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REPRODUCIBILITY IN THE CONSTRUCTION OF TRADITIONAL WOODEN AND 3D-PRINTED PLASTIC SOUNDBOARDS FOR STRING INSTRUMENTS

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ABSTRACT

This study aims to quantify the reproducibility of 3D-printed soundboards for string musical instruments by comparing the frequency responses of ukulele tops made of three materials: Engelmann spruce (traditional tonewood), Chilean laurel (local tonewood), and PLA+ (3D printing material). Traditional Latin American luthiers fabricated the soundboards and the PLA+ plates were produced using FDM printing.

The frequency response of free soundboards and admittance measurements coupling the plates to printed bodies were performed. Pearson correlation coefficients assessed the similarity between free plates' responses within each material. As expected, the results show notable variability in the wooden plates: correlations between laurel plates range from 0.19 to 0.50, and between spruce plates, from 0.36 to 0.65. In contrast, the PLA-printed plates show high consistency, with correlations close to 0.94. Similar trends were obtained comparing admittance measurements in plates coupled to printed soundboxes, although the correlation values decrease significantly when compared to those of the free plates. These findings suggest that 3D printing offers promising consistency for the construction of reproducible musical instruments, which may benefit not only the commercial manufacturing of instruments but also research based on them.

Keywords: *3D-printing, 3D-printed guitar, guitar making consistency*

1. INTRODUCTION

One of the major challenges in the construction of string instruments is reproducibility. Even when working with wood from the same trees, using identical techniques and following parallel processes to ensure identical environmental conditions, the resulting instruments will still differ. This is due to the intrinsic variability of wood [1]. This difficulty in achieving consistent construction, combined with the rapid evolution of digital design and manufacturing techniques, has led to the proposal of 3D printing as an alternative to traditional fabrication methods [2-4]. This raises the question: how reproducible are instruments made using these techniques, and how does this reproducibility compare to traditional materials? To address this question, a vibroacoustic study of ukulele soundboards was conducted. The study involved comparing the frequency response of three sets of soundboards made from different tonewoods and 3D printing material. The response was measured under free boundary conditions and when coupled to 3D-printed resonance boxes, and the comparison was done using the Pearson correlation coefficient.

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2. METHODS

This study selected three materials to fabricate ukulele soundboards: Chilean laurel (*Laurelia sempervirens*), Engelmann spruce (*Picea engelmannii*), and PLA+. The three materials' density (ρ) and elastic constants (E_L and E_R) were measured. For the wooden samples, the elastic constants were obtained applying Caldersmith's equations [5], following the method proposed in [6]. For PLA+, tensile tests were conducted on specimens with the same orthotropic geometry as applied in the soundboard printing. The tensile tests followed the ASTM D638 standard, using a Type IV specimen. The equipment used was an Instron testing machine, and the tests were conducted at a speed of 50 mm/s. All tests were repeated on three different samples of each material.

The soundboards were fabricated once the materials were characterized, including the internal bracing structure. Fig. 1 shows (a) a printed soundboard, (b) a template for constructing the wooden soundboards and (c) a 3D-printed resonance box. The wooden soundboards were crafted by local luthiers. Unlike traditional construction, the ukulele soundboards were made from a single piece, rather than by joining two identical halves. The bracings were made using Spanish Cedar (*Cedrela odorata*). (see Fig. 2). The plates were printed with orthotropic geometries, with the direction of greatest stiffness aligned parallel to the string direction.

The frequency response of the soundboards was analyzed under free boundary conditions supported by elastic bands. A Stanford SR780 spectrum analyzer generated a swept sine from 20 Hz to 1 kHz. The signal was amplified using a Gemini XGA2000 amplifier and fed into a loudspeaker, which excited the plates. The response was recorded using a PCB 356A14 micro accelerometer connected to a PCB 408E09 signal conditioner. The signal was then returned to the spectrum analyzer, obtaining the frequency response spectrum for each plate. To quantify the degree of similarity, Pearson's correlation coefficient (r) was used [7]:

$$r = \frac{\Sigma(X_i - \overline{X})\Sigma(Y_i - \overline{Y})}{\left[\Sigma(X_i - \overline{X})^2 \, \Sigma(Y_i - \overline{Y})^2\right]^{1/2}}, \quad (1)$$

Figure 1. (a) Printed soundboard, (b) Template for constructing the wooden soundboards and (c) 3D-printed resonance box.

