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Survey and evaluation of classical guitar soundboard design methods with finite element analysis

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ABSTRACT:
Designing the soundboards of guitars based on an acoustical and structural approach would ideally allow for the realization of instruments with reproducible acoustical properties and structural stability. This task is challenging because wood, the most common material used for this purpose, is a natural material with variable properties and building instruments using strict geometrical tolerances alone does not ensure reproducible results. Several approaches have been developed so far, some based on tradition and, more recently, on measurement of material properties and computer optimization. In this article, some approaches used to design classical guitar soundboards are reviewed and evaluated. An original builder-friendly method, based on simple definitions of mass and stiffness, is also considered. Finite element analysis is used to evaluate their robustness against variability in wood density and orthotropic stiffness by using the experimentally measured properties of 29 spruce specimens. The results are assessed by comparing the coefficient of variation of acoustically relevant parameters (eigenmodes, eigenfrequencies, mass, and monopole mobility) as well as structurally significant ones (mechanical stiffness of the soundboard and bridge rotation angle). Additionally, the correlation between sound radiation coefficient and monopole mobility is examined. Finally, the practical applicability of these methods is evaluated and discussed.
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I. INTRODUCTION

To design and produce musical instruments that possess a specific and reproducible musical timbre is a long-time objective of musical instrument makers, industries, and ultimately scientists. The timbre of stringed instruments in particular, depends on a number of factors, such as string properties, playing technique, and instrument vibrational characteristics—these last being of particular importance for builders. Sound radiation, in fact, occurs mainly through normal modes of vibration of their plates and body, their timbre, and sound intensity being strongly linked to their frequency distribution, amplitude, and damping.[1] In this regard, placing resonances of low frequency modes at specific frequencies is of paramount importance and certain classes of instruments show characteristic frequencies distributions. The low frequency resonances of guitars, for example, fall in typical ranges of 90–120 Hz for the first one and 170–250 Hz for the second one.[2,3] Sound radiation efficiency is another important aspect and may vary considerably between different instruments,[4,5] blind-listening, and playing evaluation, suggesting that high values are usually preferred.[6] Most stringed instruments are made of wood and to achieve a precise placement of the resonances together with a high radiation efficiency is not an easy task. As most natural materials, wood shows varying density and mechanical properties from one sample to another,[7] and it has been shown that even instruments built by highly automated processes within strict dimensional and geometric tolerances show a different vibrational response and therefore, a different timbre and sound intensity.[7–9] Other important sources of variability are (i) wood aging, (ii) environmental conditions, and (iii) the effect of climate change. Wood aging implies changes in mechanical properties and damping ratio over time[10] while environmental conditions can largely affect the physical and mechanical properties of wood and result in changes of the vibrational response.[11] Climate change leads to a gradual shift in the geographic distribution of wood species over the long term and alters wood growth patterns in the short term, particularly in old trees harvested for instrument making. This translates into changes of the wood physical and mechanical properties, making it increasingly difficult to obtain wood with properties that are similar to those used in historically prized instruments.[12] As a result, it becomes impossible to recreate old instruments using the wood available today while maintaining the same geometry. Moreover, many wood species used for musical instruments are classified as near threatened, vulnerable, or endangered, according to the IUCN;[13] therefore, it is advisable to find possible substitutes, even among alternative species, modified wood, or composite materials, and to find suitable rationales for designing instruments with them.[14] For all these reasons, it is crucial to develop methods for designing musical instrument

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components with acoustical properties that meet specific targets, regardless of variations in material properties. In this regard, instrument makers have historically attempted to obtain reproducible results empirically by selecting wood or changing the material thickness and arching following a trial and error approach, often based on their feeling and beliefs.[15] The modern development of acoustical analysis techniques allows builders to make a giant step forward in this regard, explaining how instruments work and attempting to establish a link between vibro-acoustic features of materials, musical instruments, and the perceived tone.[1,16] Scientists have also attempted to find useful methods to select wood based on its physical properties, such as density, mechanical properties, and damping,[17,18] and design certain parts of the instruments, among which the most important is the soundboard, i.e., the plate and its bracing, which most of the time is made with conifers. The earliest known study is that of French luthier Jean Baptiste Villaume and was fostered by a scientific question posed by scientist Felix Savart:

> "What sounds ought the top and back of a violin have before they are joined?"

Beneath this question laid a fundamental issue: that of understanding how to design an instrument to achieve a certain sound, using a given material. Two centuries later, a theory of free violin plates tuning was developed by Carleen Marie Hutchins and many others.[19] Another milestone is the work of Schelleng, which derived simple rules governing the behavior of soundboards.[20] Despite their extreme simplification, these rules can be conveniently used to design the thickness of plates, based on the physical and mechanical properties of wood, such as the elastic modulus or the density. Virtually, this approach would allow the use of any material to realize instruments plates, as demonstrated by realizing a balsa violin.[21] Harris proposed a rationale for free violin plate tuning based on a combination of the free-plate frequencies and mass where successive carvings and measurements allow builders to achieve a precise value of plates mechanical stiffness.[22] Eventually, a recent study reports on the use of artificial intelligence to predict free-plate modes based on material properties and geometry.[23] Most of these approaches, however, were developed for violins and rely on the belief that tuning a free plate would yield a consistent result in the final *closed-box* instruments. However, it has been recently shown that this assumption may not always be true, since there is no smooth transition from the free plate to the *closed-box* eigenmodes.[24]

