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PREDICTING THE EFFECTS OF BRACING PATTERN MODIFICATIONS ON ACOUSTIC GUITAR SOUNDBOARDS

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ABSTRACT

Wood has always been a material of choice for the manufacture of many musical instruments. Specifically, softwoods such as spruce (*Picea spp.*) are common for stringed instrument soundboards. However, manufacturers are faced with multi-causal shortage (silviculture policies, diseases, climate change, etc.). This context has been driving the search for alternatives such as lesser used wood species or composite materials. Can a soundboard's material and shape be optimally substituted so that the instrument's acoustic features remain identical ? An "Orchestra Model" flat-top guitar is considered in this study, as it is a representative of the typical steel-string guitar. This study's aim is to predict the effect of modifying properties of this soundboard on its vibratory response, in prospect of optimizing the geometry of soundboards made out of alternatives to spruce to reproduce the acoustic response of a given reference. To this end, a numerical model based on the finite element method is proposed and compared to experimental data measured on actual soundboards.

Keywords: *Numerical modeling, Experimental modal analysis, Soundboard*

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1. INTRODUCTION

The soundboards of many stringed instruments are traditionally made from softwoods such as spruce (*Picea spp.*), because of its high specific rigidity, low density, and intermediate quality factor [1]. However, manufacturers have been facing a multi-causal shortage, linked to silviculture policies, diseases caused by insects and fungi and climate change. Alternative materials for instrument making are thus sought by instrument makers and researchers. These substitutes include composite materials [2], lesser used wood species, etc. The impact of these materials on the perceived qualities of the resulting instruments have been studied for violin tops and guitar backs [3, 4]. The instrument's geometry also plays an important role in its vibro-acoustic behavior [5]. For the acoustic guitar, this is reflected in the wide variety of body shapes and bracing patterns offered by instrument manufacturers, associated with different sound aesthetics and playing styles. Can the material and geometrical properties of a soundboard be optimally modified so that the instrument's acoustic features remain the same ? In this study, a numerical model of an acoustic guitar soundboard predicting the effects of material and geometrical modifications is developed and compared to experimental data.

2. METHODS

2.1 Numerical modeling

The studied guitar soundboard is based on the 000/OM body shape introduced by the manufacturer C. F. Martin & Co in the early 20th century, as this guitar shape is emblematic of steel-string acoustic guitars. The plate is of constant thickness h_p, and its material is considered homogeneous and orthotropic along the X and Y directions presented in Fig. 1. A simplified bracing pattern of only three braces is considered : an horizontal brace located above the soundhole is denoted b_h ; the other two, characterized by their angle θ to the Y axis, are denoted $b_{\theta+}$ and $b_{\theta-}$. Braces are considered homogeneous and isotropic ; their cross-section can vary along their length.

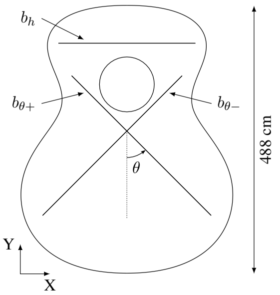

Figure 1. The studied soundboard

The plate is described using the Kirchhoff-Love theory, as it is considered thin enough for shear deformations through its thickness to be neglected. It is characterized by its density ρ, two Young's moduli E_x and E_y, the Poisson's ratio ν_{xy} and the in-plane shear modulus G_{xy}. Similarly, no shear deformation of the braces' is considered : its material is described by the density ρ, the Young's modulus E and the Poisson's ratio ν. The soundboard's plate is modeled with Discrete Kirchhoff Triangular (DKT) elements for its plate and beam elements for its braces. No discontinuity in displacement between the plate and the braces is considered. Mesh generation is handled by the *Gmsh* software at a fixed meshsize of 1 cm ; computations of the finite element problem are performed using *Cast3M*. Eigenmodes are computed by solving the eigenvalue problem corresponding to the oscillation of the conservative system described by the meshed soundboard's mass and stiffness matrices. Viscous damping can by taken into account by assuming complex elastic moduli [6], characterized by their loss factor η.

