

VARIABLE BRACING PATTERNS TO TUNE SOUNDBOARDS AND MEMBRANE SPEAKERS

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1 Introduction

The lack of consistency in the response of acoustic instruments is mainly due to variations of key parameters of wood, such as density, stiffness and strength. This is well documented, with specific data regarding spruce,^{1–3} the most widely used wood type for soundboards manufacturing.^{4–6} Recent works^{7,8} successfully employed the sine-sweep method to gather the acoustic response of a guitar using small exciters, which might be preferable to the traditional impact-hammer technique since it yields frequency responses with high coherence over a bandwidth as wide as 8 kHz.⁷

Expanding on the use of simple electro-dynamic transducers, raw spruce billets can be systematically assessed, and acoustic data of the materials coming from the suppliers can be stored and analysed (in a process that can then really be called acoustic selection!). After such initial phase, raw boards can then be thinned down (while being still rectangular in shape), aiming at an acoustic target in the sense of a specific frequency for their first resonant modes. This can be consistently done by using the sine-sweep technique. When the intention is to tune in real-time a soundboard though, a new methodology can be used. Accordingly, this paper draws from standardised practices used in R&D and production in the loudspeaker and microphone industry,^{9–11} and uses similar approaches to gather data representing the acoustic response of a guitar soundboard while being braced or, as many luthiers would say, while being *tuned*. The ideas presented here are, in the eyes of the authors, powerful and versatile alternatives to both the traditional “tapping” used by artisans, and the standardized bracing patterns used in the industry, because they suggest a broader and holistic approach to the board and its bracing in order to achieve a target acoustic response.

This paper is organised as follows: section 2 briefly summarises the combined use of exciter and sine-sweep method, and recaps the methodology used in.^{7,8} After this, section 3 details the materials and the methodology used to acoustically select three guitar soundboards of different visual quality. Afterwards, section 4 shows how to exploit the same experimental setup to perform a real-time analysis of two out of three boards by applying variable braces to achieve a target frequency response. A discussion of the presented results is given in section 5.

2 Sine-Sweep method applied to acoustic instruments

The impact hammer method is a common technique for experimental modal analysis.^{12–15} The impulse response is obtained by hitting the device under test (**DUT**) with the tip of the hammer and by recording the output using a contact sensor, a vibrometer, or a microphone. The short impact is an experimental approximation of a Dirac's delta, and finite-width effects result in a progressive loss of energy in the mid-to-high frequency range.¹⁶

A wider frequency band may be obtained by the sine-sweep method.^{17,18} Such technique has found many applications in acoustics,¹⁹ particularly room acoustics^{20,21} due to its resilience to background noise, and to the ability to separate the nonlinear harmonic distortion from the linear part of the impulse response. In,⁷ an application of this technique to measure an acoustic guitar is presented, and in,⁸ it is shown that this approach is capable of capturing changes such as the presence or absence of the

varnish on the guitar top, and alterations in bracing patterns in both the soundboard and the back of the instrument.

Considering that some works suggest avoiding using exciters or shakers to gather the impulse response of a musical instrument,^{15,22,23} it is essential to specify what type of actuators are used for the investigation presented here. In¹⁵ for example, a setar with a small board surface of about 215 cm² was excited either with an impact hammer or with a B&K exciter characterised by a very large mass of 500 grams, which proved to have a severe impact on the gathered data. In,^{7,8,24} as well as for this investigation, much larger and heavier boards are considered (their area being either 1200 cm² or 2400 cm², and their total mass ranging from 190 grams up to almost 400 grams) with a transducer weighing about 50 grams, including the putty material used to position it. Specific experiments were performed to assess the sensitivity of the methodology on un-braced wooden plates, and the results (which will be presented shortly in follow-up article) confirm that by carefully choosing the exciter's position on the plates, there is no detrimental effects due its small additional mass, while all the benefits of an extended frequency range can be exploited.

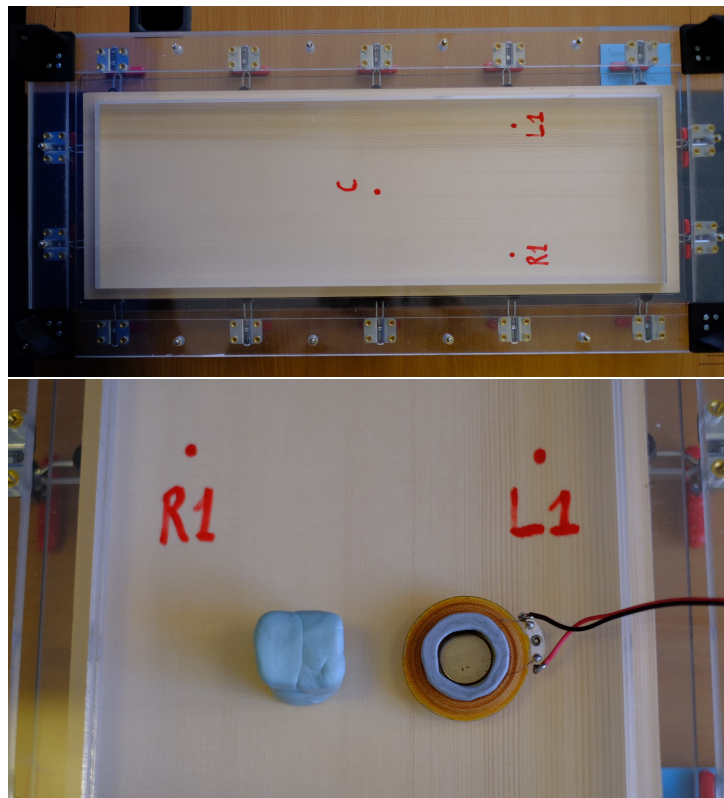


Figure 1: **(a)**: View of an example of un-braced board measurements from the bottom. Some excitation points (L1, R1, and C) are highlighted. **(b)**: Detail of the exciter compared to a small additional disc of putty of identical mass used to confirm the validity of the method.