In the field of guitars, the only existing scientific method was proposed by Gore and Gilet and consists of calculating the soundboard thickness based on the density and the orthotropic elastic properties of wood.[25] The same authors also suggest a method to design soundboard bracing based on the structural stiffness of the soundboard. Another recent study in this regard shows that it is possible to adopt a numerical method to optimize a guitar's soundboard and bracing geometry to obtain reproducible results in terms of free-plate frequencies.[26] Despite the promise of most of the approaches listed so far, no systematic studies have been made to confirm their reliability in obtaining reproducible results in the complete instruments, resulting in a lack of useful information for instrument makers. This is not surprising, since validating any of these procedures in practice implies building and characterizing several instruments, resulting in too much risk and effort both for a single maker and for a factory. A notable exception is the Bilbao project,[27] which aims at relating materials properties and geometric characteristics of the violin with its tonal qualities. At the time of writing (2024), however, this project is still in progress. Virtual prototyping is another noteworthy approach that reduces the efforts and costs associated with physical prototyping.[28] However, it requires a high level of expertise to implement effectively. From a scientific perspective, the quest to develop and validate effective design methods for guitar soundboards might not appear to be a pressing issue. This is because blind-listening tests have often demonstrated that both listeners and players struggle to reliably distinguish between similar instruments, with their judgments heavily influenced by preconceived beliefs and biases.[29–32] However, soundboard design significantly impacts characteristics that were not considered in these studies but are crucial in certain musical contexts. For example, in repertoires, such as classical music or fingerpicking, aspects like instrument loudness and the presence of wolf notes become particularly relevant. Instrument loudness is critical for soloist instruments, which need to radiate sound effectively in large performance spaces. High-end soloist instruments typically exhibit greater average soundboard mobility.[5,25] On the other hand, wolf notes arise from the coupling between string vibrations and body resonances. This phenomenon is especially pronounced in instruments with highly mobile soundboards, where coupling at frequencies near the primary body resonances can cause intonation problems or wolf notes.[3,33,34] In such cases, even small differences (e.g., 2 Hz) in the frequencies of low frequency resonances, such as the Helmholtz resonance and monopole resonance, can lead to significant intonation problems, abrupt decay, or beats on specific notes, ultimately influencing the overall quality of the instrument.

In this work, we aim at evaluating the robustness of different guitar soundboard design methods with respect to the wood properties variability and their ease of use in a guitar maker workshop. Six different design methods are described and used to determine the main soundboard design parameters, namely, the soundboard thickness and the bracing height, in the case of a classical guitar, based on the density and the mechanical properties of a set of 29 samples of spruce wood (*Picea abies*)—one of the most commonly used woods for this purpose—to mimic a potential experimental campaign. The resulting combinations of geometry and material properties were used to perform finite element analysis (FEA), using COMSOL Multiphysics, and evaluate the vibrational and structural features of the soundboard and their variability. This work corresponds to a virtual experiment where 29 guitar soundboards are built according to six different design methods, resulting in a total of 174 instruments. To realize a similar number of experiments and validate them, taking into account experimental errors, would have resulted in a much larger effort. Conversely, FEA modeling was used as a powerful quasi-experimental tool, as already demonstrated in other similar studies.[24,35] The case of a classical guitar soundboard was considered because of the relatively simple behavior of this type of instruments, where the soundboard can be considered, with some limitations (see Sec. II), as a plate with fixed edges. In addition, from a structural and acoustic perspective, a classical guitar behaves similarly to other plucked-string instruments, such as steel string guitar, mandolin, ukulele, etc. In all these instruments, the soundboard is subject to bending stress, the vibration modes ordering is similar and the longitudinal stiffness of the soundboard and the bracing plays the most important role in determining both the vibrational and the mechanical behavior.[36,37] We therefore expect the results obtained to be general. Although other factors, such as dimensional variability, differences in the assembly and gluing process,[38] varnish and other factors also contribute to acoustic uncertainty, we have intentionally excluded them from this analysis to focus on the design methods and their potential outcomes.

The paper is organized as follows: Sec. II reports the geometry of the soundboard and the finite element analyses (FEAs) details, Sec. III describes the design methods analyzed, and Sec. IV reports the metrics adopted to evaluate and compare them. Finally, Sec. V reports the results that are discussed in Sec. VI. Conclusions are drawn in Sec. VII.

II. SIMULATIONS DETAILS

A. Soundboard geometry

A three-dimensional (3D) model of guitar soundboard was realized based on an 1864 Antonio De Torres classical guitar described in detail in Ref. 39. A picture of the geometry is reported in Fig. 1. The geometry was drawn using constant soundboard thickness and bracing with a rectangular section, whose width and height are constant along the length of the bracing. Although this is not the exact geometry of a real guitar, which typically has non-uniform thickness and bracing with more complex sections, it represents realistically the geometry and is simple to parametrize. To cope with all the possible modifications resulting from the design approaches, we have parametrized the soundboard thickness and the fan bracing height directly into COMSOL Multiphysics (more details in Sec. III). The height of the two main transversal braces (above and beneath the sound hole), as well as the geometry of the bridge, was maintained fixed for all the considered configurations.

B. FEA details

1. FEA equations

Two types of FEA were run: a first analysis was used to retrieve the eigenmodes and eigenfrequencies by solving the undampened eigenvalue problem for the natural frequencies,

$$\left(-\omega_1^2 M + K\right)\phi_i = 0, \tag{1}$$

where M, K are the mass and stiffness matrices and ω_i and ϕ_i are the ith eigensolutions. A second analysis was used to quantify the bridge rotation as a consequence of the application of string forces to the bridge and to determine the soundboard flexibility when a force perpendicular to the plane of the soundboard is applied to the bridge. In these cases, the solver finds a solution to the stationary equation of motion,

$$\nabla S + f_v = 0, \tag{2}$$

where S is the stress tensor and f_v are the applied forces per unit volume. FEA were run using the software COMSOL Multiphysics and its built-in Solid Mechanics Modulus with a stationary solver and eigenfrequency analysis tool. Linearized equations of motion were solved using the built-in MUltifrontal Massively Parallel sparse direct Solver (MUMPS). To perform the simulations, we have created a non-structured tetrahedral mesh with adaptive refinement, using the built-in mesh tool of COMSOL. To determine the correct mesh size, we have initially run successive simulations refining the mesh size until convergence was achieved (difference of less than 1% in the eigenfrequencies within successive refinements). A mesh comprising elements with minimum and maximum sizes of 1.92 and 9.12 mm, respectively, for a total of 30 591 degrees of freedom proved to be sufficiently accurate in finding modes frequencies and structural deformations.

2. Boundary conditions and air coupling

In all simulations, a fixed constraint was applied to the soundboard external rim and to the areas corresponding to the neck and lower bout blocks (highlighted with a brighter color in Fig. 1). This configuration is a simplification of the real layout where the soundboard is connected to the sides that lean on the players' body, which is not infinitely rigid. Although this approach does not reflect the real conditions, particularly for the monopole mode due to reciprocal coupling of the main instrument resonances,[2,40] it is an acceptable assumption since it captures the key aspects of stringed instrument plates vibration while limiting the computational cost. Moreover, this configuration is shared among all the simulations and would not reasonably imply substantial differences when comparing the results. We also chose to neglect air coupling to reduce the complexity of the simulations. Air coupling could result in changes of eigenmodes and eigenfrequencies and strongly depends on the shape of the instrument;[1] however, this study is focused on the soundboards that will be attached to instrument boxes of the same nominal geometry. Therefore, the effect of air coupling will be reasonably similar for all of them.

