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On the use of tonewood leftovers for the elastic constants estimation of musical instruments top plates

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Estimating the elastic properties of tonewood is a crucial step when dealing with numerical models or when a specific target vibroacoustics response is desired for a new instrument. However, not always experimental measurements can be run on the real instrument soundboard. Soundboards leftovers might be used to estimate the plate elastic behavior. Various estimation methods exist involving measurement equipment and computational methods. This paper investigates the feasibility of using leftover pieces to estimate the elastic parameters of instrument top plates. First, consistency in the estimation of elastic constants is assessed under different experimental setups. The verification is then conducted by comparing vibrational patterns obtained by finite element models computed with the estimated elastic parameters to those of the actual soundboards. While consistent elastic properties can be estimated from tonewood leftovers, a single sample approach may not fully represent the material's overall elastic behavior, due to natural wood variability and challenges in establishing ideal boundary conditions. The need to define a tolerable error in the modal behavior between two musical instruments remains an open question for further research.

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1. INTRODUCTION

String-based musical instruments can radiate sound efficiently thanks to their soundboards, whose radiating surfaces can be modeled as plate-like structures. While the vibroacoustic signature of an instrument is largely influenced by geometrical design choices,[1] accurate material characterization remains important for numerical modeling and for ensuring replicability. Over the last decades, many non-destructive estimation techniques have been published to provide an accurate approximation for the main rigidity constants of thin plates used in musical instruments making. These are defined as:

$$D_x = \frac{E_x L_z^3}{12(1-\nu_{xy}\nu_{yx})}, \qquad D_y = \frac{E_y L_z^3}{12(1-\nu_{xy}\nu_{yx})}, \qquad D_s = \frac{G_{xy} L_z^3}{3}, \tag{1}$$

where E_x, E_y are Young's moduli (in Pa), ν_{xy}, ν_{yx} are dimensionless Poisson's ratios and G_{xy} is a shear modulus (in Pa). The work conducted by Caldersmith[2] and McIntrye and Woodhouse[3] introduced analytical formulae to estimate the elastic constants of thin rectangular samples under free boundary conditions (BCs). More recently, the experimental routine implemented in,[4] made it possible to accurately characterize non-standard tonewood geometries by taking advantage of finite element modelling (FEM) and advanced experimental modal analysis (EMA) setups. Neural networks were used to propose a method for the estimate of spruce thin plates which proved to speed-up computational times.[5] Finally, an experimetal method was introduced by the authors allowing for an accurate estimation of thin tonewood samples under arbitrary boundary conditions by exploiting numerical simulations and the least-squares minimisation technique.[6] While the full method is not reported here for brevity, the core of it relies on the knowledge of so-defined linear modal coefficients. These coefficients are found through a simple linear fit from a set of numerical training plates sharing the same BCs and aspect ratios of the experimental plate under test. Once these coefficients are successfully retrieved and at least three or more experimental modes of the investigated plate are correctly identified, the elastic constants can be estimated via a least-squares minimisation.[6] A comprehensive description, validation and benchmarking of the method is found in.[6]

Besides the choice of the preferred estimation approach, the reliability of using tonewood leftovers to characterize the elastic properties of the whole instrument top plate —and thus estimating their modal behavior— remains uncertain. Nonetheless, access to the original musical instrument soundboard might be restricted, either due to conservation requirements or because the instrument is no longer available. Hence, EMA campaigns can not be used to calibrate a numerical model or to set a target modal behavior for a new instrument.

This pilot study examines two cases to assess whether soundboard leftovers can be used to accurately characterize the material properties of musical instrument top plates. FEM models of a guitar and a kantele top plate will be implemented based on estimated elastic and physical properties. Simulated results will be compared against EMA measurements data on the real instruments plates to assess the accuracy of the predicted modal behaviours.