3 Methods

This section will firstly discuss the signal chain and the raw materials received from the supplier and their initial acoustic performance. Afterwards, the process of thinning the half boards (two per billet) and the corresponding complete boards will be discussed, before exploring in detail the variable bracing experiments. According to the findings of the sensitivity analysis of the exciter positioning, all experiments that follow will adopt the position L1 or R1 for the exciter (see fig.1), so that its additional mass and presence can be neglected, while focusing on the practical uses of sine-sweep and real-time analysis.

3.1 Signal chain and wooden materials

The signal chain used to implement the sine-sweep method and acquire all the IRs consists of an $8\ \Omega$ nominal impedance electro-dynamic driver weighting 48 grams with a 25 mm diameter voice-coil; 2 grams of putty are used to secure the voice-coil to the DUT (see fig.1 (b)). The device is driven by Adobe Audition 3.0 generating a 45 - 8000 Hz sine-sweep stimulus normalised at -6 dB Loudness Unit Full Scale (LUFS), which is outputted by a Focusrite Scarlet 2i2 audio interface into a 20 W linear amplifier. Each stimulus contains two sweeps, ten seconds long, with a silence interval of 5 seconds in between. For all measurements, the sampling frequency is 48 kHz and the bit-depth is 24 bit. The stimulus is calibrated at 2.83 V rms at 1 kHz to produce 1 W of power, as measured by a Fluke 177 multimeter at the exciter's terminals in free air. One Earthworks MD30 class-1 microphone is placed in the near-field of the source, at 125 mm distance from the DUT, as per typical recording techniques^{25,26} (see fig.4). The sine-sweeps are sent to the device under test, and its acoustic output is recorded by the MD30 microphone, again via Adobe Audition, as described above. By using the Aurora plugins,¹⁸ the final impulse responses are obtained by convolution. Spectral data presented in figure 2 and in all the following ones is calculated with a 32768 samples-long discrete Fourier transform (DFT), leading to a frequency resolution of approx. 1.46 Hz.

Typically, raw wood for soundboards is supplied in the form of quarter-sawn spruce billets measuring approx 600×210 mm, which are then split in two to produce what is called a *book-matched top*. The name conveys the idea that two sides of the top show a symmetrical grain pattern. A total amount of 12 billets (already split in halves) of red spruce (*Picea Rubens*) was bought from Ciresa¹, and supplied with a tight specification on the density $\rho \in [380,395]$ kg/m³; three different aesthetic grades of spruce were available, i.e. type I, II, and III, sorted according to best quality in descending order. One half of each set had a laser etched label showing the quality type, while both halves had a pencilled note indicating the measured density and the tree identification number. This helped tracking the evolution of each set. It was decided to label the laser-etched halves as "A-Sides", and the other halves as "B-sides". The raw halves were all 4 mm thick. The density of each set is presented in Table 1.

Board "ID"	Quality	ρ (kg/m ³)	f_0^{initial} (Hz)	f_0^{final} (Hz)	h^{final} (mm)
21	II	380	115	-	-
37	II	381	134	-	-
50	I	380	123	-	-
63	III	380	130	-	-
125	III	394	122	117	3.5
169	II	385	120	-	-
209	II	380	121	-	-
214	II	390	104	-	-
230	III	390	142	-	-
249	I	380	132	-	-
250	II	388	123	117	3.4
346	I	389	126	117	3.4

Table 1: Boards with corresponding quality type, density, initial f_0 before and after thinning, and final thickness values. Initial thickness is $h^{\text{initial}} = 4$ mm for all boards. The boards' identifiers are marked with "ID" numbers, coming from the trees being cut to produce them. The rows in pink highlight the boards chosen to form group S_1 .

3.2 Experimental setup for acoustic selection and thinning of un-braced half-boards

Normally, the two halves of raw materials are not measured before production, but immediately glued to form a full rectangular board measuring approx. 600×420 mm. Before doing so or applying the bracing, the sine-sweep technique can be used to assess and classify individual half-boards.

Each specimen is measured by placing the exciter in L1. This preliminary evaluation, as seen in figure 2, shows a large variation of the fundamental frequency (f_0) of each raw set, with the parameter

¹Ciresa, <https://www.ciresafiemme.it/en/>

spanning the range $f_0 \in [104, 142]$ Hz. With the aim of manufacturing three braced boards with very similar acoustic responses, data of fig.2 was analysed to pick three specimens named "125", "250", and "346", which were already performing in a similar way despite being of three different grain qualities, as per Table 1.

