FEM SIMULATIONS AND EXPERIMENTAL VALIDATION OF FREQUENCY RESPONSE PREDICTION FOR ACOUSTIC SOUNDBOARDS

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1. Abstract

In this paper FEM models of several acoustic soundboard were produced. Initially a simplified case of a rectangular plate similar to a distributed mode loudspeaker was simulated, followed by an acoustic guitar soundboard with fixed constraints at the edges. A process of model fitting was performed, in the attempt to match the orthotropic behaviour of the material used for the membranes, namely red cedar.

Thanks to this step-by-step approach, both the Eigen-modes analysis and the forced response were computed in order to predict the overall frequency spectrum of the acoustic guitar soundboard. Eventually, an informative comparison between simulated data and measurements was obtained.

Results indicate that FEM modelling and a measurement system could become vital manufacturing tools to optimise the workflow in the luthier shop when a specifically tailored response needs achieving. Data also shows that even a simplified FEM model exploiting wood's specific anisotropic properties can be accurate and helpful when designing new bracing patterns or analysing specific instrument's resonances.

Future research will expand the presented FEM simulations to include the guitar's body with its Helmholtz resonator, and the mutual coupling of the sides and the backplate. This will increase the accuracy of the available predictions and will possibly capture more similarities between acoustic instruments and loudspeaker enclosures.

1. Introduction

Literature is well populated with studies dedicated to the modelling and design of acoustic guitars' soundboards and bracing patterns. In recent years a growing set of PhD researches and articles regarding the prediction of the modal behaviour of simplified plates using FEM analysis and software [1,2,3] also emerged, and most of it was collected and made accessible by Gore in his exhaustive book [4].

Also, the authors penned a few articles discussing the pros and cons of two alternative measurement methods which could be easily undertaken in a small luthier shop or in an End of Line (EOL) test [5,6] of a larger manufacturing facility.

This paper wishes to bring together the two sides of the problem; indeed, with the correct assumptions regarding the wood structure and characteristics, FEM simulations are now capable of predicting the behaviour of a guitar soundboard placed on fixed constrains, and measurements can validate the models.

While such setup is not identical to a fully assembled guitar, the readers can understand how the approach could be used to reverse engineer already-made instruments, thus setting new standards for guitar manufacturing, especially considering the scarce availability of some wood species. Indeed, the need for a sustainable guitar manufacturing industry strongly suggests to maximise the yield and make the best use of resources [7, 8, 9, 10, 11, 12].

Simulations help us understand wood's behaviour, and pave the road to more robust manufacturing processes in which the design of bracing and soundboards could be tightly correlated to a target performance, despite difference in density and stiffness of each peculiar material.

Indeed, it is now possible to simulate the output of one geometry implemented using different types of resonant wood (e.g. cedar or spruce), or to evaluate the subtle tonal nuances produced by different species of spruce coming from Asia, Europe or America. This can foster the use of local wood species, an evident trend in the market of folk instruments, which is again a more sustainable approach to manufacturing.

The paper starts addressing a simplified scenario, consisting of a rectangular plate constrained at all edges. Thanks to this initial study, presented in Sect. 2, the necessity of including the anisotropic characteristics of wood is justified.

In Sect. 3, a more accurate FEM model is used to predict the first five modes and Eigen-frequencies of a guitar soundboard, which is simulated and measured in a fully constrained setup.

Section 4 shows the use of simulations to design an alternative bracing pattern with different performance criteria, while section 5 comments about the results and the discrepancies between the simulations and the experimental measurements, and leaves the readers with a few open questions and the direction of future studies.

2. FEM model of a constrained rectangular plate

In this section we present a basic FEM model to predict the first six modes and Eigen-frequencies of a rectangular plate. The material used is red cedar, whose standard characteristics can be found here (https://www.wood-database.com/western-red-cedar/).

The average density of such material is 370 kg/m^3, while its elastic modulus is approx. 7.66GPa. What it's not stated clearly though is that while the former could be reasonably stable in a normal quarter sawn cut used to make a book-matched soundboard (which is a board manufactured from a thick plate, which is cut in half on the longitudinal direction and then glued back to double its width), the latter could vary of a factor 10 depending on whether it's measured *along* the grain, or *across* it. Figure 1 shows a typical log with the axis used in the description above and, more importantly, in the FEM models and simulations.