Figure 2. Wooden soundboards.

where X and Y are the two datasets being compared, and $\overline{X}$ and $\overline{Y}$ are their respective means. This coefficient is a statistical measure that quantifies the linear relationship between two variables. It ranges from -1 to 1, where: (a) r = 1 means a perfect positive correlation (both variables increase together, (b) r = -1 means a perfect negative correlation (one variable increases while the other decreases), (c) r = 0 means no correlation (the variables are independent). The usefulness of this coefficient has been demonstrated in various studies where it was necessary to compare spectra obtained through different techniques as Raman Spectroscopy, Infrared Spectrometry, among others [8-10].

After characterizing the soundboards, they were glued to 3D-printed ukulele bodies. The assembled bodies were again supported on elastic bands, and their admittance was measured at the bridge position. This was done using a PCB 086C03 impact hammer and a PCB 356A14 micro accelerometer. The measurements were performed using the ObieApp software (see Fig. 4). The resulting spectra were again compared using Pearson's correlation coefficient.

3. RESULTS, ANALYSIS AND DISCUSSIONS

Table 1 presents the results of the measured properties for the different materials. Additionally, it indicates from which specific plates each soundboard plate was extracted.

Fig. 3 shows the spectra obtained for the printed plates, while Fig. 4 presents the spectra associated with the wooden plates. In each case, a zoomed-in view is included to observe the low-frequency behavior. It is possible to observe significant differences in the spectra of the wooden plates (Fig. 3a,b), while more similar behaviors are observed in the printed plates (Fig. 3c). The quantification of these similarities is shown in Fig. 4.

Table 1. Properties of the applied materials

Material	E_L (GPa)	E_R (GPa)	ρ (kg/m³)	Soundboard
Engelmann Spruce A	7.96 ± 0.66	0.70 ± 0.06	317 ± 11	1 - 2
Engelmann Spruce B	8.40 ± 0.47	0.59 ± 0.04	331 ± 8	3
Chilean Laurel A	16.23 ± 1.73	0.83 ± 0.09	505 ± 24	1 - 2
Chilean Laurel B	10.98 ± 1.17	0.77 ± 0.08	513 ± 24	3
PLA+	2.05 ± 0.03	1.83 ± 0.04	1039 ± 214	1 - 2 - 3

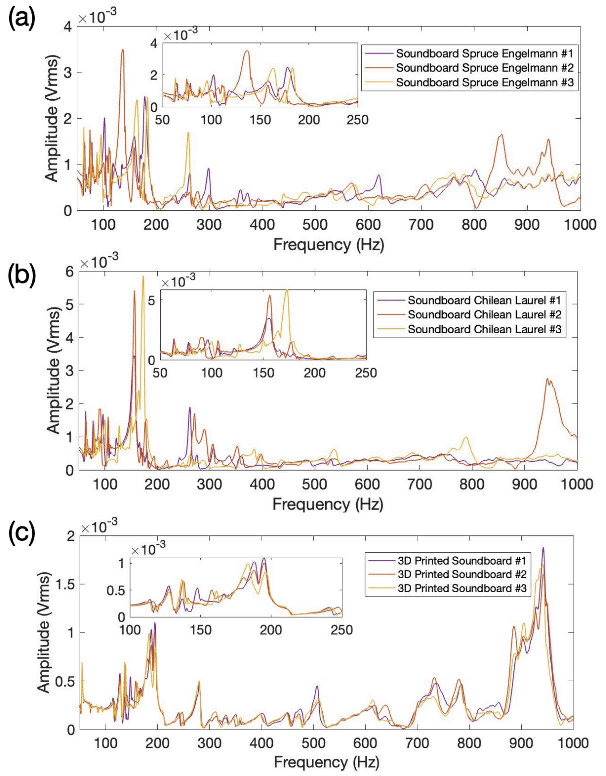

Figure 3. Measured spectra for (a) Spruce Engelmann soundboards, (b) Chilean Laurel soundboards, and (c) 3D-Printed soundboards.