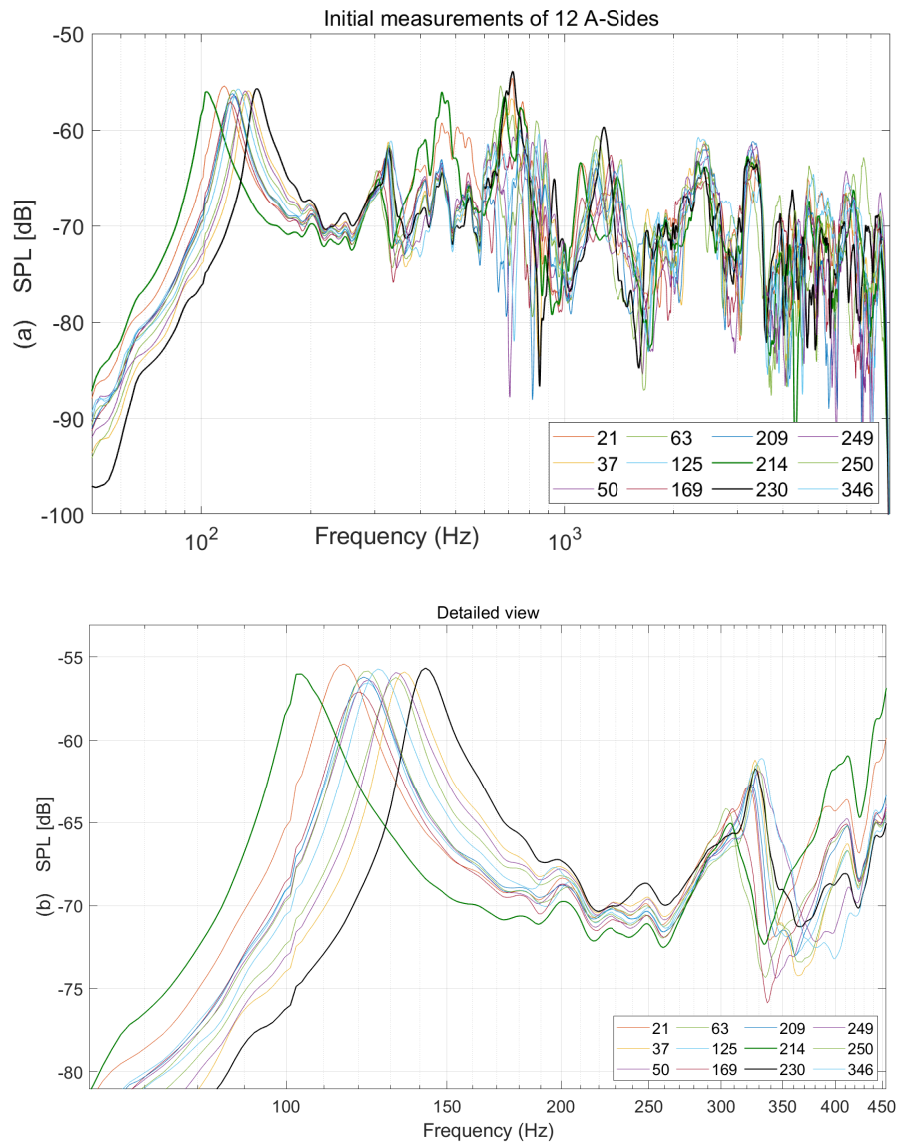


Figure 2: **(a)**: initial measurements of 12 A-Sides, exciter located at point **L1** (left-hand side of the board). **(b)**: detailed view of the first resonance modes' frequencies. All boards and corresponding "IDs" are shown, suggesting the large variation of acoustic responses despite very similar densities.

The three candidates will be called Group S_1 . The frequencies of first resonant modes of these boards are 122 Hz, 123 Hz, and 126 Hz respectively (see table 1). Since the initial thickness of 4 mm is too high, further measurements can be performed to test how closely the first resonance modes can be tuned and matched by re-working the thickness of the half-boards before gluing, thus informing the selection of the halves in production by acoustic measurement. The responses before thinning ($h = 4$ mm) can be seen in panels (a) of figure 3. The thinning process is expected to produce a lowering in frequency of the first mode of vibration since, in a lumped-element approximation,^{27,28} the stiffness k varies with the cube of the thickness and the mass m only changes linearly. Accordingly, when the boards are thinned down by approx 0.5 mm, the first mode for all three specimens is aligned at 117 Hz, as per Fig. 3(b).

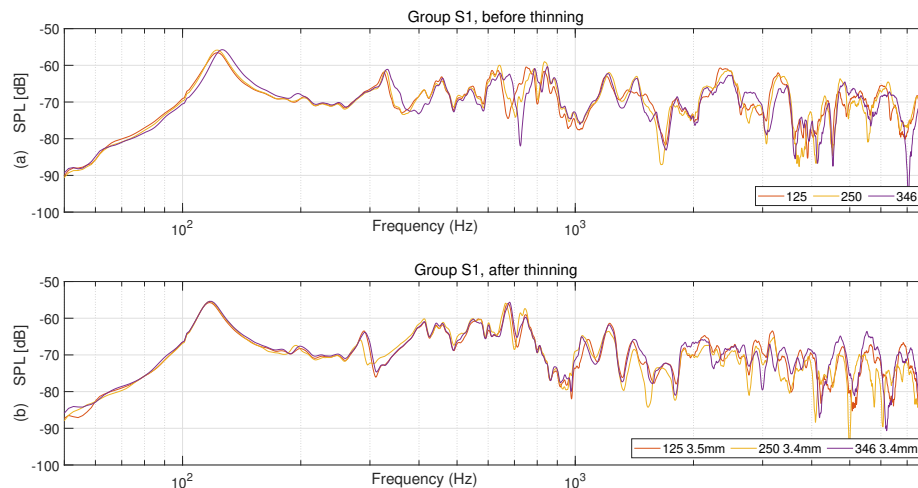


Figure 3: Acoustic responses of half-boards (A-Sides) S_1 , with their corresponding "IDs" in the legend. **(a)**: before thinning (all boards have thickness $h = 4$ mm). **(b)**: after thinning (thicknesses as indicated).

