point and incentive to update the classification and grading procedures of spruce tonewood. Towards this end, two main steps are still required. Firstly, the impact of each parameter on the vibro-acoustics of each instruments must be quantified. Secondly, the association between tonewood mechanical properties and musical instrument sound preferences has to be studied.

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