3. Materials definition

We have implemented wood by creating orthotropic materials in COMSOL. The different grain orientations used for the soundboard, the braces, and the bridge, were created

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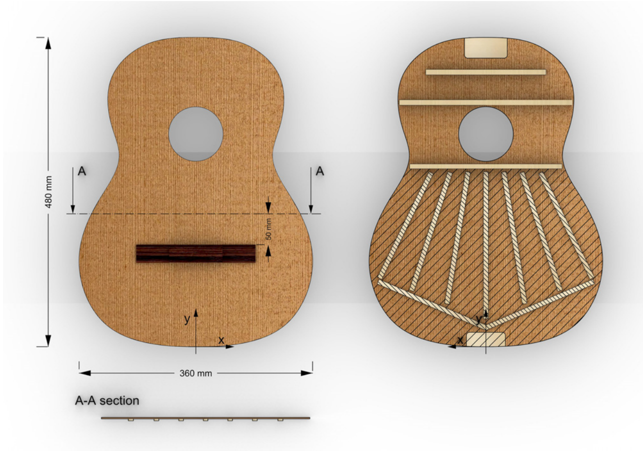

FIG. 1. Soundboard geometry and frame of reference used in this study. Left: front view, right: back view. The hatched region is the part considered as the active area of the soundboard. Section view is considered for the calculation of the FR (see Sec. III). The average soundboard thickness is 2 mm (details in Sec. III).

by orienting the main directions of wood growth [longitudinal (L), radial (R), and tangential (T)[41]] with respect to the frame of reference of the soundboard geometry as reported in Table I. Soundboard and bracing wood density and orthotropic mechanical properties were defined based on the characterization of 29 boards of Italian red spruce *Picea abies* wood coming from the same Italian region (the Paneveggio Forest in northern Italy) and purchased by wood seller Rivolta SNC. Seventeen boards are the same as the ones characterized in a previous work,[18] while the remaining were characterized subsequently with the same acoustical method.[42,43] The measured properties are reported in the supplementary material, along with the sound radiation coefficient (SRC) ($SRC = \sqrt{E_L/\rho^3}$, where E_L is the longitudinal elastic modulus and ρ is the density) and are very similar to those reported in the literature for Sitka spruce.[41] Bridge wood (*Dalbergia latifolia*) properties were retrieved from Ref. 25 and kept constant in all the simulations to limit the possible combinations and because the effect of bridge wood density and stiffness was already studied in detail in other works.[7,44] In the characterization, only three mechanical properties were measured, namely the longitudinal elastic modulus, E_L, the radial elastic modulus, E_R, and the shear modulus, G_{LR}. These constants are strongly correlated with the vibrational behavior of thin plates. All the other mechanical constants required to define orthotropic materials have a relatively little influence on the vibrational behavior and were taken from the literature.[41] Although wood damping is important in determining the radiation efficiency at frequencies close to the resonance modes, it was neglected in the simulations, since this study is focused on the eigenfrequencies and, for slightly dampened materials, damping has only a negligible effect on them. For a damped resonator, the resonance frequency is $\omega_d = \omega_0\sqrt{1-\eta^2/2}$, where ω_0 is the undamped resonance frequency and η is the damping ratio.[45] Even by considering a very high damping ratio for wood, i.e., $2 \cdot 10^{-2}$, the relative difference between ω_d and ω_d is extremely small ($2 \cdot 10^{-4}$).

TABLE I. Wood species used for the soundboard parts and wood grain orientation with respect to the soundboard geometry.

Element	Wood species	Orientation
Soundboard	Spruce[a]	$X=L, Y=R, Z=T$
Transv. bracing	Spruce	$X=T, Y=L, Z=R$
Fan bracing	Spruce	$X=L, Y=R, Z=T$
Bottom braces	Spruce	$X=T, Y=L, Z=R$
Bridge	Rosewood[b]	$X=T, Y=L, Z=R$

[a]*Picea abies*.
[b]*Dalbergia* spp.

III. DESIGN APPROACHES

Among the existing approaches known in the literature, we have selected those that we believe are the most luthier-friendly, namely, (i) are based on relatively simple measurements either acoustic or of the material properties, (ii) can be implemented in a spreadsheet and do not need any advanced computer skills, and (iii) can be easily incorporated in the workflow of a luthier. While some of these methods do not require any knowledge about the materials properties, others require characterization of the wood properties before being applied; therefore, we have indicated the number of properties that need to be evaluated for each of them. These methods are resumed in Table II and described in detail in the following.

A. Traditional (TR)

The TR method consists of building the instrument with the exact geometry (within manufacturing tolerances) of the original instrument drawing (in this case the Torres guitar), regardless of the properties of wood. This implies building the soundboard with the prescribed thickness, t_{sb}, and the bracing with the prescribed width, w_{br}, and thickness, t_{br}.

B. Vibrational stiffness (VS)

This method was developed by Gore and Gilet,[25] and consists of considering the guitar soundboard as a rectangular plate with clamped edges and the same overall

TABLE II. Design methods considered in this study and parameters used for the design of the classical guitar soundboard.

Method[a]	Soundboard thickness	Bracing height
TR	$t_{sb} = 2$ mm	$t_{br} = 3$ mm
VS	$f_p = 51.65$ Hz	$t_{br} = 3$ mm
VS+FR	$f_p = 51.65$ Hz	t_{br}: $EI = 10.4$ Nm^2
PM	$m_{target} = 129.4$ g	$t_{br} = 3$ mm
SB	$m_{target} = 129.4$ g	t_{br}: $EI = 10.4$ Nm^2
PM+BT	$m_{target} = 129.4$ g	t_{br}: $f_{monopole} = 131$ Hz
PM+FPT	$m_{target} = 129.4$ g	t_{br}: $f_{free-plate} = 52$ Hz

[a]See Sec. III for acronyms meaning.

dimensions of the real one. The thickness is calculated so that the frequency of the monopole-type vibration mode of the board, without bracing, is kept constant, whichever the material properties, according to Eq. (3),

$$h = \frac{0.959\,77 a^2 \rho^{0.5} f_p}{\left[E_L + \left(\frac{a}{b}\right)^4 E_R + \left(\frac{a}{b}\right)^2 (0,029E_L + 1.12G_{LC})\right]}, \tag{3}$$

where a and b are the overall length and width of the soundboard (along y and x directions, respectively, referring to Fig. 1) and f_p is called by the authors *vibrational stiffness* (although it is strictly a frequency and not a stiffness) and is a variable that is exact for a rectangular plate and, by proper tuning, yields the correct results in a guitar-shaped plate.[46] Notably, this method takes into account the orthotropic properties of wood, which, in some cases, are very important[18] but does not take into account bracing and its effect on the mass and stiffness of the board that may likely result in large changes of eigenmodes, eigenfrequencies, and sound radiation.[36,47]

C. Plate mass (PM)

An approach often adopted by makers is that of keeping the soundboard mass constant either without or with bracing. This choice is reasonable because an important part of the rigidity of wood can be expressed as a function of the density and therefore, trying to reach the same mass, is also a way to achieve similar stiffness. Herein, we consider the first case, since it implies less complexity. It is possible to calculate the thickness of the soundboard, based on the wood density as

$$h = \frac{m_{target}}{\rho S}, \tag{4}$$

where m_{target} is the desired soundboard mass, ρ is the wood density, and S is the surface area of the soundboard.