3.3 Thinning of the complete boards

The process presented above for "A-Sides" of group S_1 was repeated for their corresponding "B-Sides", reaching analogue values for the first resonance modes and thicknesses. The next step consisted in gluing the 6 half-boards into 3 full ones, and in measuring the acoustic behaviour of the complete rectangular tops. A different frame is used, as per figure 4. This frame weight approx. 8 kg, which is again a mass considerably larger than the one of the boards under test, and for which the same comments expressed in section 2 are valid.

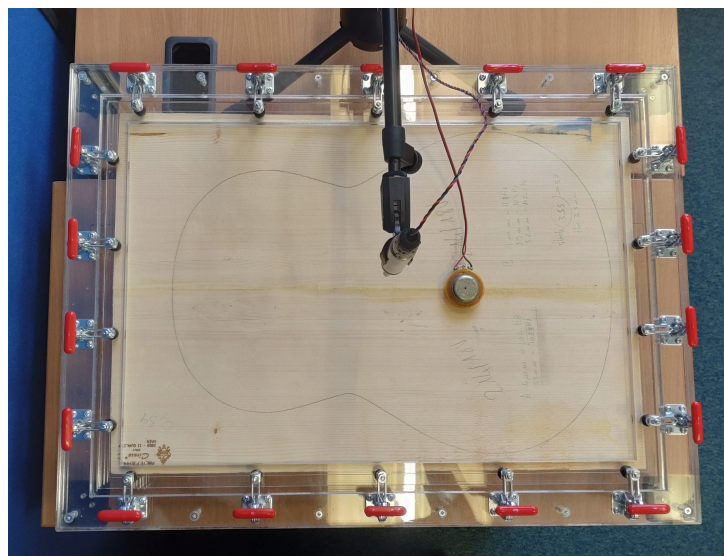


Figure 4: Frame for full board measurements. The exciter is visible, and placed roughly in correspondence of the bridge on a complete soundboard.

The resulting responses are shown in panels (a) of figure 5. The tops are again thinned and measured until their first modes are tuned to reach 60 Hz, as presented in panels (b) of fig. 5. Another set of measurements was done on the un-braced boards of group S_1 , namely a complete modal identification analysis. By using the exciter in two positions (L1 and a modified centre position), the frequency spectrum was scanned and modes identified using tea leaves to show the typical Chladni patterns. When naming the modes, two indices (x, y) representing the number of antinodal lines visible along the X-axis (across-the-grain) or Y-axis (along-the-grain) are used (as visible in fig. 4). This means that, for example, mode $(1, 0)$ has one antinodal line dividing the plate in two halves along the grain.

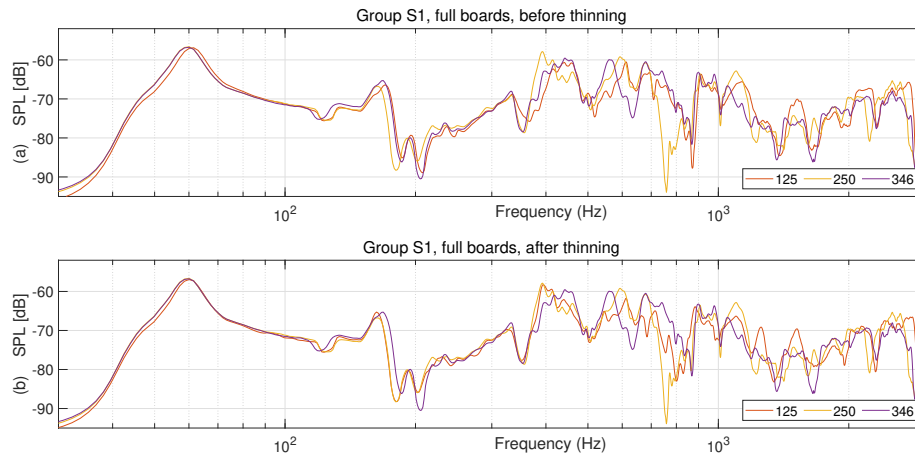


Figure 5: Thinning of complete boards from S_1 . **(a)**: before thinning. **(b)**: after thinning.

