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Model-based evidence of the dominance of the guitar brace design over material and climatic variability for dynamic behaviors

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Abstract

It is generally alleged that the design choices of acoustic guitar bracing patterns lead to a specific sound of the instrument. However, in the presence of strong uncertainties due to variability of material properties and climatic conditions, the robustness of the soundboard dynamics has yet to be investigated. In this study, three types of bracing patterns are studied using physics-based models and stochastic analyses are performed to account for material and climatic uncertainties. It is shown that the choice of a brace design leads, at least in the low frequency domain, to a dynamic behaviour that is not stackable with another design, even in the presence of strong aleatory uncertainties. This assessment supports the conjecture that guitar brace design choices have a greater impact than material variability where guitar soundboard dynamics are concerned. More generally, these results illustrate the usefulness of detailed physics-based models in the understanding, design and making of guitars.

Keywords: Physics-based modelling, Virtual prototyping, Uncertainty quantification, Screening analyses, Guitar braces, Spruce tonewood

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1. Introduction

Part of this work and results and figures have been published in the PhD of first author [1], whose download link is given in reference. Acoustic guitars comprise a wide range of instrument types, prices and qualities. Different families of instruments exist each with specific orientations and shapes of the stiffening ribs known as bracing patterns. During the fabrication process, guitar makers adapt the bracing design to insure a desired static and dynamic behaviours of the soundboard. It is often alleged that the design of a guitar is more important than its material properties. This implies that the design choices made by a guitar maker to achieve a desired behavior go beyond the injunction to simply use the “best” tonwoods. Moreover, some instrument makers have purposely used low quality wood to support this idea [2]. Nevertheless, it remains a belief, shared by instrument makers and many musicians, that high grade woods and specific species are key factors involved in achieving a desired guitar sound [3]. Considering that current wood availability issues affect more and more wood species, it is reasonable to ask if this approach remains valid.

Musicians attribute a specific sound and timbre of the instrument depending on the wood species and its anatomical features. However, this attitude is not justified and generally belied by rigorous studies. In [4], it was shown that musicians could not distinguish between guitars with backs made with different wood species. The material properties of the wood of a given specie vary widely, and an overlap may be possible with other species, which may explain why a specific wood specie may not be identified.

Acoustic guitar dynamics have been the subject of many studies, based on analytical and experimental approaches but also numerical methods using physics-based models. The experimental approach has been used for decades to observe the resonance modes of guitar soundboards, either isolated or when coupled with the sides and the remaining parts. As an example, it has been

31 used in a deterministic manner for the comparison of different guitar families in
32 relation to their bracing patterns [5]. The experimental approach is also useful
33 to study the global dynamics of the guitar and its radiated sound by dealing
34 with a macro response of the instrument [6, 7].

35 More instrument making based studies have also been performed. As an
36 example, the different fabrication steps have been studied to evaluate their im-
37 pact throughout the construction process, using modal testing [8] or both models
38 and experiments [9]. In order to highlight the variability of the guitar beha-
39 viors, even when their geometries are identical, other experimental techniques
40 have been used, such as studying the bridge admittance [10] as detailed in [11].
41 Similarly, the impact of the bridge has been investigated using experimental
42 harmonic analysis, visualisation, and simulation techniques [12].

43
44 These different approaches have proven useful for the study of the impact of
45 the bars on the guitar body response, [13] and to compare them to nominally
46 identical numerical models of the body, where the variability of the wood was
47 not implemented [14]. Using the Chladni method, it has been shown that, for
48 a given body shape, the differences in the body dynamics made of different
49 braces increase with the frequency [15]. Experimentally, at low frequencies, the
50 deformed shapes were similar, but later the different areas created by the braces
51 exhibited very different behaviour. Moreover, it has also been observed that,
52 for the perception of a sound and timbre, the damping and frequency of the
53 modes may be less important than the effective mass and area of the considered
54 modes [8, 9]. Despite the fact of studying existing instruments, experimental
55 studies are limited when considering the relationship between instrument makers
56 geometrical choices and the measured dynamic features. The main reasons for
57 these limitations are the wood variability, the irreversibility of the modifications,
58 as well as the time and cost of such approaches. To overcome these limitations,
59 physics-based models are now considered as a powerful method that enable the
60 study of a parameter effect, where all else unchanged.