D. Flexural rigidity (FR)

Both the mechanical and the vibrational behavior of a guitar soundboard strongly depend on its mechanical stiffness. For a non-rigid structure, it is possible to describe the stiffness in terms of *FR*, a quantity that describes how a structure resists to bending stresses. Because wood is highly anisotropic ($E_L/E_R \sim 10$), the soundboard stiffness is governed mainly by the longitudinal elastic modulus, E_L, and by its geometry.[25,37] For these reasons, it is possible to consider it as a beam-like structure where the FR can be defined as $FR = E_L I$, where I is the second moment of inertia of the beam section, expressed in m^4. The geometry of the soundboard is not constant along its length. For this reason, Gore and Gilet[25] suggest that it is possible to consider as a representative section that located 50 mm away from the bridge saddle toward the sound hole, as reported in Fig. 1. This section comprises the soundboard and the fan bracing, but not the bridge, that would make the calculation of the FR more complex but not more indicative of the soundboard stiffness. Calculation of I for this section follows straightforward geometrical rules and is not reported here. Bracing width was considered constant (7 mm) and bracing height was optimized using a spreadsheet to achieve the desired value of FR, in this case, $10.4\,\mathrm{N/m^2}$ (the same of the Torres geometry, by considering $E_L = 10\,\mathrm{GPa}$).

E. Simplified beam method (SB)

Following an approach similar to that developed by Schelleng[20] and the considerations about the soundboard stiffness reported in the previous paragraph, a guitar soundboard can be approximated as a vibrating bar of constant section A, whose frequencies of vibration depend on the mechanical properties, the density, and the geometry, as

$$f \propto \sqrt{\frac{E_L I}{\rho A}}, \tag{5}$$

where the numerator represents the beam stiffness and the denominator its mass.[48] In this equation, which is valid for any boundary conditions, the term $1/L^2$ (where L is the beam length) was included in the proportionality, since it is assumed as constant in all cases. In a guitar plate, most of the mass is comprised within the board and only a smaller part in the bracing (in the geometry considered in this study, $m_{bracing}/m_{board} \sim 0.21$ over the active area of the board). It follows that, even if bracing geometry changes slightly to accommodate for different wood properties, the variation of total mass would be small and Eq. (5) can be approximated as

$$f \propto \sqrt{\frac{E_L I}{m_{board}}}. \tag{6}$$

This means that a suitable design method is to combine PM and FR methods (see combinations in Table II) into what we called the SB method.

F. Brace tuning (BT)

This method is similar to that adopted in guitar construction by some builders and consists of tuning the fan bracing height until one or some of the eigenmodes reach a target frequency. In this case, we have used the optimization toolbox embedded in COMSOL to optimize the fan bracing height until the first eigenfrequency (that of the monopole) reached a target value of 131 $\pm$ 0.5 Hz. This accuracy corresponds realistically to that achievable in practice using a microphone and a spectrum analyzer. The soundboard thickness in this case was determined with the PM method.

G. Free-plate tuning (FPT)

This method consists of carving the bracing and/or the soundboard while this is not yet attached to the sides to tune one or more eigenfrequencies. The target can be to achieve one or more target frequencies, a target relative intensity or timber, or a certain sound duration, or a combination of these. The results are usually evaluated either with a spectrum analyzer or by ear and assessed by experience. Although there are no scientific evidences supporting FPT, this technique is often used in violin[19,22] and guitar making. In this study, we have determined the soundboard thickness with the PM method and attempted to optimize the bracing height using the COMSOL optimization tool to achieve a target frequency in the lowest longitudinal mode of the free plate. This mode was chosen because it largely depends on the longitudinal stiffness/mass ratio of the soundboard, as are the constrained edges modes, and is reported in Fig. 2. Since the difference in the total mass owed to the change in bracing height during tuning is relatively small, this approach would mainly affect the stiffness and is similar to that developed by Harris for a violin plate.[22]

H. Considered methods and combinations

By combining the methods described previously, it is possible to design the soundboard and the bracing according to different procedures. Table II reports the combinations considered in this study and the target values used to retrieve the soundboard thickness, t_{sb}, and the bracing thickness, t_{br}.

IV. EVALUATION OF THE DESIGN APPROACHES

For each design method, the soundboard thickness, t_{sb}, and the fan bracing height, t_{br}, were calculated by considering the properties of each of the wood boards characterized experimentally and the methods parameters listed in Table II. This results in a total of 29 sets of wood properties for each method and a total of 174 different combinations of geometries and material properties, corresponding to the same number of virtual instruments. These combinations were used to run FEAs and retrieve

- eigenmodes and eigenfrequencies;
- soundboard mechanical stiffness, k;
- bridge rotation angle, θ;
- effective monopole mass, m^*, and monopole mobility, M;
- soundboard active area mass, m_{act}.