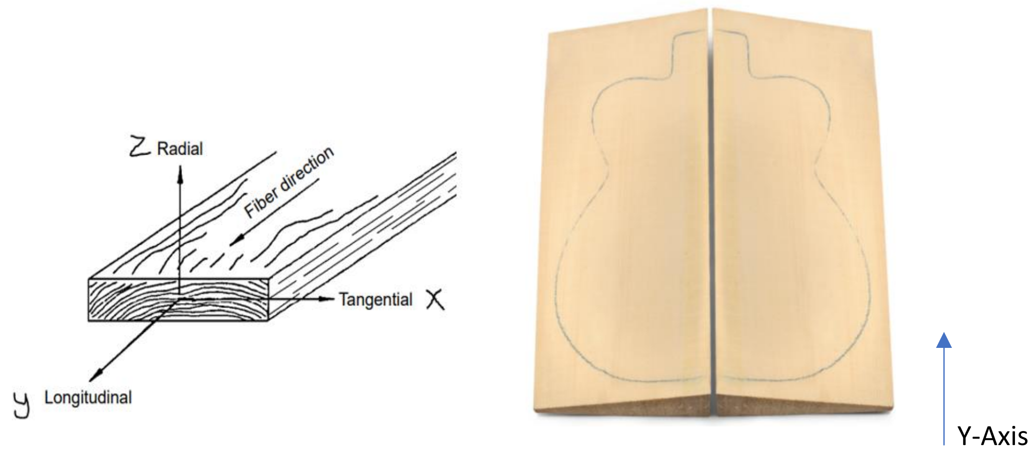

Fig. 1. Left: quarter sawn wood cut, details of the axis orientation. Right, example of book-matched cedar top, where the grain runs along the longitudinal axis. The Y-Axis is the grain orientation.

Such a large variation of the stiffness along or across the grain is also measurable in the velocity of sound propagating accordingly, which again could vary of a factor 10.

This initial study is indeed meant to highlight the anisotropic behaviour of cedar wood (which is shared with spruce and its many varieties), and to prove the necessity of including the orthotropic characteristics of the wood grain.

A support chassis was designed; the Eigen-frequencies of the modes and their corresponding shapes were measured using both an impact hammer method [5] and Chladni patterns visualization. A sample of red cedar with thickness similar to the one used for a classical guitar top was used as reference material, as depicted in figure 2 and 3.

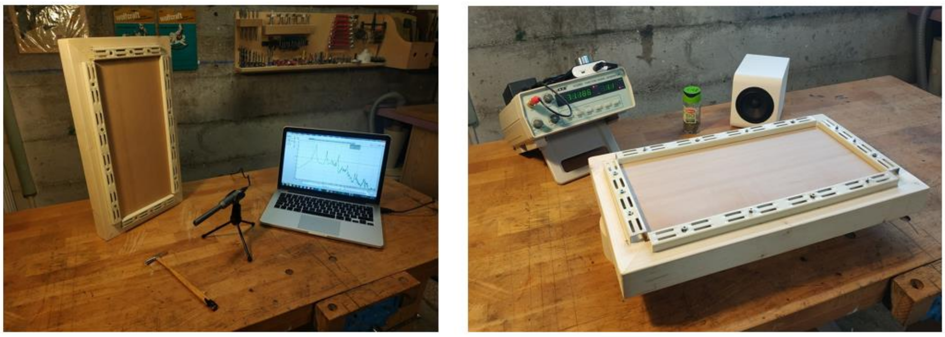

Fig.2. Left, frame used to constrain the rectangular plate, microphone and measurement system used to record modal Eigen-frequencies. Right, signal generator, small loudspeaker and basil leaves used to visualise the Chladni patterns of the resonance modes.

