Measurements of Mechanical Properties of Adirondack Spruce

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1 Introduction

Adirondack spruce (*Picea rubens*), also known as Eastern red spruce or Appalachian spruce, is a conifer found primarily in New England, the Appalachians and eastern Canada. This wood has been historically used in the production of fancy foods such as spruce beer and spruce gum (from the needles especially), but also as construction lumber, pulpwood and even as Christmas trees. Adirondack spruce wood began to be used in the 19th century for piano, guitar and mandolin soundboards. Prior to World War II, it was indeed the preferred soundboard tone wood for several guitar makers and is still widely in use for this purpose. Despite its large use in various fields, Adirondack spruce's mechanical properties (like Young's moduli in longitudinal and radial directions, and damping loss factor) are not well documented. In this work, several methods are used to evaluate such properties of twelve quarter-cut orthotropic plates selected for guitar soundboards (2nd grade). The identified values for the elastic and damping constants of this orthotropic material are summarized and compared as a function of frequency.

2 Tested structures and test conditions

The tested structures are twelve quarter-cut plates intended to be used as left and right parts of six guitar soundboards (see Fig. 1). The measured mean dimensions of the plates are 560 mm x 227 mm x 5 mm (Length L_x x Width L_y x Thickness h, with a variation of $\pm$ 1 mm for length and width, and $\pm$ 0.2 mm for thickness). The mean mass density, ρ, is obtained from geometrical measurements and a balance of 0.1 kg precision, and equals 443 kg/m^3. Two series of measurements are conducted. The first consists in impact testing using a miniature impact hammer (PCB 086E80) and an single-axis accelerometer (PCB 353B18). Excitation and measurement point are identical and positioned on each side of the soundboard. Acceleration over force frequency response functions (FRF) are calculated using five averages and the H1 estimator (sampling frequency is 20280 Hz, frequency resolution equals 1.25 Hz). The raw time domain signal from the accelerometer is used to calculate the loss factor using the decay rate method. The second series of measurements uses a piezo exciter (see Fig. 1) with a white noise input. Using a scanning laser Doppler vibrometer (LDV Polytec PSV400), the spatial vibration measurement is measured over two grids corresponding to two frequency ranges : 19 $\times$ 9 points (for modal identification between 50 and 400 Hz), and 77 $\times$ 37 points (for IWC method between 400 and 5000 Hz). For all tests, the boards are supported by two bungees at two attachment points, as shown in Fig. 1.

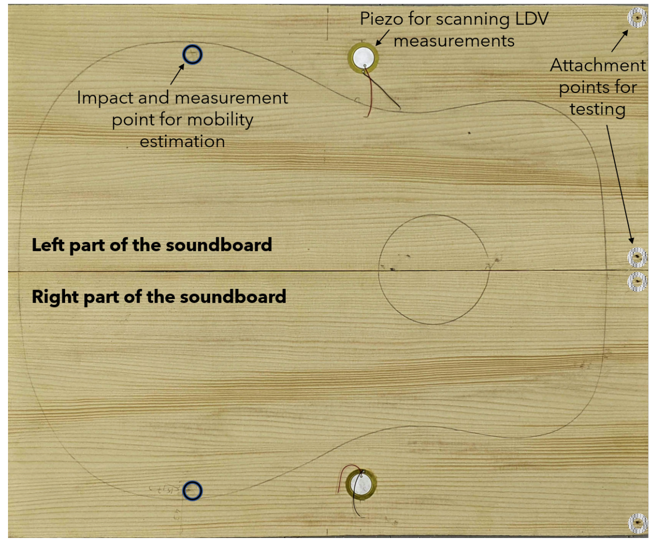

Figure 1: Left and right parts of soundboards 6L and 6R, including position for mobility measurement, position of the piezo exciter and attachments points.

3 Methods

Modal identification. In [1], a simple yet reasonably accurate method is detailed for the determination of 'elastic and damping constants of orthotropic sheet materials'. These constants are deduced from the identification of the lowest 'bending beam' vibration modes using their corresponding shapes in free-free boundary conditions. From the resonance frequencies of these modes ($f_{r,l}$, subscripts $_r$ and $_l$ standing for radial and longitudinal directions), the rigidity constants $D_{1,3}$ for orthotropic materials in x and y directions can be estimated following the approximated relation $D_{1,3} \simeq 0.0789 f_{r,l}^2 \rho L_{x,y}{}^4 h$. By linking rigidity to corresponding Young's modulus $E_{x,y}$ in x and y directions, $D_{1,3} = \frac{E_{x,y} h^3}{12(1-\nu_{xy}\nu_{yx})}$ and finally $E_{x,y} = \frac{D_{1,3} 12(1-\nu_{xy}\nu_{yx})}{h^3}$.

Inhomogeneous wave correlation (IWC). The IWC method uses the 2D wave field of a vibrating plane structure, in order to identify the angle-dependent dispersion curve by comparing it with an inhomogeneous wave (i.e. a damped plane wave). It results into the identification of a complex wave number [2]. In this work, the real part of the identified wave number in the longitudinal and radial directions is used to estimate the corresponding Young's moduli. Spatial vibration measurements (LDV) are post-processed at frequencies of 500, 1000, 2000, 3000, 4000 and 5000 Hz.