2.2 Experimental protocol

In order to measure the effects of the braces on a soundboard's modal behavior and compare them to the numerical model, two spruce soundboards were built, as presented in Fig. 2. They are respectively designated as being *X-braced* (θ =45°) and *V-braced* (θ =15°) : they are considered different enough that effects associated with brace positions can be estimated from a single pair of soundboards, as they are assumed to be large in comparison to the variability due to the material and manufacturing tolerances.

Figure 2. *Left,* V-bracing ; *right,* X-bracing

Vibratory measurements were carried out at several manufacturing stages : the measured free vibration of suspended rectangular plates and beams is employed to estimate elastic moduli that can be used in the numerical model [6], while the modal analysis of the finished soundboards serves to validate the model. The latter will be developed here. Free boundary conditions are approximated

Figure 3. Setup for transfer functions measurement

by hanging the soundboard with two pieces of fishing line passing through its soundhole. An impact hammer is used to excite the soundboard, to which two accelerometers are attached in order to measure its vibration. The overall experimental setup is shown on Fig. 3. 26 regularly spaced impact points were selected : 5 measures of the soundboard's response were performed for each of them. Modal analysis of the resulting frequency response functions was performed using an existing Matlab program based on least-square frequency domain estimators.

3. RESULTS

3.1 Input parameters

Tab. 1 presents the elastic properties of spruce, estimated from measurements performed on the rectangular plates used to build both soundboards. ν_{LR} is not experimentally estimated, as its effect on the measured vibratory behavior of the plate is weak compared to that of the other moduli. The value $\nu_{LR} = 0.38$, which is typical for spruce wood, is assumed for the rest of this study [7]. η_L, η_R and η_{LR} are loss factors associated with E_L, E_R and G_{LR}.

Table 1. Estimated material parameters

ρ	460 ± 10 kg.m^{-3}
E_L/ρ	30 ± 2 MPa.kg^{-1}.m^3
E_L/E_R	17 ± 5
G_{LR}/ρ	1.8 ± 0.1 MPa.kg^{-1}.m^3
η_L	0.65 ± 0.04 %
η_R	2.5 ± 0.5 %
η_{LR}	2.0 ± 0.1 %

A plate thickness of h_p = 0.3 cm, braces heights of h_{b_h} = 1.5 cm and h_{b_θ} = 1.0 cm, and braces width of w_b = 1.0 cm are assumed for both soundboards, and will be used in the numerical model alongside the material properties of Tab. 1.

3.2 Model validation

The *Complex Frequency Domain Assurance Criterion* (CFDAC) is used to assess the similarity between the measured and predicted modal behavior of both soundboards [8]. The CFDAC matrices comparing experimental and numerical results for both soundboards are shown on Fig. 4.

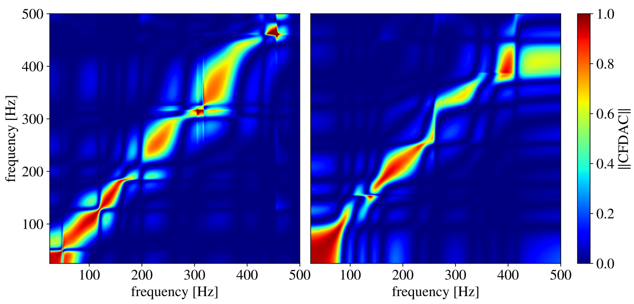

Figure 4. CFDAC matrices for the measured versus simulated V (*left*) and X-braced soundboard (*right*)

An overall similar behavior can be observed between measured and simulated soundboards, reflected by high value on the matrices' diagonals. However, the numerical model does not fit the X-braced soundboard as well as it does the V-braced one : under 200 Hz, the highest CFDAC values are above the diagonal, which means that the experimentally measured behavior is encountered in the numerical model at higher frequencies. A similar phenomenon occurs around 350 Hz. This discrepancy is attributed to the assumption of isotropic braces : the X-bracing pattern implies a significant radial contribution from the braces at their intersection.