61 Physics-based models of guitars have been developed for decades [16]. The

62 evolution of computational power enabled more and more sophisticated models
63 such as the complete processus of the production of sound, from the plucked
64 guitar string to the radiated sound [17]. One of the most complex model, combi-
65 ning complete structure and fluid-structure interactions, has been developed in
66 [18] and enabled the computation of the radiated sound around the instrument.
67 More recently, models have reached an even higher level of detail, and simulated
68 the interactions and collisions that occur on several kinds of acoustic guitars,
69 such as the viola Caipira [19].

70 In addition to the computation of the modal basis of guitar soundboards, the
71 models have been used to compute the bridge admittance of the guitar [20]. Ano-
72 ther feature, the complex frequency domain assurance criterion has been used to
73 evaluate the impact of a non-invasive restoration [21] and validate a model [22].
74 As for the violin, methods have been proposed to modify the shape of the braces
75 to tune specific modes, and the height of the braces has been considered as the
76 most influential parameter [23]. Recently, in [24], a study has performed the
77 optimization of the geometrical characteristics of guitar soundboards (thickness
78 of the top and height of the braces) based on the sound pressure level output.
79 But such methods are only justified if the brace patterns have more impact on
80 guitar behaviour than the full variability of wood.

81

82 Hence the importance of comparing the relative influences of wood variabi-
83 lity and brace design on the vibratory behaviour of guitars.

84

85 Toward this end, physics-based models will be used to explore the modal
86 behavior of a large number of soundboard characteristics taking into account
87 uncertainty in both the material properties (spruce tonewood and braces) and
88 the climatic conditions (temperature and humidity). Therefore, stochastic simu-
89 lations are needed to describe the probabilistic nature of the parameters of a
90 wood specie and climate.

91 In the next section, the finite element models and analyses are described.
92 Then, the results are given and discussed. Finally, a conclusion sums up the key

93 results of this study and gives perspectives for further studies.

94 **2. Models and methods**

95 Three guitar bracing patterns will be considered with all else unchanged.

96 – The classical nylon string guitar (C_{guitar}), has a soundboard made of spruce
97 or western red cedar. The braces are perpendicular to the soundboard grain
98 with bars on the top part and fan-like bars on the bottom part of the sound-
99 board.

100 – The steel-string acoustic guitar (A_{guitar}) is generally built in different body
101 types. One of the characteristics of this type of guitar is the cross shaped
102 braces.

103 – The Selmer guitar (S_{guitar}) is a type of steel string guitar. This style of guitar
104 generally has a small oval or “D” shaped sound-hole along with a cutaway.
105 The braces are glued perpendicular to the grain.

106 *2.1. Soundboard geometry*

107 The models possess different brace types but the same sound-hole, rosette,
108 bridge and cutaway. The geometries considered here are inspired from traditional
109 templates. The template for the classical guitar is provided by the book “classical
110 guitar making” [25], the template for the Selmer guitar brace is provided by
111 François Charle [26], a luthier in Paris. The steel string guitar style braces are
112 inspired from the book “Build your own acoustic guitar” [27]. The geometries of
113 the three soundboards are made with the computer-aided design (CAD) software
114 SOLIDWORKS[®]. Top and bottom view of the soundboards are represented in
115 the figure 1. The side of the soundboards where the bridge, saddle and rosette
116 are represented are the same for each soundboard and their material parameters
117 are fixed. For the three soundboards considered, only the other sides where the
118 braces are glued are different. The thickness of each soundboard without braces
119 is equal to 3 mm. The guitars with classical, steel string and Selmer braces will
120 be labeled C_{guitar} , A_{guitar} , and S_{guitar} , respectively.

121 *2.2. Meshing of the assembly*

122 The CAD are imported into PATRAN[®] and the volumes (generally up to
123 20) are meshed with tetrahedral elements with quadratic interpolation (TET10)
124 to increase the number of degrees of freedom in the thickness and avoid bending
125 issues of solid elements. The mesh shows coincident nodes at the numerous
126 interfaces. At the end of the process, the number of elements depend on the
127 brace types and are close to 58000 elements and 105000 nodes. Once the volumes
128 are meshed, clamped boundary conditions are applied to the contour of the
129 soundboard. This is evidently an idealization the soundboard is in reality glued
130 on the sides and linings and some parts of the soundboard are removed to glue
131 the bindings. Once the mesh and the boundary conditions are completed, the
132 material properties are introduced.