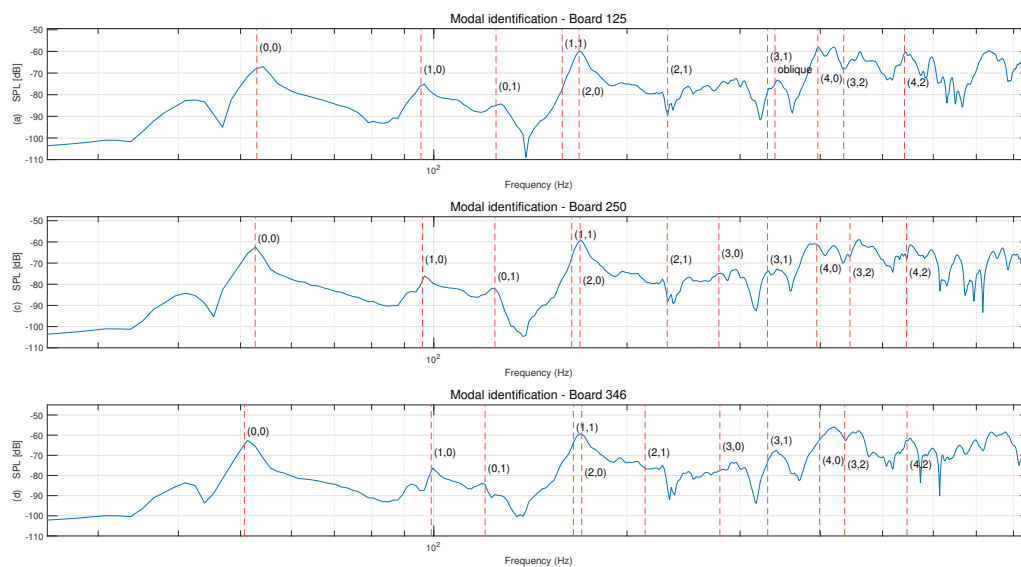


Figure 6: Modal identification of complete boards from S_1 : panel **(a)** is "125", **(b)** is "250", and **(c)** "346".

The acoustic responses of group S_1 , are shown together with vertical dashed lines indicating the location of the modes in figure 6. It's interesting to notice that despite the frequency responses being very similar amongst the three candidates, board "125" showed some differences; mode (3, 0) was not visible and a particular shape called "oblique" in fig.6 was present close to mode (3, 1) instead. This might be a limitation due to use of the exciter placed on the board instead of using an external loudspeaker to excite the plates by sympathy, and requires further investigation.

4 Variable X-Bracing and closed loop measurement

After producing rectangular plates with their first resonant modes located at the same frequency, the last experiments used a new approach derived from loudspeaker R&D and practice. While leaving the hardware signal chain and its calibration untouched, pink noise normalised at -6 dB LUFS was outputted by the audio interface to the power amplifier and exciter. The recording chain was identical in terms of hardware, but the software used was the Real Time Analyser from REW. While performing the variable bracing tests, spectral data (coming from the usual 32k sample-long DFT) required time averaging (8 averages are used) to be monitored, while 1/12th of octave frequency weighting was used to smooth the curves. The experimental setup with microphone and exciter is shown in figure 7.

Visible in the image is the variable X-brace designed for these experiments. It's made out of the same

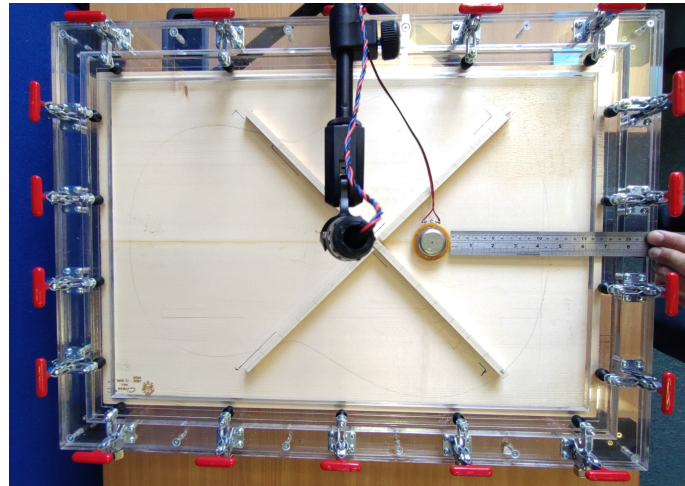


Figure 7: Measurement setup for closed-loop tuning using the variable X-Brace. The DUT is board "250", and the X-brace is set to 90 degrees

quarter-sawn spruce, with density equal to $390\text{kg}/\text{m}^3$. The grain is aligned to the longitudinal direction of the braces, and perpendicular to the board underneath. The dimensions of each "leg" of the X-brace are $8 \times 16 \times 435\text{ mm}$. Flushed to the surface of each "leg", 14 holes of 4 mm diameters are bored to host small N42 neodymium magnets of 4 mm diameter and 4 mm height. Accordingly, when the X-brace is placed on the spruce soundboard, 28 additional magnets are positioned on the other side of the plate to hold it in place, for a total number of 56 magnets. All magnets' North poles are pointing to the same direction, which maximise the attraction between the brace and the counter-magnets.

The total mass of the variable X-brace plus the counter-magnets is 64 grams. Each individual magnets weights approx. 0.35 grams, resulting in 19.6 g of additional mass, from which the mass of wood removed from the X-brace to host the magnets (approx. 2.15 g) must be subtracted. This results in a net additional mass of 17.45 g that would not be present if the X-brace were glued in the traditional way to the plate (without considering the weight of the water based glue). This difference, although relevant, is nonetheless necessary to change the absolute position and angle of the X-brace, not to mention to reuse it on more than one board, which is at the core of the closed-loop measurements that was meant to be demonstrated here.

Considering the modal identification analysis carried out before, it was decided to start the real-time tuning using only board "250" and "346", due to their virtually identical modal distribution over their frequency responses. Starting by moving the variable X-brace on board "250", many possible responses were visible. The position visible in fig.7 was eventually chosen because it resulted in a remarkable response characterised by a strong peak-trough-peak sequence, as shown by the red dashed line of figure 8; in the same image it's shown the response of board "346" (solid blue line) when the X-brace is positioned in the same location with respect to the frame. The two responses are substantially different.