3.3 Comparing the effect of the braces

Comparing the soundboards directly can represent a challenge, as they are too different from each other for individual modes or frequency responses to be properly paired using indicators such as CFDAC matrices. In order to circumvent this problem, "intermediate" modes can be computed : reducing incrementally the braces height h_{b_θ} allows to link the modes of fully braced soundboards to those of one without the braces b_θ, and in turn to link the modes of both braced soundboards. 50 simulations were carried out for each bracing pattern with values of h_{b_θ} ranging between 0 and 1 cm. The *Modal Assurance Criterion* (MAC) is used to pair the modes obtained with successive values of h_{b_θ} : their difference is small enough that corresponding modeshapes are near identical, yielding MAC values of almost 1.

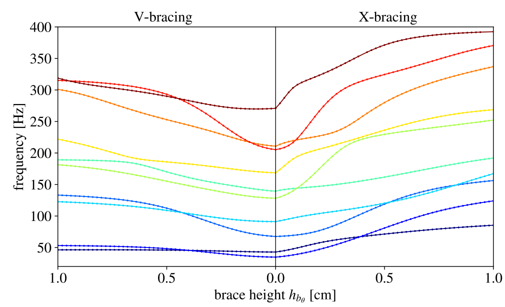

Figure 5. Frequencies of the first 10 modes in function of h_{b_θ} for an X-braced and V-braced soundboard. Paired modal frequencies are connected with a line and are of the same color.

Fig. 5 shows the evolution of the soundboard's first ten modal frequencies in function of h_{b_θ}. It can be observed that modes decrease in frequency as they approach

$h_{b_\theta} = 0$ cm for both bracing patterns : the braces expectedly stiffen the plate more than they weigh it down. Having linked the first modes of both soundboards, the effect on a given mode of a bracing pattern change can be expressed experimentally and be compared with the numerical results.

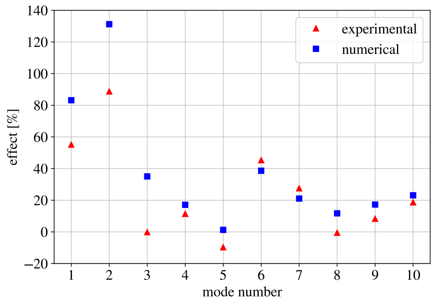

Figure 6. Measured and computed effect on modal frequencies of changing from V to X-braces

Fig. 6 presents the measured and computed relative difference in modal frequencies between V and X-braced soundboards. The overall behavior of the numerical model is consistent with the experimental data, apart from the overestimated effect of the X-bracing on the first three modes. This discrepancy corresponds to the one observed on the CFDAC matrix, which is caused by the assumption of isotropic braces. It can be observed that the X-bracing provides an increase in almost all modal frequencies over the V-bracing, and especially for the first two modes. These two correspond in the V-braced soundboard to a radial bending mode and a twisting mode, that are almost unaffected by the braces because of the small angle θ. When replaced with an X-bracing pattern, the diagonal braces stiffens them significantly.

4. CONCLUSION

A numerical model of a braced guitar soundboard was developed and compared to experimental using indicators such as CFDAC matrices and differences in the modal frequency of two soundboards paired through the parametric study of the braces' height. A reasonably good agreement between the measured and modeled soundboards was observed. This numerical model can provide information about the influence of its material and geometrical properties on the resulting frequency response : in the later parts of this study, the soundboard's geometry will be optimized to maintain given vibratory properties when material parameters are substituted. The optimization results will finally be tested through a perceptive study that will employ synthesized audio samples of guitar playing, using the optimized frequency responses.

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