2. CASE STUDY 1: GUITAR TOP PLATE LEFTOVER

A guitar top plate was obtained by first gluing together two book-matched rectangular halves. The board was then thinned to reach the desired thickness of $\approx 3.3mm$. Finally, the board was shaped and a suitable leftover sample was identified as shown in Fig. 1. The trivial known properties of the shaped guitar plate are reported in Table 1.

A $[m^2]$	h $[m]$	$\rho\ [Kg/m^3]$
$\approx$ 0.16	$\approx$ 0.0033	$\approx$ 385

Table 1: Known geometrical properties and measured density of the guitar top plate.

The sample was constrained to cantilever BCs (C-F-F-F), as illustrated on the right side of Fig. 1. Because the leftover was stored under different environmental conditions, the density of the sample was estimated before running the estimation routine. The dimensions of the vibrating plate's area are reported in Table 2. Variations in wood density are expected even within the same tonewood reference.[7] Furthermore, changes in fiber orientation, annual rings arrangement and moisture content can lead to local density variations.[8,9] For the purposes of this study, these uncertainties were not addressed.

$L_x\ [m]$	$L_y\ [m]$	$h\ [m]$	$\rho\ [Kg/m^3]$
$\approx$ 0.077	$\approx$ 0.093	$\approx$ 0.0033	$\approx$ 390

Table 2: Known geometrical properties and measured density of the leftover from the guitar top plate.

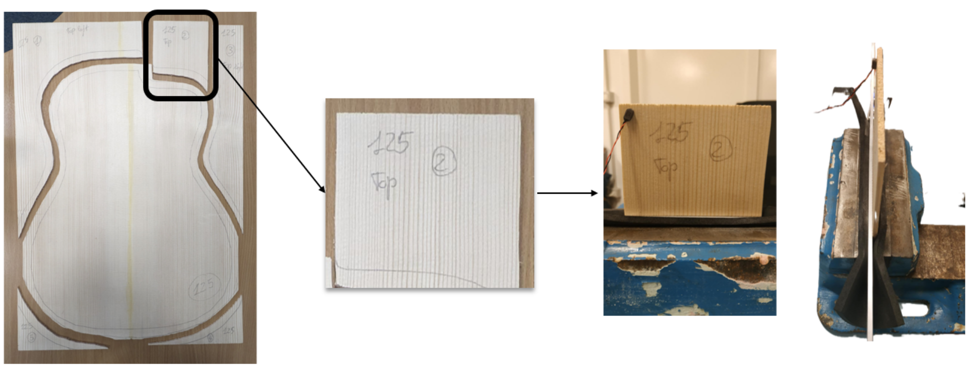
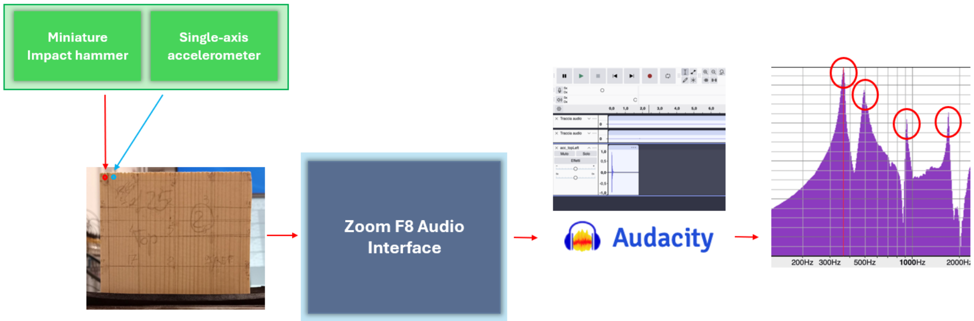