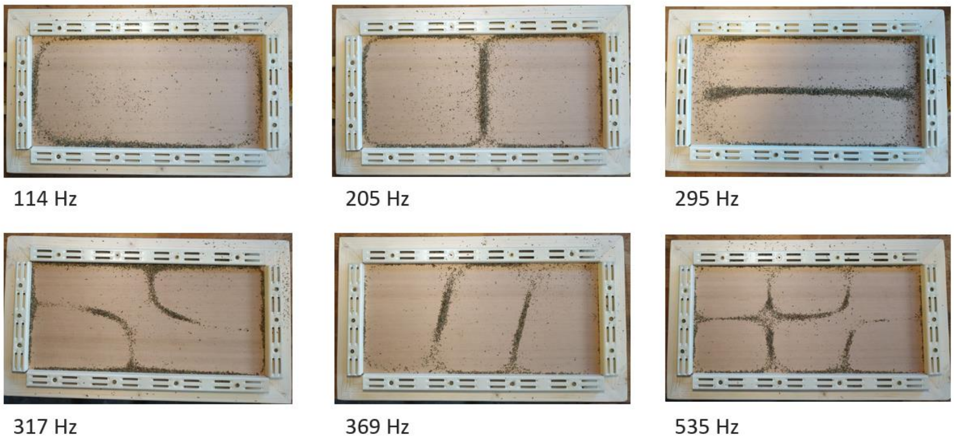

Fig.3 Measurements of the fully constrained plate, showing the first six Eigen-frequencies and their corresponding shapes (Chladni patterns).

The software used for the FEM simulation was COMSOL Multiphysics, and the parameters used in the simulation were the following: density = 500 kg/m^3, Young's modulus = 3GPa, fixed edges constraints on all the perimeter of the rectangular board, and Eigen-Frequency analysis was the implemented study. The resulting modes and Eigen-frequencies predicted by the software are shown in figure 4.

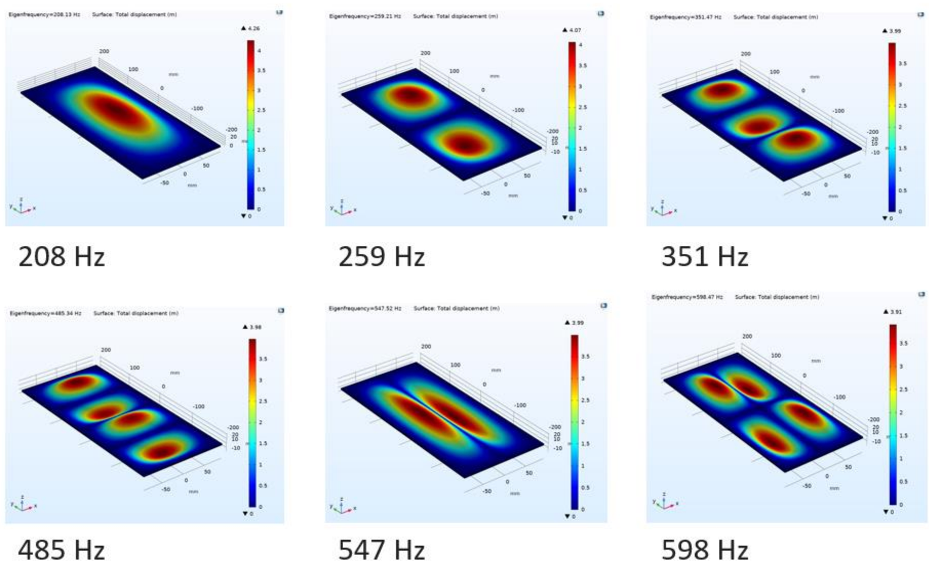

Fig.4 Simulation results of the first six Eigen-frequencies and their corresponding shapes. Isotropic material characteristics makes the numerical prediction largely different from the real measurements.

It's clear that the data nicely corresponds in *shape*, but greatly differs in the values of the Eigen-frequency, the best example of which is the third mode of the prototype being a longitudinal one with Eigen-frequency equal to 295Hz, which in the simulation was predicted appearing much higher in frequency, around 550Hz.

The use of anisotropic material properties made the simulations' results far from the reality of the measured ones. Accordingly, the orthotropic characteristic of the cedar was introduced by modifying the Young modulus of the material in COMSOL. Wood's density was kept at 500 kg/m^3, but the Young's modulus was now defined as a vector, with values equal to (1GPa, 10GPa, 1GPa), for the (x, y, z) axis respectively. Fixed edges constraints on all the perimeter of the rectangular board were kept, as well as type of study. The new results showed a good numerical correlation to the measurements of the real scenario, as per fig. 5.