133 *2.3. Material properties*

134 The material properties introduced to represent the spruce variability are gi-
135 ven in the table 2 [28]. The dependence of the material properties with respect
136 to the relative humidity is taken from [1]. The guitar soundboard and bars are
137 entirely made of spruce wood which is treated as an orthotropic material. It is
138 defined with 12 parameters, three Young's moduli E_i , three Coulomb's moduli
139 $G_{ij} = G_{ji}$ and six Poisson's ratios. The Poisson's ratio are related by the equa-
140 tion $\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j}$. The bridge and rosette are often made of rosewood, *Dalbergia*
141 which represents a wide variety of species. The properties of the rosewood parts
142 are given in the table 1 [29], [30], [31]. It is a denser wood than spruce but
143 exhibits similar rigidity in the longitudinal direction, and twice the rigidity in
144 radial direction. The saddle is made of polyoxymethylene (POM). The POM
145 is defined as an isotropic material with Young's modulus, Poisson's ratio and
146 specific gravity equal to 3.1 GPa, 0.35 and 1.42 respectively. Once the material
147 parameters are introduced in the model, it is possible to estimate the mass of
148 the three soundboards, which are reported in the table 3.

149

150 The mass of the three soundboards vary with a maximum difference of 58
151 g, over 20 % more compared to the lightest soundboard (classical braces). The
152 braces may significantly increase the mass which tends to inhibit the radiation
153 of the sound. Moreover, this higher mass is supposed to decrease the resonance
154 frequencies, although the stiffening effect of the bars may compensate this effect,
155 especially when oriented perpendicular to the grain braces. Once the models are
156 complete, they are used to compute the eigenmodes of each brace configuration.
157 The prestress state is not taken into account in the model, nevertheless, it has
158 been shown that prestressing a plate in vibration tends to increase or decrease
159 the eigenfrequencies of the plate depending on the degree of plate curvature
160 [32]. The current comparison aims to highlight trends instead of exact vibratory
161 behaviour of the soundboards, and thus, the models are simplified.

162

163 *2.4. Eigensolution calculation*

164 The solution of the eigenvalue problem yields the undamped model eigenvalues.
165 The modal basis is computed in the [20 ; 2500 Hz] frequency band and leads
166 to a number of modes comprised between 40 and 50. For each eigenmode, the
167 deformed shapes are displayed and the bridge admittance is computed with the
168 modal superposition method. A modal damping ratio based on the experimental
169 values is used ($\xi = 1.15\%$) [22] for the bridge admittance calculation. In this
170 study, a stochastic analysis is performed based on the probabilistic definition of
171 the material parameters. For each brace configuration, 1000 computations are
172 performed and the features of interest are extracted.

173 *2.5. Morris sensitivity analysis*

174 A Morris sensitivity analysis is performed [33] as described in [28]. Five stiffnesses
175 and the density of each component, in addition to the temperature and
176 the relative humidity are considered. The implementation of the dependence of
177 the material properties with respect to the climatic parameters is similar to that
178 found in [28], [1]. The material parameters and their nomenclature, used in the

179 results section, are given in the table 4. In total, 14 parameters are considered
180 for the sensitivity analysis, and the Morris sensitivity analysis is performed with
181 20 trajectories, leading to 301 runs ($14 \text{ parameters} + 1 \times 20 \text{ trajectories} + 1$).

182

183 *2.6. Modal overlap factor*

184 The modal overlap factor (MOF) has been calculated for the defined third
185 octave band and for all of the soundboard simulations. The low frequency do-
186 main (L.F.) is generally considered for a MOF inferior to 0.3. The mid frequency
187 domain is considered for a MOF comprised between 0.3 and 0.7 and the MOF
188 is calculated according to eq. 1,

$$MOF = M_d \times f_c \times \eta \quad (1)$$

189 with M_d the modal density by third octave bands, f_c the central frequency of
190 the third octave band. The modal density is given by eq. 2,

$$M_d = \frac{\Delta N_m}{\Delta f} \quad (2)$$

191 where ΔN_m represents the number of modes that exist in a specific bandwidth
192 Δf , the bandwidths is defined as third octave band here. η is the loss factor
193 of the system in the bandwidth and is considered here equal to 2.3 %, which is
194 twice the modal damping value measured on guitar soundboards in [22], [10].

195 *2.7. Out of plane bridge admittance*

196 The bridge admittance is computed on the point shown in the figure 3. The
197 out-of-plane displacement (Z) is considered for a given input force in both X and
198 Z directions equal to 1 N, which represents the input force of a string exhibiting
199 motion in the XZ plane.

200 *2.8. Correlation coefficient*

201 In addition, a correlation coefficient is proposed to evaluate the relation bet-
202 ween the material/climatic parameters and the bridge admittance amplitude.