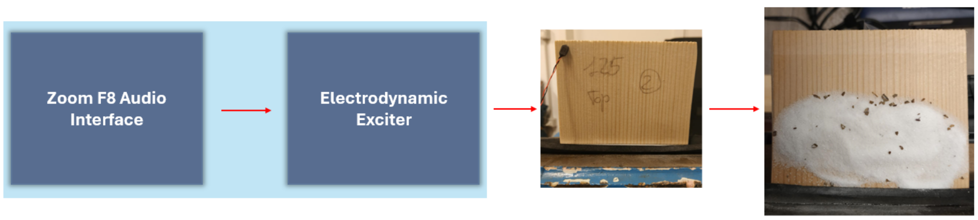
Figure 1: Identification of the guitar top plate leftover sample. On the left: Guitar plate after cutting to final shape. On the right: selected guitar plate leftover constrained under cantilever boundary conditions (C-F-F-F) using a bench vise. A layer of foam is placed between the vise and the plate to prevent denting or damage.

A. EXPERIMENTAL ESTIMATION SET UPS ASSESSMENT

Two experimental setups were tested to check the consistency of the estimation routine. In both cases a small impact hammer was used to excite the sample while a single axial accelerometer was used to acquire the response signal. In the first set up, only the accelerometer's signal was recorded through a zoom F8 audio interface and stored in Audacity. A simple visual peak identification was conducted by looking at the spectrum computed through the software Fast Fourier Transform (FFT) algorithm. Chladni pattern tests[10] were run on the specimen by generating pure tone signals corresponding to the identified frequency peaks through a dedicated patch implemented in PureData and available online at: https://github.com/Nemus-Project/pd-utilities/tree/main/signals_2_soundboards . A simple illustration of the measurement chain is illustrated in Fig. 2.



(a) Step 1: From left to right: illustrative diagram for the frequency peaks identification measurement chain. One accelerometer position (light blue) and one impact hammer location (red) are chosen at the top-left corner of the sample.



(b) Step 2: From left to right: illustrative diagram of the measurement chain for the identification of the ODSs through Chladni patterns tests.

Figure 2: Experimental Setup 1 for the Guitar leftover.

In the second experimental set up, the accelerometer roved across 11 different measurement locations on the tonewood specimen. Both the impact hammer and the accelerometer signals were acquired through dedicated National Instruments Compact DAQs. The force and acceleration data were then processed using the BK Connect software which computed the different frequency response functions (FRFs) per each point and reconstructed the experimental modal shapes. Fig. 3 illustrates the measurement setup.

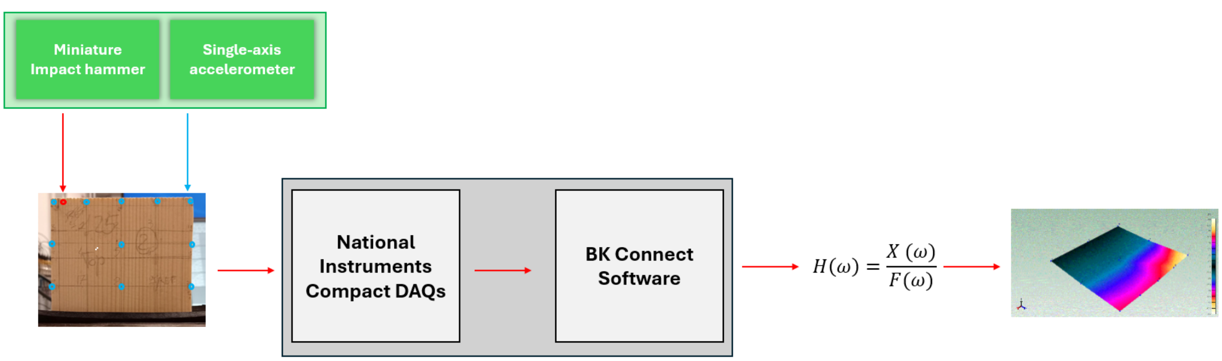


Figure 3: Experimental Setup 2 for the Guitar leftover. From left to right: Illustrative diagram for the second experimental setup used to compute the necessary modal parameters through BK Connect software. Eleven accelerometer positions (light blue) and one impact hammer location (red) are identified on the plate.