This comparison is highlighted because this is what the traditional manufacturing would yield. Multiple boards would be braced by identical struts whose position is dictated by the guitar model's specs. The power of the real time closed loop analysis is now easy to grasp. Imagining that the response of board "250" were a desirable target (e.g. an instrument belonging to a famous artist), a luthier or skilled operator can *play around* with the variable X-brace until the acoustic response of another board is *tuned to* the target. The task proved to be non-trivial at all. While reproducing pink noise, both the absolute position and the angle of the variable X-brace were altered and monitored, trying to tune board "346" to the target defined by board "250". This resulted in the response depicted in dotted purple in figure 8. This configuration for board "346" showed a better match for the first resonant mode located around 69 Hz, although the pattern of peak-trough-peak of board "250" was still missing.

After many combination of absolute position and angle of the X-brace failed to recreate the desirable pattern in the response, adding a secondary brace was attempted. Such small additional strut was 50 mm long and contained only two N42 magnets, which required corresponding additional counter-magnets to be tightly fixed on the plate. The effect of moving the secondary brace around the spruce top while the main X-brace was kept in a fixed position was relevant, and eventually the peak-trough-peak pattern was reproduced, as per figure 9. In the image, two responses are shown together with the original one

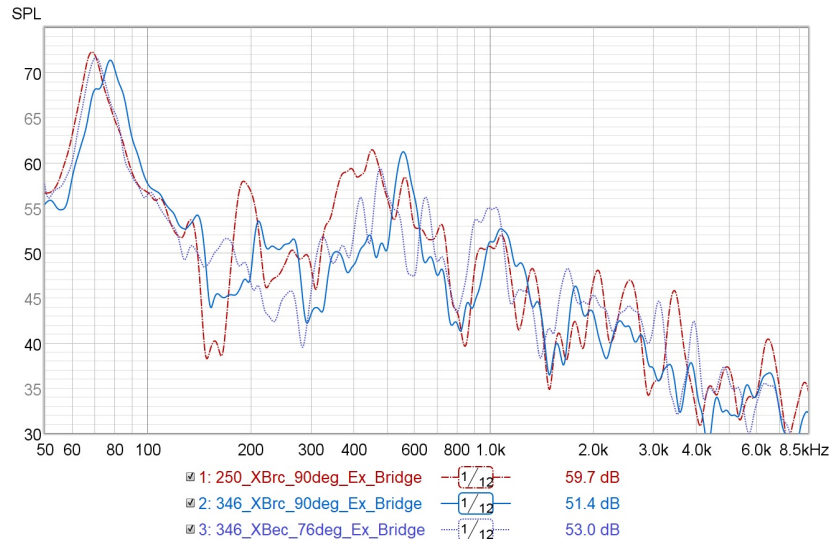


Figure 8: Acoustic responses of board "250" (red), and board "346" with X-brace set to 90 deg angle, (solid blue), or X-brace set to 76 deg (dotted purple). The centre of the X-brace was kept constant on both plates. The change in angle for the X-brace only improves the matching of the first resonant mode frequency.

from board "250": the continuous green curve is board "346" with the secondary brace and the X-brace open at 76 degrees, while the dashed green one shows the effect of increasing the X-brace angle to 85 degrees.

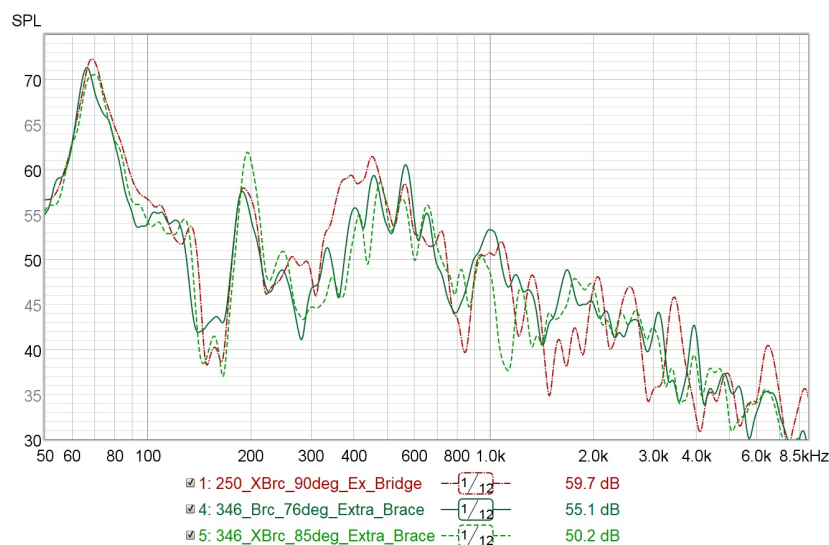


Figure 9: Acoustic responses of board "250" (red) kept as reference, and board "346" with additional brace, and X-brace set to 76 deg (solid green), or X-brace set to 85 deg (dashed green). The peak-trough-peak pattern is reproduced accurately.

Looking at the acoustic responses, the good agreement between the first resonant mode's peak and the trough-and-peak- pattern located up to 220 Hz of the latter configuration is remarkable. Still, some differences are visible in the region between 250 Hz and 430 Hz, indicating that another brace or additional mass could help replenishing this midrange region, as suggested by Bourgeois in his work²⁹ and used by the authors in the past.⁸ This was implemented by adding a third very small brace of only 10 mm length containing a single N42 magnet. The final arrangement can be seen in figure 10, where a compromise on the X-brace angle was found at 81 degrees. The final acoustic response is depicted in light blue in figure 11.