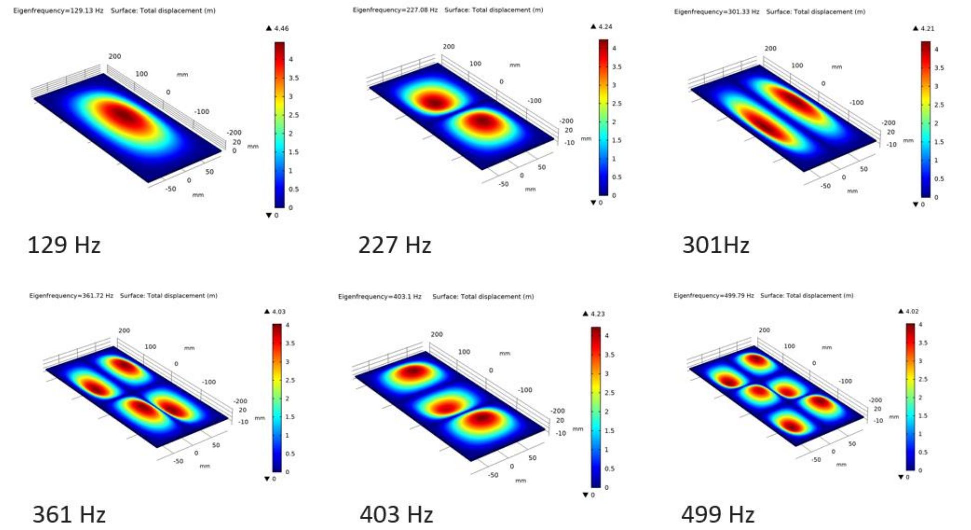

Fig.5 Simulation results of the first six Eigen-frequencies and their corresponding shapes Orthotropic material characteristics makes the numerical prediction very similar to the real measurements

Eventually, the good match between FEM predictions and real-life measurements indicates that, if simulations should inform a manufacturing process, the orthotropic material's properties of resonant wood is a "must-have" for any further investigation.

3. FEM model of a constrained guitar soundboard

In this section we describe how a guitar soundboard with its typical geometry (but without the sound hole nor the usual bracing pattern) was simulated and measured to test the FEM prediction's accuracy further. Again, the soundboard was fully constrained at the edges on a rigid frame. It's important to remind the readers that such a scenario is not fully representative of the real mechano-acoustic behaviour of a guitar soundbox though.

Indeed, in the latter case the edges of the board are glued to the sides, which are also bonded to a back to form a "body"; such a constrain and, more importantly, the effective mass of the real sides is just a fraction of the one of the fixing jigs used for the measurements performed and presented here (see [4] for an analytical and visual explanation of the consequences of such difference).

This setup is nonetheless representative of the problem at hand, since the message to deliver here is that FEM simulations can be a manufacturing tool. With such mindset, we can think of a guitar soundboard as a sub-assembly of a more complex driver, such as the "dome-voice-coil-surround" assembly of a compression driver for example. It's common in the industry to create measurement jigs and EOL tests to check that such components are within the correct tolerances before letting them progress on the manufacturing line to become a fully functional product.

With the same approach, while designing a prototype of a guitar we can measure and record its response, the density and the stiffness of the wood used (in both longitudinal and tangential directions). Once the final prototype would become a "golden reference" for the maker, the measurements of its soundboard could then become a reference for the next soundboard tuning and manufacturing. This obviously require a similar approach when building the back, and a correct measure of the mass of the sides as stressed by Gore in its book [4], but it truly is the foundation of an acoustic-driven manufacturing process.

Referring to figure 6, the crucial resonances of the soundboard are generally found below 500-600 Hz. These resonances can also be theoretically predicted with lumped element models, as well as corrected with simple techniques in the luthier's workshop; this makes them a correct tuning target for the instrument [4].