Fig.4 reports the first four modes that were successfully identified from each measurement campaign. It can be seen that the differences between the identified frequency peaks are $\leq 3\%$ and good agreement is also observed when comparing the reconstructed modal shape with the observed chladni figures.

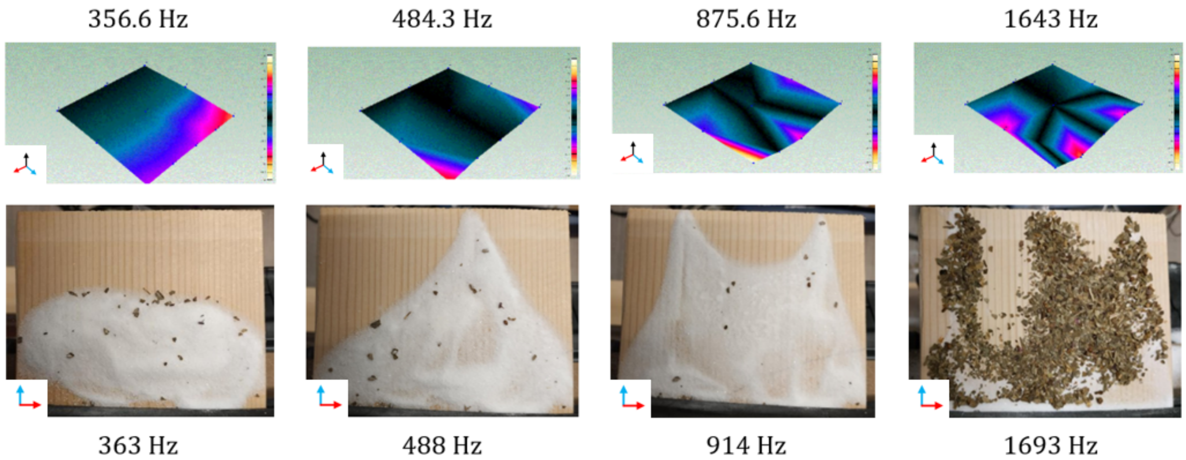


Figure 4: Modes detection comparison between the two experimental setups. Top row: Computed experimental modal shapes. Bottom row: Observed operational deflection shapes (ODSs) on the leftover sample.

Table 3 reports the estimated mean values along with the standard deviations for the young moduli and shear modulus obtained by considering the two sets of frequencies identified from the different setups.

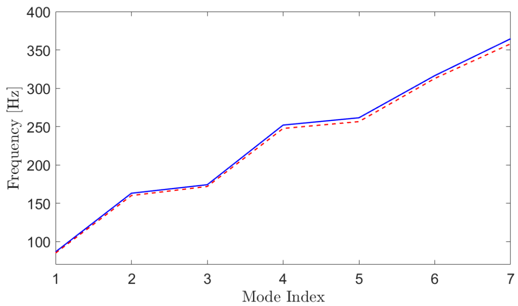
		$\tilde{E}_x$ (GPa)	$\tilde{E}_y$ (MPa)	$\tilde{G}_{xy}$ (MPa)
Experimental Setup1	mean	6.3	788	563
	rel. std	1.22%	2.55%	3.57%
Experimental Setup 2	mean	6.2	763	507
	rel. std	2.12%	4.5%	6.79%

Table 3: Estimated elastic constant mean values and relative standard deviations for the two experimental setups.