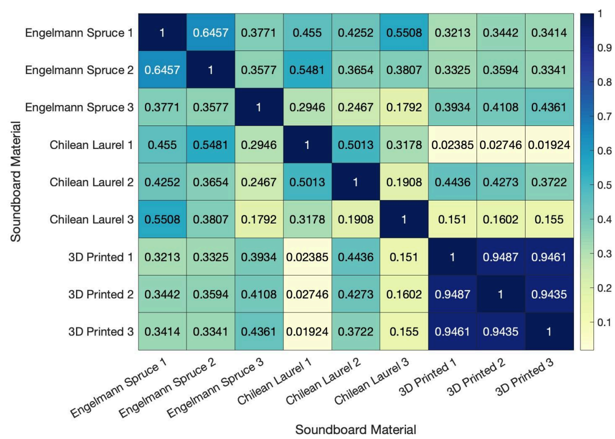

Figure 4. Pearson correlation coefficient obtained for each pair of plates.

Correlations between laurel plates range from 0.19 to 0.50, and between spruce plates, from 0.36 to 0.65. In contrast, the 3D-Printed plates show high consistency, with correlations close to 0.94. Similar trends were obtained comparing admittance measurements in plates coupled to printed soundboxes, although the correlation values decrease significantly when compared to those of the free plates (see Fig.5). In the case of the wooden soundboards, it can be observed that those made from the same plate have a higher correlation coefficient when compared to each other.

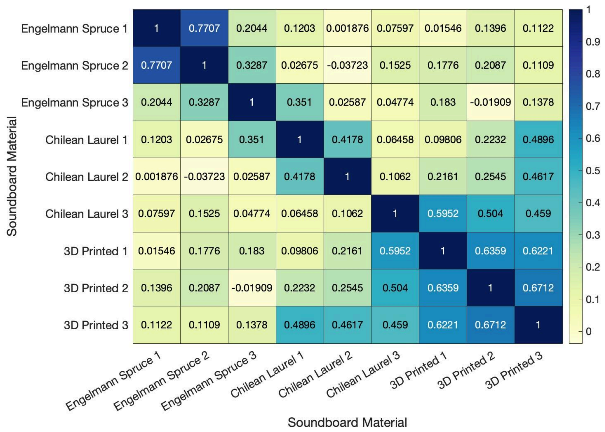

Figure 5. Pearson correlation coefficient obtained for each pair of plates coupled to 3D-Printed soundboxes.

4. CONCLUSIONS

Resonance plates for ukuleles have been made from different materials, including a traditionally used wood, a local wood, and PLA+ (a 3D printing material). The reproducibility of their vibratory behavior was assessed through acoustic response and admittance tests on both free plates and plates coupled to 3D-printed resonance boxes. The similarity between resonance spectra was measured using the Pearson Correlation Coefficient, showing that 3D-printed plates generally exhibit better reproducibility in their responses compared to wooden plates.

The fact that the Pearson Correlation Coefficient decreased with the coupled bodies (despite these being 3D printed and therefore expected to have the same level of reproducibility as the soundboards) highlights the relevance of the vibratory behavior of elements that are often overlooked, difficult to control, measure, and even model numerically, such as adhesives and joints between parts.

In any case, the consistency observed in the behavior of the printed parts could be useful for exploring other factors, such as how geometry affects the acoustic behavior of individual components from traditional instruments, while eliminating variability due to material differences.

These results highlight the potential of 3D printing as a manufacturing method that offers greater consistency in vibratory behavior, which could be advantageous for instrument design and production.

5. ACKNOWLEDGMENTS

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