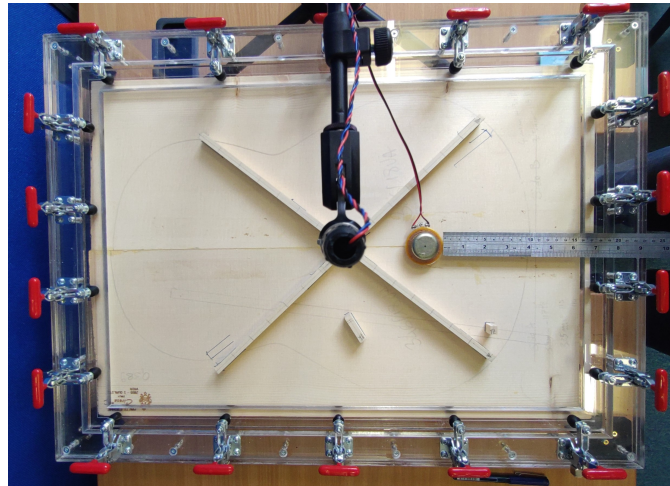


Figure 10: Final arrangement of board "346" with X-brace angle equal to 81 deg, secondary brace and small additional mass.

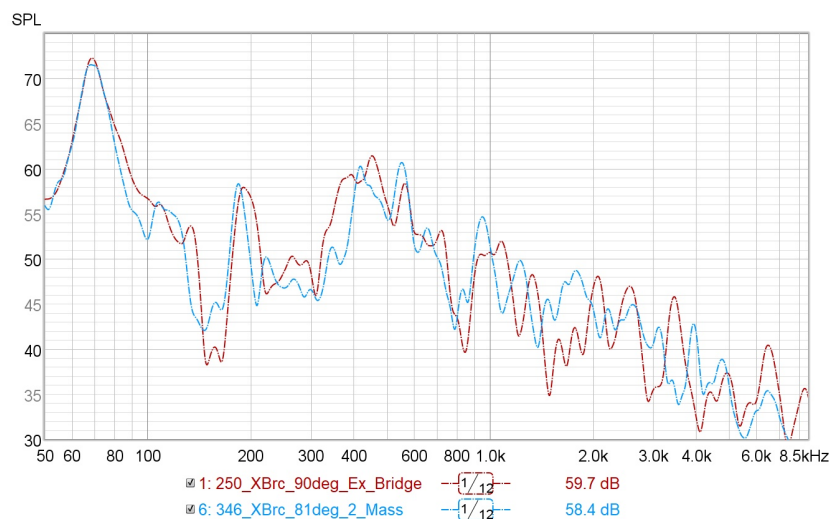


Figure 11: Acoustic responses of board "250" (red) kept as reference, and board "346" (dashed light blue) with X-brace set to 81 deg, secondary brace located as before, and a third additional small brace.

5 Result analysis and comments

The use of sine-sweep measurements together with the process of thinning of the boards has proved capable of checking and setting the fundamental mode of resonance of raw spruce billets, implementing a practical *acoustic selections* of materials which is independent of the visual quality of wood.

The use of closed-loop continuous measurements with pink noise demonstrated how even an operator with small experience in guitar bracing could replicate with good accuracy a target acoustic response in a relative short time (approx. 1 hour). When analysing figure 11 a reader with some knowledge of loudspeaker manufacturing tolerances could appreciate that in the frequency region between 50 Hz and 300 Hz the responses of board "250" and "346" lay within a ± 2 dB tolerance. There is then a difference in the 300-400 Hz region, after which the same tolerances are met up to 1 kHz, which is promising. While the guitar was considered here, the same techniques may be applied to other cases, such as panel loudspeakers, or instruments with even a broader range of fundamental frequencies, such as the piano. The presented approach opens a realistic opportunity to assess alternative materials which could yield a very similar acoustic response with respect to traditional wood species, which are now critically endangered, and act to improve the sustainability of the industry.³⁰

6 Conclusions and future work

In this paper, the use of small exciters with the sine sweep technique allowed to gather reliable acoustic data up to 8 kHz when measuring the mechano-acoustic response of spruce soundboards for musical instrument manufacturing. It was shown that partial tuning of spruce boards is achievable by reducing the thickness of the raw material before applying a bracing pattern. Better results can be achieved by using a variable X-brace together with the proposed closed-loop real time measurement method which exploits pink noise and real time spectral analysis in a similar way as used in testing and prototyping loudspeakers.^{9,11} Future research involving listening tests done both in person and by the use of recorded materials played through the tuned boards is necessary to assess and quantify *just noticeable differences* between the tonal responses of the boards used in the presented experiments. This could be approached using methodologies derived, for example, from the ISO standard describing the methodology to discern reverberation times in room acoustics.³¹ Other directions of investigation could include the use of multiple microphones and/or an artificial torso to implement binaural recordings of the boards, for auralisation and virtualisation purposes.