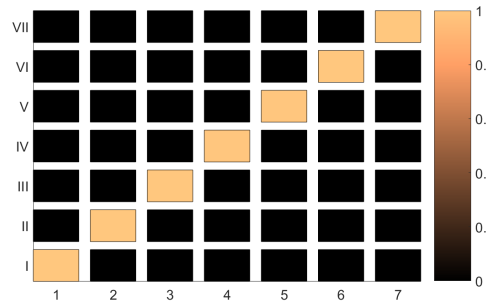
To further assess the impact of the different estimated elastic properties on the plate modal behavior, a FEM model of the guitar top plate was implemented in COMSOL Multiphysics and two different eigenfrequency studies were carried out by using the two datasets of elastic constants. For the purpose of the study, the estimated leftover density from Table 2 was used as input value. Fig. 5a compares the first seven eigenfrequencies obtained using the first and the second experimental setups (respectively in solid blue line and dotted red line). Discrepancies are reported in Table 4. Fig. 5b also shows a comparison conducted based on the Modal Assurance Criterion (MAC),[11] demonstrating an high correlation between the two series of mode shapes. Given the results, consistency is confirmed, and differences between the setups are considered negligible.

Mode Index	1	2	3	4	5	6	7
$2\frac{\lvert f_1-f_2\rvert}{f_1+f_2}$ [%]	≈ 1.7	≈ 1.8	≈ 1.3	≈ 1.8	≈ 1.9	≈ 1.2	≈ 1.8

Table 4: Discrepancies in the estimated eigenfrequencies using the two sets of elastic constants values.



(a) Eigenfrequencies comparison.



(b) Eigenshapes comparison.

Figure 5: Modal comparison between the two sets of estimated elastic constants from the different experimetal setups. The first seven modes are considered.(a): Blue solid line: simulated eigenfrequencies from Experimental Setup 1. Red dashed line: simulated eigenfrequencies from Experimental Setup 2. (b): MAC analysis between the two sets of simulated eigenshapes.

B. TOP PLATE EMA MEASUREMENTS

EMA measurements were conducted on the real guitar plate in order to compare the resulting modal behavior to the FEM model. To this purpose, a dedicated clamping system was used to fully constrain the guitar board. Two plate impulse responses were collected by exciting the board with an electrodynamic transducer (i.e. exciter) and using the exponential sine sweep method (ESS).[12] The exciter roved over two different excitation points on the left and on the right waist of the board (see red circles in Fig.6) while the response was recorded using a small single axial accelerometer located on the top right side of the board (see light blue circle in Fig.6). Further information about the validation of the presented set up and on the use of electrodynamical transducers for EMA can be found in.[13] In the same manner as it was described for the first experimental measurement setup described in section 2.1, *Chladni patterns* tests were carried out on the board after a visual inspection of the peaks from the plate frequency spectra.

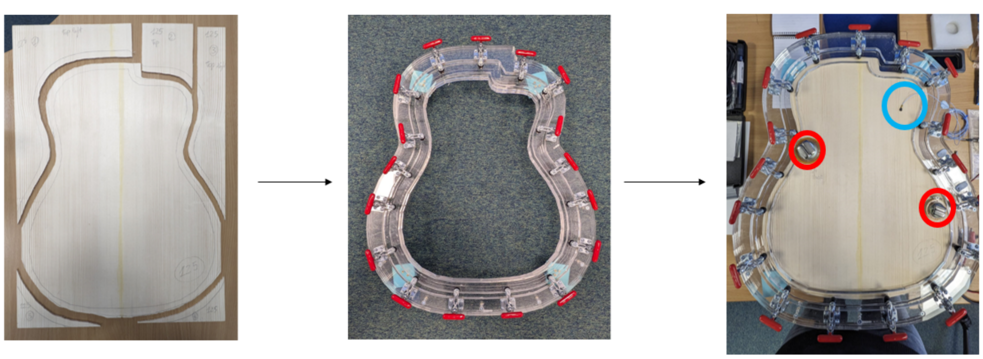


Figure 6: On the left: guitar top plate after being cut to shape. In the middle: Clamping system used to implement the experimental clamped BCs. On the right: Guitar top plate under fully campled BCs. In red on the right the two different exciter positions and in light blue the accelerometer measurement location.