Eigenmodes and eigenfrequencies are direct results of the simulations. The other quantities were calculated as follows: soundboard stiffness, k, was measured by applying a force of 1 N, directed along the -z direction to the bridge. The resulting displacement was measured and the stiffness was calculated as: $k = F/d$, where F is the force and d is the bridge displacement along the z direction. This procedure is the same used in practice to determine the soundboard stiffness.[25] Bridge rotation angle, θ, is related to the structural integrity of the guitar and was evaluated by applying a force of 1 N on the bridge saddle in the direction of the string tension in the FEAs and measuring the resulting rotation of the bridge. The value was then scaled to the total string force of 450 N, typical of classical guitars strings. Both k and θ were calculated since stability is important to keep presets of the instrument, which are very important to players and makers. M is a variable that combines mass and stiffness and is an indirect measurement of the monopole admittance, related to sound radiation efficiency of guitars. It is defined as: $M = 1/\sqrt{km^*}$,[25] where k is the soundboard stiffness and m^* is the effective monopole mass, a measure of the mass portion associated with the first eigenmode. m^* can be estimated by considering the monopole as a harmonic oscillator as: $m^* = k/4\pi^2 f_t^2$, where f_T is the monopole frequency. The masses associated with the vibration of each eigenmode and particularly that of the monopole have a substantial influence on the tonal qualities of plucked-string instruments;[33] therefore, we have evaluated the mass relative to the active part of the soundboard m_{act} (see Fig. 1). The variability of the results was quantified for each design method by calculating the coefficient of variation (COV) across the 29 sets of material properties. COV is defined as: $COV = \sigma/\mu$, where σ is the standard deviation and μ is the mean value of the studied population.

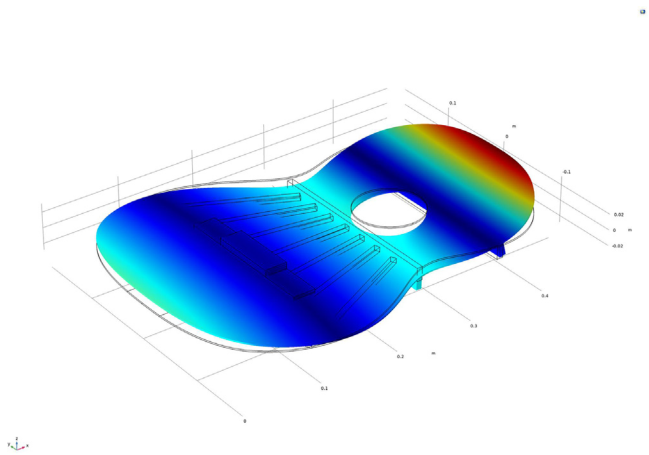

FIG. 2. First longitudinal eigenmode of the guitar soundboard with free edges.

A. Correlation between *M* and SRC

SRC is commonly used to grade wood for musical instruments[49] and samples with high SRC are supposed to produce louder instruments.[17] To determine whether different design approaches are more or less sensitive to the SRC, we have plotted M as a function of SRC for the 29 sets of wood properties of each method and fit the data with a linear regression to retrieve the coefficient of determination R^2.

B. Sensitivity to wood anisotropy

Spruce wood exhibits significant variations in its anisotropy. This may impact the vibrational and mechanical properties of musical instruments, resulting in a shift of the

TABLE III. Wood properties and number of measurements required to measure them with luthier-friendly methods (see Sec. IV C) for each design method.

Method	Wood properties	No. of measurements
TR	None	0
VS	ρ, E_L, E_C, G_{LC}	7
VS+FR	ρ, E_L, E_C, G_{LC}	7
PM	ρ	4
SB	ρ, E_L	5
PM+BT	ρ	4
PM+FPT	ρ	4

eigenfrequencies, a change of eigenmode shapes, and mechanical stiffness or a change in eigenmodes order. This can be especially relevant when wood with anomalies, such as indented grain (IGR) spruce, having a high radial stiffness is used.[11] Although this study focuses on regular spruce, we have quantified this effect by running a parametric sweep over the anisotropy ratio $\alpha = E_L/E_R$. Details are reported in Appendix A and show that, for a classical guitar soundboard, wood anisotropy variation within the regular spruce range has a relatively little influence on the vibrational properties. Conversely, the use of IGR spruce may result in noticeable differences with respect to regular wood.

C. Complexity of the methods

We have listed the number of wood properties required to apply each design method and the number of physical measurements required to quantify them in Table III. In this evaluation, we have considered the case where density is measured as mass/volume and the elastic properties by free-plate tap testing[43] being these luthier-friendly methods. Since most properties are retrieved by indirect measurements, this variable is strongly related to the time and expertise required to apply each method.

V. RESULTS

A. FPT

In the FPT method, the attempt to optimize the bracing height to achieve the target free-plate frequency did not succeed in most cases. For this reason, the results relative to this method were not reported in the following. To have a better understanding of the effect of bracing height on the free-plate eigenmodes, we have run a supplementary simulation. The result and the relative discussion are reported in Appendix B.

B. Eigenmodes and mode eigenfrequencies

The first ten soundboard eigenmodes calculated by FEA are reported in Fig. 3 along with the corresponding average eigenfrequencies. These last were averaged across the 29 samples for each method. The average values do not show differences among the six design methods, so only one figure was reported for each eigenmode. Since the 29 sets of wood parameters show large variations, it is likely to expect some changes in eigenmodes or their order within a certain method. To quantify such differences would require the calculation of modal assurance criterion.[50] Nevertheless, the eigenmodes did not show significant variations within the considered samples and design methods. The only switch in order regards modes 5 and 6 whose eigenfrequencies are very similar (more detail in Appendix A).

C. Results average values

Table IV resumes the average values of active area mass, m_{act}; effective mass, m^*; FR, E_{LI}; soundboard stiffness, k; bridge rotation angle, θ; monopole mobility, M; soundboard thickness, t_{sb}; and bracing height, t_{br}, of each design method. The minimum and maximum values of the soundboard thickness and bracing height are also reported to provide a reference for practical building considerations.

D. Results variability

The COV of the results is reported in Fig. 4. Figure 4(a) reports the results relative to the eigenfrequencies. To provide more concise data, only the COV relative to the first eigenfrequency (the monopole) and the average COV across the subsequent nine modes were reported. Figure 4(b) reports the COV of the soundboard stiffness, k, and bridge rotation angle, θ, Fig. 4(c) reports the COV of the active area mass, m_{act}, and effective monopole mass, m^*. Figure 4(d) reports the COV of the monopole mobility, M.

E. Correlation between *M* and SRC

The correlations with the SRC were evaluated by plotting M as a function of the SRC for four design methods, namely TR, VS+FR, SB, and BT. The results are reported in Fig. 5.