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7 REFERENCES

- [1] A. Steffenrem, P. Saranpää, S. Lundqvist, and T. Skrøppa. Variation in wood properties among five full-sib families of norway spruce (*picea abies*). *Annals of forest science*, 64(8):799–806, 2007.
- [2] John R Moore, Andrew J Lyon, Gregory J Searles, Stefan A Lehneke, and Daniel J Ridley-Ellis. Within-and between-stand variation in selected properties of sitka spruce sawn timber in the uk: implications for segregation and grade recovery. *Annals of forest science*, 70:403–415, 2013.
- [3] V Gryc and P Horáček. Variability in density of spruce (*picea abies* [L.] karst.) wood with the presence of reaction wood. *Journal of forest science*, 53(3):129–137, 2007.
- [4] D. Boak and R. Johnston. *Martin Guitars: A Technical Reference*, pages 1–315. Hal Leonard Books, 2009.
- [5] E. Whitford, D. Vinopal, and D. Erlewine. *Gibson's Fabulous Flat-Top Guitars*, pages 1–232. Backbeat, 2009.
- [6] T. Gore and G. Gilet. *Contemporary Acoustic Guitar Design and Build: Build*, pages 1–450. Trevor Gore, 2011.
- [7] L. Ausiello, L. Yule, G. Squicciarini, and C. Barlow. Guitar soundboard measurements for repeatable acoustic performance manufacturing. In *Proc. Reproduced Sound 2018*, Bristol,UK, 27-29 November 2018.
- [8] L. Ausiello and V. Hockey. Quantitative measurements to enhance performance of acoustic musical instruments and improve manufacturing. *Acoustic Bulletin*, 47(2), 2021.
- [9] IEC. *Sound system equipment - Part 21: Acoustical (output-based) measurements*. 60268-21. International Standard, 2018.
- [10] IEC. *Sound system equipment - Part 4: Microphones*. 60268-4. International Standard, 2018.
- [11] AES. *AES recommended practice for professional audio - Subjective evaluation of loudspeakers*. 20-1996. AES Standard, 2008.
- [12] N. Giordano. Mechanical impedance of a piano soundboard. *J. Acoust. Soc. Am.*, 103(4):2128–2133, 1998.

- [13] D. Brown, R. Allemang, and A. Phillips. *Forty Years of Use and Abuse of Impact Testing: A Practical Guide to Making Good FRF Measurements*. In: De Clerck, J. (eds) *Experimental Techniques, Rotating Machinery, and Acoustics, Volume 8.*, pages 221–241. Springer, Cham, 2015.
- [14] MJ Elejabarrieta, A Ezcurra, and C Santamaria. Evolution of the vibrational behavior of a guitar soundboard along successive construction phases by means of the modal analysis technique. *The Journal of the Acoustical Society of America*, 108(1):369–378, 2000.
- [15] H. Mansour, G. Scavone, and V. Freour. A comparison of vibration analysis techniques applied to the persian setar. In *Acoustics 2012*, 2012.
- [16] W. G Halvorsen and D. L. Brown. Impulse technique for structural frequency response testing. *Sound and Vibration*, 63(1):S81, 1978.
- [17] A. Farina. Simultaneous measurement of impulse response and distortion with a swept-sine technique. In *Proc. AES 108th convention 2000*, pages 1–24, Paris, France, 19-22 February 2000.
- [18] A. Farina. Advancements in impulse response measurements by sine sweeps. In *Proc. AES 122nd convention 2007*, pages 1–21, Vienna, Austria, 5-8 May 2007.
- [19] P. Guidorzi, L. Barbaresi, D. D’Orazio, and M. Garai. Impulse responses measured with mls or swept-sine signals applied to architectural acoustics: An in-depth analysis of the two methods and some case studies of measurements inside theaters. *Enrgy Proced*, 78:1611–1616, 2015.
- [20] F. Policardi. Mls and sine-sweep technique comparison in room-acoustic measurements. *Elektroteh. Vestn./Electrotech. Rev.*, 78(3):91–95, 2011.
- [21] M. Garai, F. Morandi, D. D’Orazio, S. De Cesaris, and L. Loreti. Acoustic measurements in eleven italian opera houses: Correlations between room criteria and considerations on the local evolution of a typology. *Build Environ*, 94:900–912, 2015.
- [22] T. Duerinck, J. Segers, E. Skrodzka, G. Verberkmoes, M. Leman, W. Van Paepegem, and M. Kersemans. Experimental comparison of various excitation and acquisition techniques for modal analysis of violins. *Applied Acoustics*, 177:107942, 2021.
- [23] M Pyrkosz and C Van Karsen. Comparative modal tests of a violin. *Experimental Techniques*, 37:47–62, 2013.
- [24] L. Ausiello and G. Nicoletti. Fem simulations and experimental validation of frequency response prediction for acoustic soundboards. In *Proc. Reproduced Sound 2021*, Bristol, UK, 16-18 November 2021.
- [25] G. Caldersmith. Guitar as a reflex enclosure. *J. Acoust. Soc. Am*, 63(5):1566–1575, 1978.
- [26] B. Katz. *Mastering Audio: The Art and the Science*, pages 1–334. Elsevier/Focal Press, 2007.
- [27] T. Neville. Loudspeakers in vented boxes: Part 1. *J. Audio Eng. Soc.*, 19(5):382–392, 1971.
- [28] R. H. Small. Vented-box loudspeaker systems—part 1: Small-signal analysis. *J. Audio Eng. Soc.*, 21(5):363–372, 1973.
- [29] D. Bourgeois. Voicing the steel string guitar. *American Lutherie*, 24:1–16, 1990.
- [30] S. Carcagno, R. Bucknall, J. Woodhouse, C. Fritz, and C. J. Plack. Effect of back wood choice on the perceived quality of steel-string acoustic guitars. *J. Acoust. Soc. Am.*, 144(6):3533–3547, 2018.
- [31] ISO. *ISO 3382-1:2009 Acoustics — Measurement of room acoustic parameters — Part 1: Performance spaces*. 3382-1. International Organization for Standardization, 2009.