C. ESTIMATED VS OBSERVED MODAL BEHAVIOUR

A visual comparison between the estimated and observed deflection patterns of the guitar top plate is presented in Fig.7. A good agreement can be seen for the majority of the identified mode shapes and ODSs and differences between estimated eigenfrequencies and identified natural frequency peaks vary from 0.5% up to $\approx 9\%$ (SD = 3.1%).

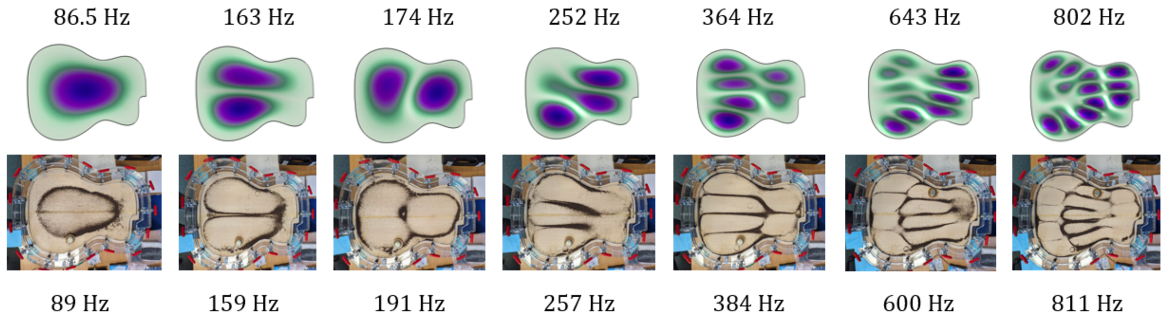


Figure 7: Comparison of simulated and experimental mode shapes of the guitar top plate. Top row: Simulated eigenshapes from the guitar plate FEM model. Bottom row: Observed ODSs through Chladni patterns tests, Frequencies are reported for each mode.

3. CASE STUDY 2: KANTELE TOP PLATE

For the second case study, a concert kantele top plate is considered. The instrument was originally built by gluing together several planks of tonewood and then shaping the board to the desired geometry. In this case, a small rectangular leftover from one of the remaining used planks was considered and fixed to the same set of BCs as for the guitar plate leftover. The leftover is shown in Fig. 8. The trivial properties of the kantele top plate and those of the leftover are reported in Tables 5 and 6.

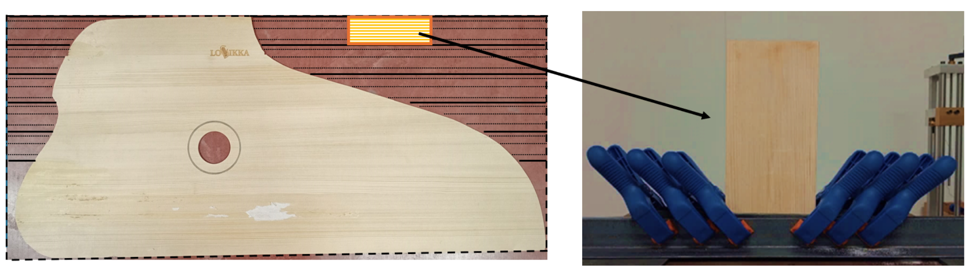


Figure 8: Kantele plate leftover sample constrained under cantilever boundary conditions (C-F-F-F). The selected rectangular piece, cut from the original top plate, is clamped using the same setup as in the guitar plate case.

A $[m^2]$	h $[m]$	ρ $[Kg/m^3]$
$\approx$ 0.35	$\approx$ 0.0039	$\approx$ 464.4

Table 5: Known geometrical properties and measured density of the kantele top plate.