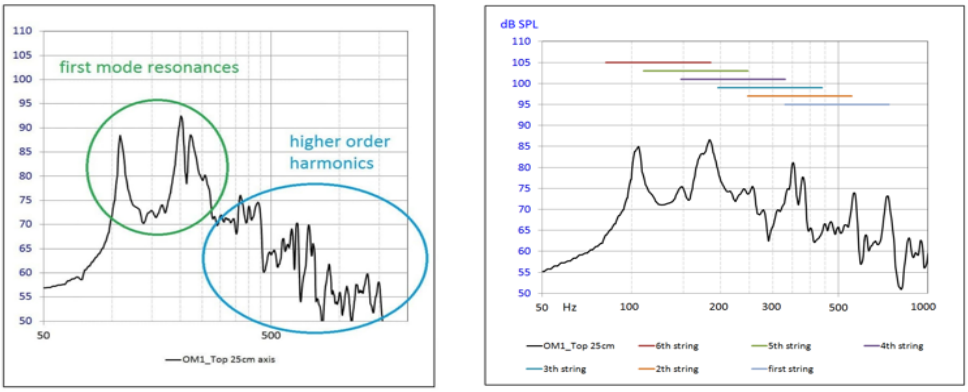

Fig.6 Left, typical modal distribution of a guitar soundboard. Right, modal distribution and its relationship with the range of the fundamentals of the notes found on each one of the six strings.

The following simulations used all prior knowledge used in section 2. The frequency limit of the calculation was set at 500Hz because this was enough to predict the behaviour of the first fives modes and compute their corresponding frequencies in the fully constrained case.

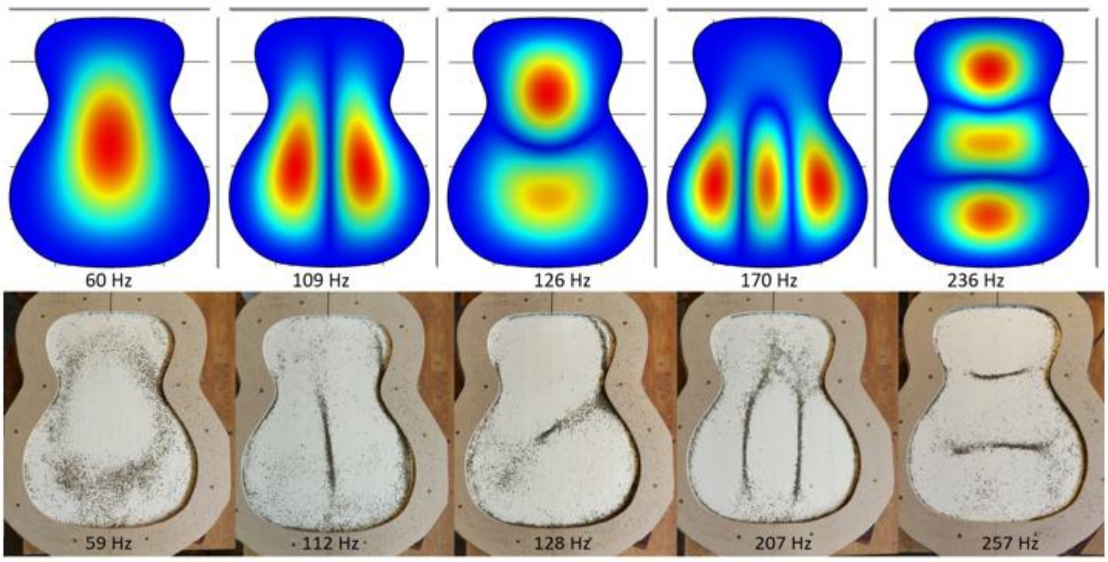

Fig.7 Very good agreement between the predictions and the experimental data measured from the prototype.

The results obtained (Fig. 7) closely matched with the prediction calculated by the model, and they pushed our curiosity further to see whether we could then try to predict the behaviour of the soundboard once, for example, a bracing pattern was added to its geometry.

4. Braced soundboard and modal drive: FEM as a design tool

Once good accuracy in predicting the vibrational behaviour of the soundboard was achieved, the investigation led us to increase the complexity of the geometry of the guitar top by introducing a bracing pattern and a sound hole. Initially one top was modelled according to a traditional bracing pattern, and secondly a different bracing was simulated with some specific performance criteria in mind.

The new COMSOL studies had an internal hierarchy, according to which firstly the Eigen-frequencies were computed, and then the forced modal response was calculated in a neighbourhood of each individual frequency. This resulted in a faster computation than the standard COMSOL frequency domain study.