VI. DISCUSSION

The eigenmodes indicate that the soundboard vibration is localized mostly in the lower bout, beneath the two main transversal braces with the only exception of mode 6. In this mode, the bridge is positioned within a nodal region. In a real instrument, the fretboard would provide additional stiffness, shifting the mode to higher frequencies. As a result, mode 6 becomes significantly less mobile and is therefore acoustically irrelevant. These considerations support the initial guess of considering the lower bout as the active area of the soundboard. The average values presented in Table III are remarkably similar across the methods studied, with the exception of FR, which is slightly higher for the PM and PM+BT methods. The maximum and minimum thickness values of the soundboard indicate that methods involving mass control require greater thickness variations compared to TR and VS. Nevertheless, taking as a reference the guitar plans reported in Ref. 39, these design parameters remain well within acceptable building tolerances. The same consideration applies to bracing height. Eigenfrequencies

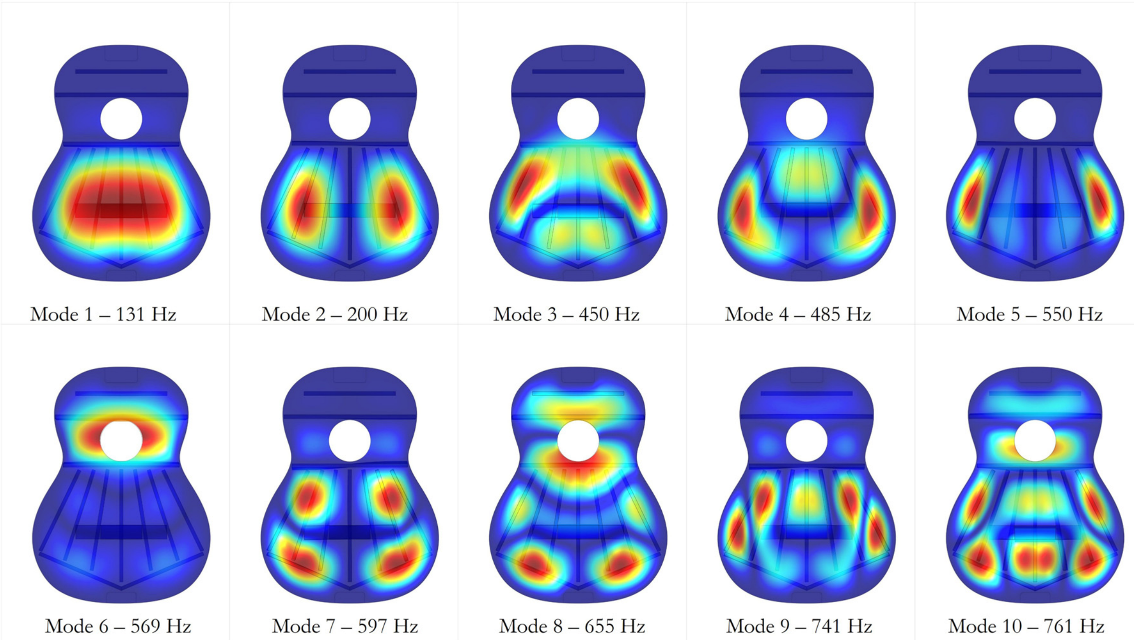

FIG. 3. The first ten eigenmodes and eigenfrequencies of the guitar soundboard calculated by FEA. Eigenfrequencies values are averaged over the 29 sets of wood properties and the six design methods considered.

variability shows that the TR method leads to the most dispersed results: 5.9% (7.7 Hz) and 6.2% (34.1 Hz) for the monopole and for modes 2–10, respectively. This variability is slightly higher than that reported in previous studies on complete instruments manufactured industrially using highly reproducible procedures, which recorded values of 3.11% in Ref. 39 and 4.25% in Ref. 51. In these studies, however, no information about the material properties was reported and the smaller variation observed may be attributed to the use of soundboard wood sourced from the same batch, leading to reduced variability in material properties compared to the sample set analyzed in this study. Additionally, in complete instruments, the interaction between the soundboard and the Helmholtz resonance slightly mitigates the dispersion of the monopole frequency.[2,40] All the other methods exhibit lower eigenfrequency variability compared to the TR approach. The PM+BT method yields the best results, and with fine-tuning, can virtually eliminate dispersion in the monopole mode. Generally, controlling plate thickness, regardless of the method, reduces eigenfrequency variability. However, the PM method outperforms VS in this regard. From a guitar maker perspective, the PM approach is significantly more practical, as it only requires measuring wood density. Incorporating FR into the design further reduces eigenfrequency variability, especially when combined with soundboard mass control, as in the SB method. This suggests that, to achieve more consistent eigenfrequencies, makers can determine PM based on density (as in PM design) and either: (i) design bracing height based on FR, $E_L I$, or (ii) carve bracing progressively from an overbuilt pattern to reach a target monopole frequency (BT case). The latter is only feasible if the instrument-building process allows for modifying the bracing height while the soundboard is attached to the sides, or if the sound hole is large enough to permit post-assembly modifications to the bracing. By controlling the monopole frequency, variability in higher-frequency modes also decreases, making it a practical approach to manage low frequency eigenmodes. While design methods based on wood properties can limit

TABLE IV. Average values of active area mass, m_{act}; effective mass, m^*; FR, E_{LI}; soundboard stiffness, k; bridge rotation, θ; monopole mobility, M; soundboard thickness, t_{sb}; and bracing height, t_{br}, of each design method. Numbers between parentheses are the maximum and minimum values across the 29 wood samples.

Design method	m_{act} (g)	m^* (g)	E_{LI} (Nm^2)	k (N/m · 10^4)	θ (°)	M (s/Kg · 10^3)	t_{sb} (mm)	t_{br} (mm)
TR	78.3	48.6	10.4	3.31	3.92	25.1	2.0 (2.0–2.0)	3.0 (3.0–3.0)
VS	78.3	48.6	10.4	3.29	3.92	25.0	2.0 (1.9–2.2)	3.0 (3.0-3.0)
VS+FR	78.3	48.6	10.4	3.30	3.90	25.0	2.0 (1.9–2.2)	3 (2.7–3.4)
PM	78.0	48.6	11.6	3.29	3.92	25.1	2.0 (1.7–2.4)	3.0 (3.0–3.0)
SB	78.1	48.6	10.4	3.30	3.90	25.0	2.0 (1.7–2.4)	3.0 (2.7–3.4)
PM+BT	77.9	48.6	11.5	3.27	3.94	25.1	2.0 (1.7–2.4)	3.0 (2.3–3.9)