L_x $[m]$	L_y $[m]$	h $[m]$	ρ $[Kg/m^3]$
≈ 0.223	≈ 0.114	≈ 0.003	≈ 473.9

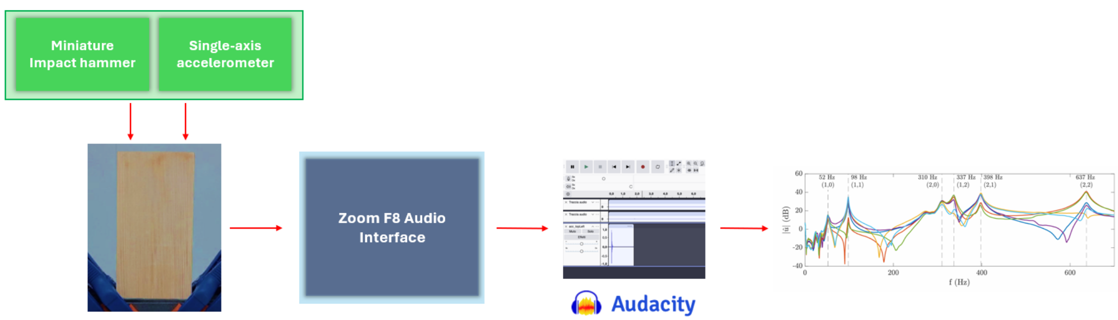
Table 6: Known geometrical properties and measured density of the kantele top plate.

A. EXPERIMENTAL ESTIMATION SET UP

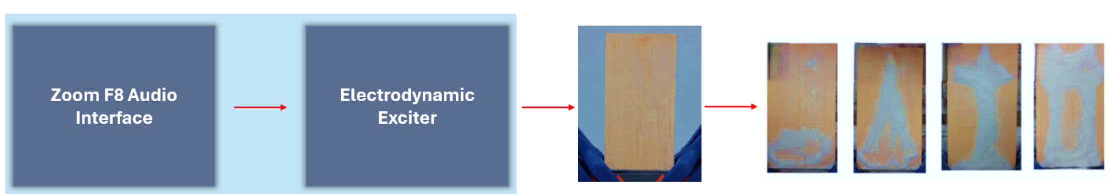
As for the first experimental setup on the guitar leftover, a similar measurement chain was used here. The impact hammer roved across six different excitation points and the computed averaged accelerometer spectrum was used to identify the main natural frequency peaks. The experimental measurement setup is described in[6] and the estimated elastic constant values are reported here from the same study.

	$\tilde{E}_x$ (GPa)	$\tilde{E}_y$ (MPa)	$\tilde{G}_{xy}$ (MPa)
mean	13	700	668
rel. std	4%	2.2%	6.5%

Table 7: Estimated elastic constant mean values and relative standard deviations for the kantele leftover.[6]



(a) Step 1: From left to right: Illustrative diagram for the frequency peaks identification measurement chain. One accelerometer position and one impact hammer location are selected on the sample.



(b) Step 2: From left to right: Illustrative diagram of the measurement chain for the identification of the ODSs through* Chladni patterns *tests.

Figure 9: Experimental Setup for the Kantele leftover.

B. TOP PLATE EMA MEASUREMENTS

For the EMA measurement campaign, the kantele top plate was resting on three small foam pieces, emulating ideal free BCs. An impact hammer was used to excite the board in one excitation point while a laser doppler vibrometer (LDV) was scanning over the entire vibrating plate surface. Finally, a method based on the Complex mode indicator function (CMIF) was used as described in,[14] allowing the reconstruction of the plate modal shapes.