Also, the approach correctly mimicked the real instrument’s behaviour, since it predicted the response of a linear mechanical structure subject to harmonic excitation in a neighbourhood of several frequencies. As in the real guitar, the force was applied at the bridge position on the saddle, to simulate the actual real modal driving of the plate.

For the saddle, the material properties were defined as isotropic. The braces used the orthotropic characterisation used in sec. 2 and 3, and the bridge and the bridge plate were still orthotropic in nature, but described using the corresponding density and stiffness of rosewood and quarter sawn maple (which are typically used for these components and would have been consequently used for the real prototype to be built later).

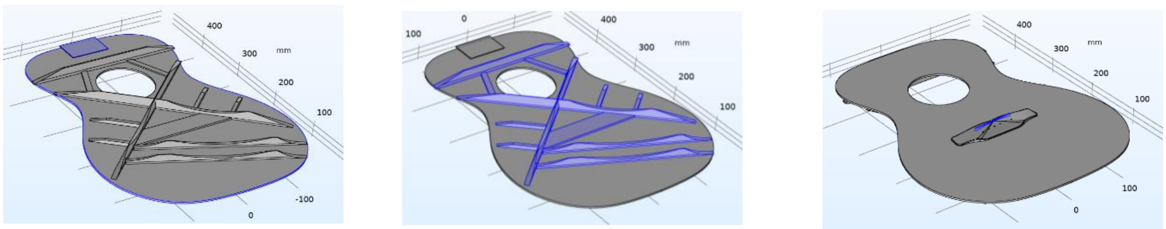

Fig.8 Geometry of the soundboard. Note the X-bracing pattern (centre) and the bridge (right) where the excitation is applied when the simulations are computed

The first attempt involved a classic design, i.e. a soundboard with a X-bracing pattern. This is a typical “de-facto” standard in the industry, which makes it a scenario worth analysing. The geometry is depicted in figure 8, and also described in detail in [6]. In figure 9 we see the first three modal resonances being simulated.

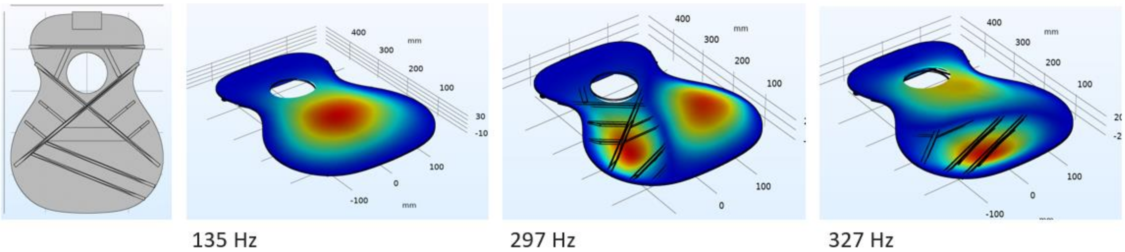

Fig.9 Typical X-bracing pattern and first three resonance modes of the board as simulated using orthotropic model of the red cedar top and of the spruce braces.

When adding the bracing pattern, some care must be used to correctly model the geometry of the braces (especially their vertical cross-section, as per [4]) and to represent the orientation of the grain which is used therein within COMSOL. If we use the same nomenclature discussed in [6], we need to define a local reference system when designing the X-braces, the tone bars, or the secondary braces, which should all have the Y-axis oriented along the wood grain, as explained here in section 2.

When comparing fig. 7 and 9, the first interesting comment is that all the modes appeared much higher in frequency. The first monopole, called $T(1,1)_2$ as per [4,5,6], which was showing in a neighbourhood of 60Hz, shifted its frequency of more than an octave. Together with it, also all other resonances shifted up too.

This is indeed the product of the increased rigidity of the soundboard, and it really is the proof of the efficiency of the X-bracing pattern in producing a greater stiffness to counterbalance the static tension of the steel strings [4,6]; without such strengthening effect, dramatic permanent deformations of the board would shortly appear, not to mention an even more typical lifting of the bridge from its location, either by breaking the bond of the glue, or by splitting the wood grain of the soundboard underneath.

Again, the prediction is effective because it captures the correct vibrational behaviour, the shapes of the modes, and also the order of magnitude of the resonances involved. Consequently, it is important to highlight that with the correct material's properties used in the FEM analysis, the designer has now a substantial freedom to re-think the bracing pattern a possibly achieve other performance criteria which might be of interest.