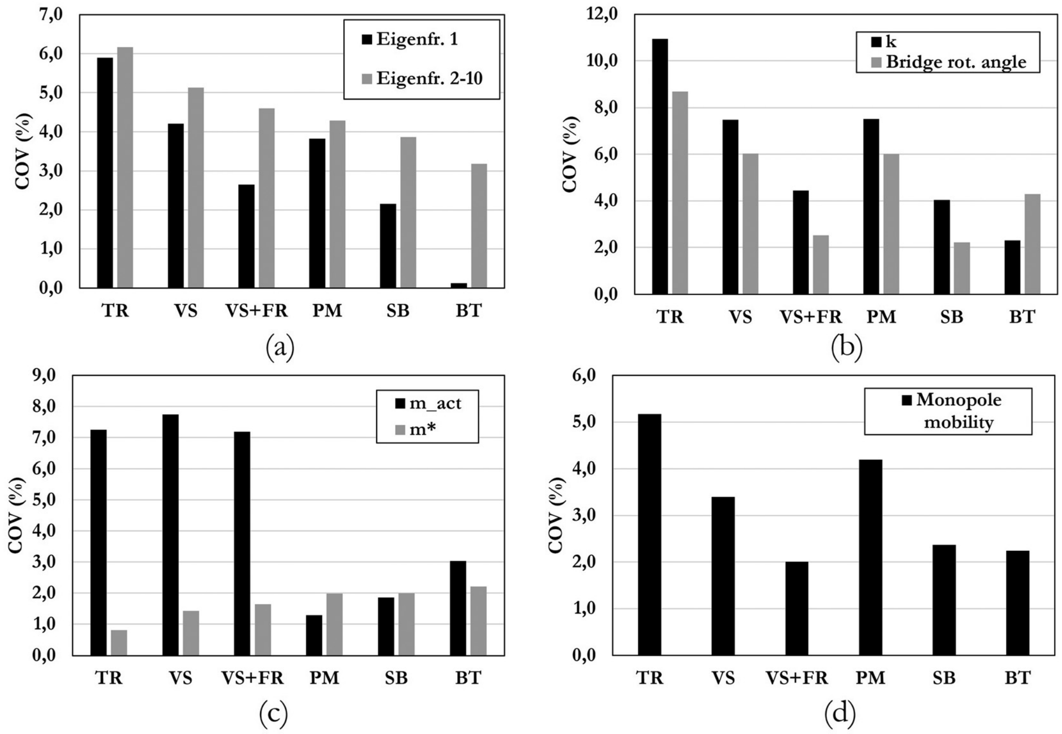

FIG. 4. Variability of the results obtained by considering the properties of 29 samples of spruce wood for each design method. (a) eigenfrequencies; (b) soundboard stiffness, k, and bridge rotation angle, θ; (c) active area mass, m_{act}, and effective monopole mass, m^*; (d) monopole mobility, M.

eigenfrequency variability, only the PM+BT method provides sufficient accuracy in placing the monopole resonance to avoid wolf notes. In practice, these methods are more effective than TR for placing resonances near their target frequencies, but subsequent fine-tuning is still necessary. VS, the only method that accounts for wood anisotropy, does not lead to more consistent results with respect to other methods than TR. This finding supports the hypothesis that ρ and E_L are the most important properties for guitar soundboards. Controlling plate thickness through either VS or PM methods reduces variability in bridge rotation and soundboard stiffness, enhancing the structural stability consistency. Further reducing of variability, especially in bridge rotation angle, can be achieved by controlling the FR. Eventually, the BT method offers the most effective control over soundboard stiffness. Methods involving soundboard mass control, such as PM and SB, yield the most reproducible results for soundboard active area mass. In contrast, the VS method exhibits variability similar to the TR method. Interestingly, effective mass, m^*, shows an inverse trend, although the differences between methods are less pronounced. To enhance reproducibility in monopole mobility (M), adopting a design method other than TR is always advantageous. Specifically, controlling soundboard thickness improves reproducibility, and further reductions can be achieved by controlling FR (VS+FR or SB) or tuning bracing height to control the monopole frequency (BT)—the latter approach yielding better results. The correlation between monopole mobility (M) and SRC varies significantly across different design methods. TR exhibits highly scattered results and a negligible correlation with SRC, rendering wood selection based on this metric ineffective for improving radiation efficiency. Given the relationship between M and sound pressure level, a variability range of 22.9 to $27.7 \cdot 10^{-3}\mathrm{sKg}^{-1}$ would in principle translate to a 1.7 dB difference. Studies on differential thresholds show that differences as low as 1 dB can be detected, especially within the 100 Hz to 1 KHz range,[45] suggesting that the observed variability may be perceivable. Frequency-based design methods, like VS and BT, exhibit a strong positive correlation with SRC. This aligns with the definition of SRC for vibration frequency-based designs.[49] In contrast, mass- and stiffness-based methods, such as SB, show a negative correlation. This may be due to the fact that, once the soundboard mass is determined independently of density, a denser, more rigid wood with a lower SRC can achieve the required stiffness more efficiently. This finding suggests that the SB method is more suitable for designing soundboards with rigid materials having a low SRC, supporting the notion that materials with unconventional properties, including alternative woods and other materials, can be effectively used in stringed instrument construction.[36] This challenges the common trust that only high-grade materials are suitable for such instruments and may widen perspectives for guitar makers. However, determining the precise range of wood properties that could still be compensated for by using this method requires further investigation and remains an open question. As a final note on practical applicability, while the TR method requires no knowledge of material properties, it offers limited control over

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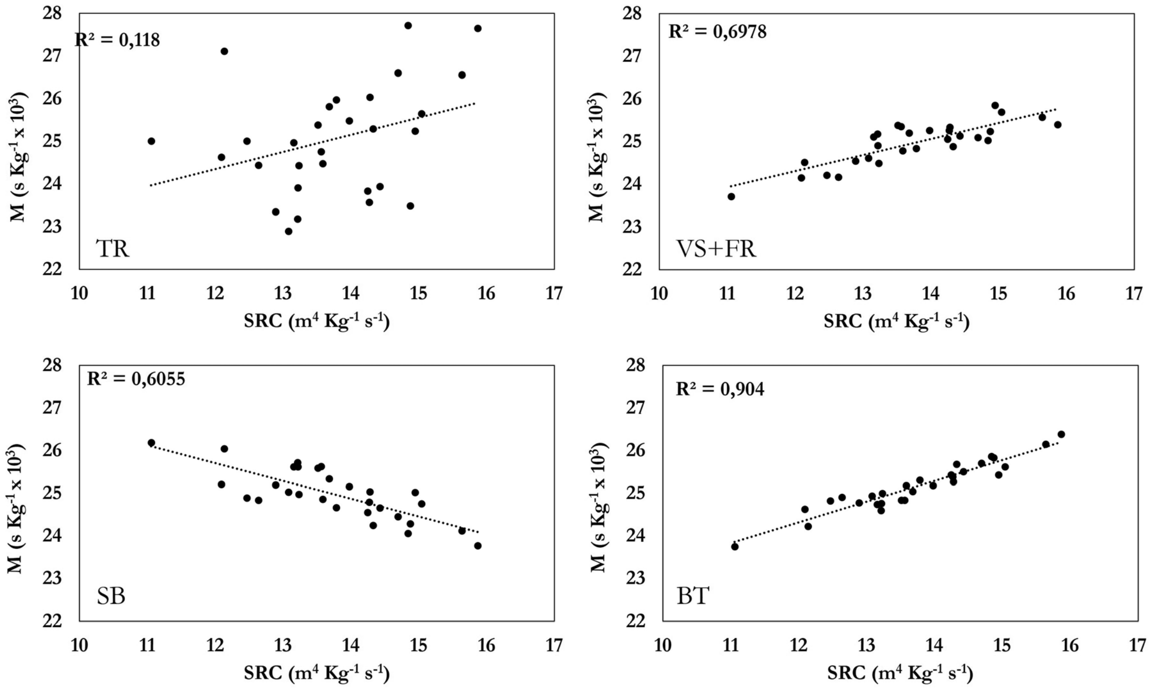