Decay rate method. In this case, the measured impulse response is filtered in the time-domain using third order band-

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pass Butterworth filters (with lower and upper frequencies bounds defined following those of third octave bands between 125 Hz and 1250 Hz). The Schroeder's backward integration method is then applied to each time-filtered signal, and the slope is identified over a 10 dB decay using a first order polynomial curve fitting. The loss factor η equals $Dec/27.3f$, where Dec is the identified decay in dB per second and f is the central frequency of the considered third octave band [3].

Half-power bandwidth method (-3 dB method). In this method, the resonant frequency f_p for each well-separated vibration mode is identified, as well as the upper and lower frequencies ($f_{2,1}$) around this peak for which the amplitude equals the amplitude at resonance divided by the square root of two (-3 dB for 20 $\log_{10}$ of the FRF). The loss factor η is now calculated following $(f_2 - f_1)/f_p$.

4 Results

In table 1, the results obtained using the identification of specific vibrations modes are summarized (Left and Right parts of soundboards are indicated by letter L or R, respectively). The mean values (and standard deviation) for E_x and E_y are 9.66 GPa (0.38 GPa) and 0.89 GPa (0.14 GPa), respectively.

Table 1: Results obtained following the approximation from [1]

Soundboard	1L	1R	2L	2R	3L	3R
ρ (kg.m^{-3})	422	408	442	429	427	424
E_x (GPa)	10,17	9,07	9,39	9,10	10,04	9,49
E_y (GPa)	0,61	0,69	1,00	0,98	1,00	0,99
-	4L	4R	5L	5R	6L	6R
ρ (kg.m^{-3})	461	460	456	461	459	464
E_x (GPa)	9,99	9,45	9,72	9,68	10,18	9,60
E_y (GPa)	0,72	0,84	0,96	0,94	0,92	0,97

Theses results are compared with those obtained using IWC methods in the upper part of Figure 2. The estimated value of E_y is fairly constant with increasing frequency, and the methods based on [1] and [2] provide similar results, with a mean value of 0.63 GPa. The estimation of E_x shows larger variations. The IWC method is indeed sensitive to measurement noise and provides more biased estimations in the high frequency domain when the energy is more localised near the source. Based on these first results, the implementation of the method will be applied with a finer frequency step and will include other directions than only longitudinal and radial ones, as well as loss factor estimation. Concerning this parameter, the mean estimated values using the Decay Rate Method and the Half Bandwidth Method are 1.95% and 2.19%, respectively (see lower part of Figure2).

The values presented in this section for Adirondack spruce are in the range of those reported in the literature for spruce. Identified orthotropic ratio ($E_x/E_y \approx 10$) and loss factor ($\approx 2\%$) are also consistent with published studies on other resonant woods [4,5]. One can note that the experimental systematic estimation of structural loss factor of wood for musical instruments up to 1 kHz is not common in the literature.

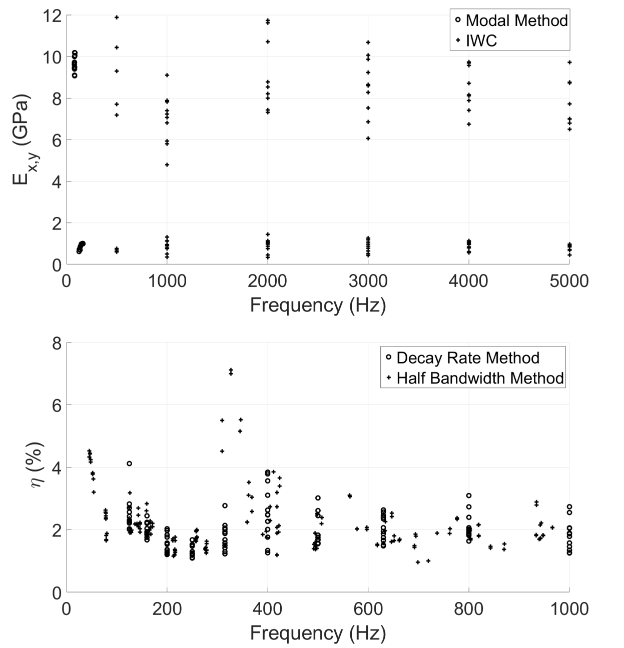

Figure 2: (Upper part) Summary of the results obtained concerning Young's modulus in principal (E_x) and longitudinal (E_y) directions - (Lower part) Summary of the results obtained concerning loss factor estimation.

5 Conclusions

This paper reports identified values for the elastic and damping constants of Adirondack spruce soundboards. The next steps of this work are (1) to link those parameters to grading criteria used in tone wood selection for guitar crafting, and (2) to develop classification indicators that will be evaluated along the whole crafting process (i.e. from the initial soundboard selection to the final instrument).

Acknowledgments

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