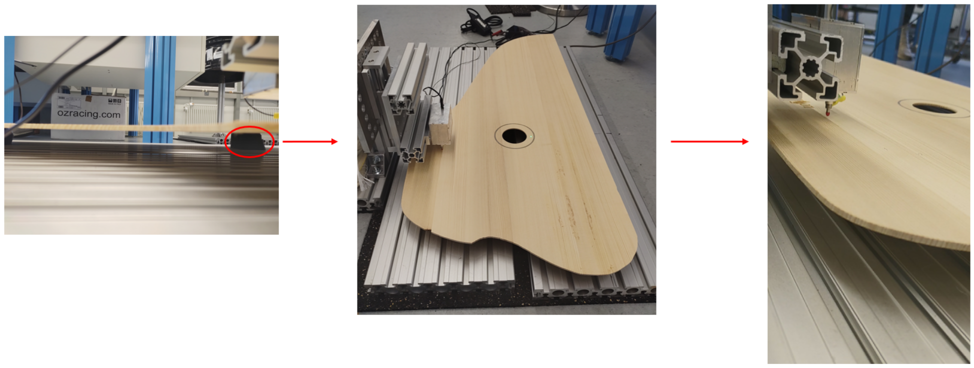


Figure 10: EMA setup on the kantele top plate. Three pieces of foam are used to implement experimental BCs. One impact hammer position is selected on the plate's surface and the LDV is used to scan over the vibrating surface.

C. MODAL COMPARISON

Fig. 11 shows the visual comparison between estimated and measured modal shapes. Here, while some similarity is observed between the results, larger discrepancies are observed with respect to the guitar plate case scenario with variations ranging from 5.6% up to 30% (SD = $\pm 8.4\%$). These differences might be explained by different sources of uncertainty. First, the difficulty in setting up experimental free BCs could have led to variations between the measured and estimated data. Furthermore, the estimation was solely based on a relatively small sample from one of the different planks used to build the instrument soundboard so the estimate may not have been representative for the overall elastic behavior of the top plate.

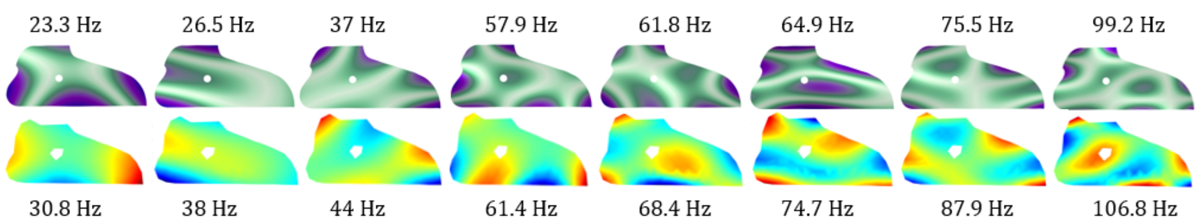


Figure 11: Comparison of simulated and experimental mode shapes of the kantele top plate. Top row: Simulated eigenshapes from the kantele plate FEM model. Bottom row: Computed experimental modal shapes. Frequencies are reported for each mode.

4. CONCLUSION

This paper presented a first pilot study on the use of tonewoods leftovers for accurate material characterization of musical instruments soundboards. The results demonstrated how a consistent elastic constants estimate can be obtained when comparing different measurement and data processing set ups under the same set of experimental BCs. Specifically, the use of cantilever BCs (C-F-F-F) proved to be well suited for the modal detection on common leftover samples.

A good estimate of the guitar plate's modal behavior was achieved with maximum discrepancies among the first identified modes $\leq 9\%$. On the other hand, larger variations were observed in the case of the kantele plate. These discrepancies are probably due to the challenges in achieving ideal experimental BCs. It is also important to note that estimating elastic properties from a single tonewood specimen taken from a single plank may not sufficiently characterize the entire board's material and physical properties. This is due to natural variations in fiber orientation and ring distribution, which are common in stringed instruments manufactured using traditional methods. Additionally, this study did not account for the moisture content of the different leftover samples, which introduces further uncertainty in the estimation of elastic constants. Future research will address this limitation.

Finally, while eigenfrequencies distribution is not sufficient to fully inform numerical models, it still remains relevant for repeatability purposes in instrument making. Thus, the identification of a tolerable error and just noticeable differences (JNDs) in the modal behavior when comparing two musical instruments (or their top plates) remains an open question for further investigations.

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