In our specific case the design goals were the following:

- A mass reduction of 20% was the target for the complete soundboard. In correct analogy with loudspeaker design, less mass makes the resulting actuator more efficient, hence the acoustic instrument more desirable, since there is a clear correlation between the loudness of a musical instrument and the preference expressed by the players [4, 13].

- A symmetric bracing pattern was desirable to improve the spatial response of the instrument

- A modal response as close as possible (in shapes, frequencies and their respective spacing through the overall spectrum) to that of the original X-bracing pattern.

The newly design bracing pattern is depicted in figure 10. The expert reader might find similarities among the proposed structure and either the Falcate bracing preferred by Gore [4], or the old parallel bracing developed by Gibson in the '20s [14].

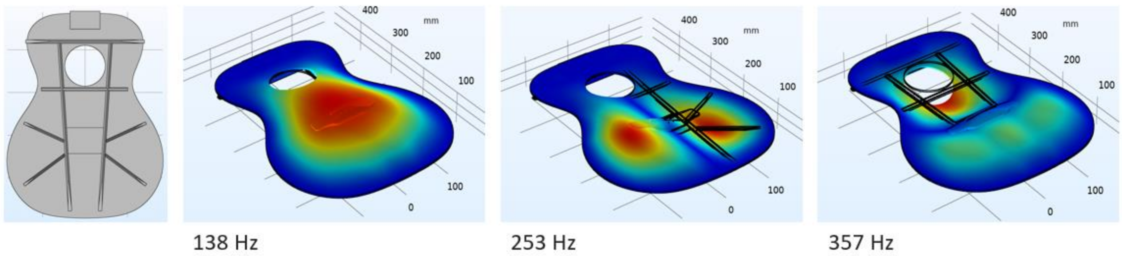

Fig.10 Left, new bracing pattern. Right, corresponding prediction results of its resonance modes

The very last simulation was expanded to include a bridge, onto which a forced excitation was applied (on the saddle), and a Rayleigh integral to compute the Sound Pressure Level (SPL) at one meter (on-axis). This would eventually offer a final SPL prediction which could be compared with the measurements of a complete guitar build.

5. Final comments and future research.

The ideal end of this investigation required to build the two soundboards and with them two complete instruments whose measurements could fully validate this study. At the time of writing, the X-braced guitar was completed and measured as per figure 11.

Fig. 11 Complete build of the instrument using the X-bracing pattern simulated here (see fig. 9)

The reality of the complete guitar seems, at first, to differ from the FEM prediction, and this requires some comments and explanations. The main monopole of the soundboard now measures 180Hz, while the prediction said 135Hz. This is due to the presence of the air resonance $T(1,1)_1$, namely the Helmholtz resonator of the acoustic guitar body. The two resonators are repelling each other (see ref. 4 and 6 for the physical model and for further experimental data), and accordingly a raise in frequency of the $T(1,1)_2$ is expected and not a limitation of the FEM model per se.

In fact, this is a good indication of the discrepancies the designer has to expect due to the difference between the fully constrained scenario of the sole guitar top and the real case scenario of the soundboard coupled with the guitar body.

The other modes are also showing at higher frequencies, but still the ratios between higher modes' Eigen-frequencies and the main monopole $T(1,1)_2$ computed in the simulations are preserved in the measurements of the complete instrument.

To this point, one lesson learned is that more research must be carried out to fully couple the model of a braced soundboard with the Helmholtz resonator of the guitar body via the limited mass of the sides.

Nonetheless, the authors are positive that this research could inform quantitative designs, where alternative and novel bracing patters could be correctly compared in their capability to provide the necessary stiffness and show a more or less interesting set of resonant modes, which is in the end the starting point to any design based on scientific knowledge and measured data and not on tradition and guess.

A last comment for those who are interested in using resonant wood and bracing patterns to design distributed mode loudspeakers. In the last simulation a clear application point for an external excitation was included (the saddle and the bridge glued on the guitar top), and a forced excitation study was used in COMSOL. This means that the actual FEM model is almost ready to predict the SPL performance of a resonant board driven by a standard electro-dynamic motor, especially if the membrane is used as a dipole and not in a closed or vented enclosure.

Acknowledgements

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