FIG. 5. Monopole mobility (M) as a function of the sound radiation coefficient (SRC) for four of the considered design methods.

acoustic and structural characteristics. The VS method, though potentially useful when anisotropy ratio varies consistently, is more complex, and requires the measurement of four material properties, offering only a modest reduction in variability. Methods involving soundboard mass control are simpler to implement and provide higher consistency, especially when longitudinal wood stiffness is considered. The BT method, requiring only density measurement, emerges as the most accurate and user-friendly approach when post-assembly BT is feasible.

VII. CONCLUSIONS

This study investigates and compares various TR and more recent design methods that can be used to determine plate thickness and bracing height for classical guitar soundboards. A FEA approach was used to evaluate the efficacy of these methods in terms of consistency of mode frequencies, mass, structural stability, and sound radiation efficiency (monopole mobility) with respect to wood properties variation. Results demonstrate that geometric-based design methods yield significant variability in outcomes. In contrast, methods incorporating material properties or frequency measurement on the instrument offer improved consistency in eigenfrequencies, structural stability, and sound radiation. Methods controlling both soundboard thickness and FR exhibit a high level of consistency but require subsequent fine-tuning if a precise placement of the resonances is sought. Eventually, the simplest method requiring the knowledge of the wood density alone is also the most effective in placing the instrument resonances at specific frequencies and ensuring consistent structural stability. Regarding the relationship between wood properties and SRC, TR geometric methods show a weak correlation, suggesting limited effectiveness in wood selection based on this figure. Methods based on plate frequency mass and/or stiffness instead exhibit a stronger correlation. Furthermore, the study highlights the practical advantages of methods requiring only density measurements, such as the ability to achieve reproducible results with a wider range of wood species, including sustainable and readily available options and, potentially, alternative materials. These findings highlight the significance of material characterization in guitar design. They suggest that integrating material properties into the design process could lead to more predictable and consistent results, potentially reducing acoustically perceptible differences between instruments.

SUPPLEMENTARY MATERIAL

See the supplementary material for wood properties and free plate tuning data.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material.

APPENDIX A: EFFECT OF WOOD ANISOTROPY

Multiple FEAs were run with the average spruce properties reported in the supplementary material but varying E_R over a wide range, resulting in a variation of the anisotropy ratio α from 5 to 30. This range covers both regular and IGR spruce (IGR spruce data were retrieved from Ref. 11). Eigenfrequencies, shown in Fig. 6, show only a weak dependence on the anisotropy, especially across the regular spruce range. Low frequency modes in particular show a weak dependence on α (e.g., 2.1% for mode 1 across the standard deviation), while higher order modes show a slightly stronger dependence across this range. IGR spruce, being stiffer across the grain, shows a lower anisotropy, with a more important effect on eigenfrequencies. Only modes 5 and 6 switch their order with α across the whole considered range.

APPENDIX B: FREE PLATE TUNING

We have simulated the effect of changing the bracing height on the frequencies of the free-plate modes by running multiple FEAs with bracing height increasing from 0.5 to 5.5 mm. The results are reported in Figs. S1 and S2 in the supplementary material and show that bracing height has little influence on the lowest eigenfrequencies. For this reason, carving the bracing cannot be used as an effective method to tune the lower resonance modes when the soundboard is detached from the rest of the instrument. By looking at the first eigenmode, when the edges of the soundboard are constrained, the fan bracing lies within a nodal region. Conversely, when the edges are free, most of it lies across a nodal line. For this reason, it is not surprising that a change in stiffness or mass of this part would not result in a substantial change of the eigenfrequency. High order modes show instead a strong dependence on the bracing height, suggesting that they may be used to tune the plate. These modes, however, are usually more difficult to measure, especially in a makers' workshop and may likely depend on many other parameters, such as transversal bracing height or transversal elastic modulus, which have little effect on the behavior of the soundboard when it is attached to the sides for most stringed instruments.[25,37] These considerations support the hypothesis that FPT may be inaccurate in predicting the frequencies when the instrument soundboard edges are successively constrained by gluing them on the instrument sides, as suggested by other previous studies.[35,43,47] Further work is needed, however, to have a better understanding of this method and its potential usefulness.

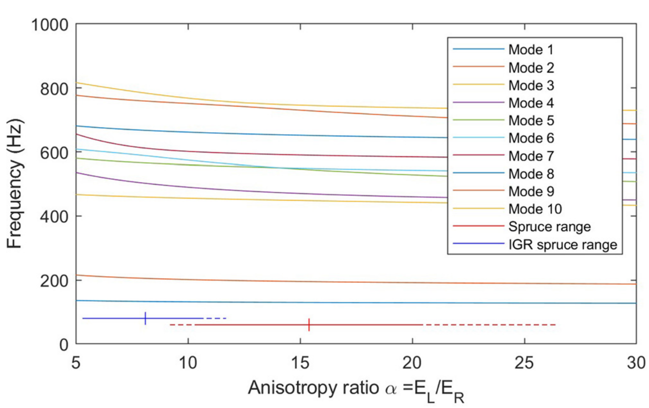

FIG. 6. Eigenfrequencies of the guitar soundboard as a function of wood anisotropy. Lines at the bottom show the ranges of regular spruce (red) and IGR spruce (blue). Dashed line, complete range; solid line, standard deviation; bar, average value.

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