203 This feature will be used to evaluate which parameter has an influence on the
 204 value of the bridge admittance, for each frequency step, and gives the effective
 205 domains of a parameter in regard with the vibratory response of a given struc-
 206 ture. For two variables X_i and X_j , the correlation coefficient is given by the
 207 eq. 3.

$$C = \frac{Cov(X_i, X_j)}{\sigma_{X_i} \sigma_{X_j}} \quad (3)$$

208 With $Cov(X_i, X_j)$ the covariance between the variables X_i and X_j , and σ_{X_i}
 209 and σ_{X_j} their respective standard deviation.

210 3. Results & discussion

211 In this section, the results obtained with the 1000 computations of each cases
 212 are given. Firstly, a basic comparison of the modal basis of the three cases with
 213 initial values are given to qualitatively compare the soundboards.

214 3.1. Deterministic results

215 The modal bases of each nominal configuration are given in this section. The
 216 three modal bases possess up to 50 modes in the [20 ; 2500 Hz] frequency band.
 217 The first eight modes of each family of soundboard brace patterns are displayed
 218 in the figures 4, 5, and 6.

219 The deformed shapes are shown for comparison : the first mode of each sound-
 220 boards is a monopole mode, which is an expected result, nevertheless, the zone
 221 associated with this mode differs for each brace family. Considering the fre-
 222 quency of the first mode, the average value is equal to 216, 169 and 291 Hz for
 223 C_{guitar} , A_{guitar} and S_{guitar} , respectively, with a coefficient of variation com-
 224 prised between 5 and 6 %. Although the studied soundboard, thickness shape
 225 (with a cutaway), bridge type and sound hole size is a mix of different type
 226 of guitars, the trends are similar for real soundboards, whose first monopole
 227 is close to 200, 188 and 250 Hz for C_{guitar} [34], A_{guitar} [4] and S_{guitar} [35]
 228 respectively. Nevertheless, the high variability in term of soundboard shape and
 229 thickness, sound hole size and brace modifications prevent from consolidated

230 test-model comparisons. The soundboards exhibit dipoles in both the X and Y
231 directions, not necessarily in the same order. As an example, the frequency of
232 the dipole mode of S_{guitar} in the X direction is much higher than the other
233 cases, which can be easily linked to the bars mainly glued in the X direction,
234 where the rigidity of the soundboard (radial direction) is much smaller than in
235 the Y (longitudinal) direction. Besides these simple modes, it is seen that the
236 deformed shapes become rapidly more complex and the modes of the different
237 configurations are no longer comparable as shown by the Modal Assurance Cri-
238 terion. The detailed MAC of the modal basis of each configuration compared
239 two at a time is given in the table 5.

240 This table shows that, out a total of 50 modes computed for each case, only a
241 few modes exhibit close deformed shapes in the low frequencies domain, which is
242 coherent with the results of [36], [13], [14] and [15]. The matched eigenfrequen-
243 cies error is very high and it is clearly seen that the vibratory behaviour of the
244 soundboards is very different in the considered frequency domain and for the
245 nominal designs. The bridge admittances are shown in the figure 7. These curves
246 are constructed with the modal bases and thus are consistent with the eigenfre-
247 quencies and the eigemode shapes at the driving point used for the admittance
248 synthesis. Considering the first peak related to mode 1, a large frequency discre-
249 pancy is observed. Nevertheless, above 400 Hertz, these differences are smaller
250 and bridge admittances can be similar despite the differences observed in the
251 eigenmode shapes. The bridge admittance is a local evaluation and does not
252 reflect the complete shapes of the eigenmodes.

253 *3.2. Morris screening analysis results*

254 Figure 8 shows the results of the Morris sensitivity analyses for each brace
255 configuration. These results highlight a small dominance of the soundboard pro-
256 perties over the brace properties, regardless of the brace pattern. The longitu-
257 dinal specific modulus and densities of the soundboard and braces are the most
258 important, and the impact of the relative humidity is relatively high. Then the
259 specific radial modulus followed by the shear modulus in plane LR. Moreover,

260 it is shown that the ranking of the parameters depends of the brace configura-
261 tion. For the remainder of the stochastic study, only the longitudinal and radial
262 Young's moduli, and LR shear modulus of the soundboard and braces have been
263 considered as uncertain elastic parameters.

264

265 *3.3. Modal overlap factor*

266 The modal overlap factors for the three soundboard configurations are dis-
267 played in figure 9 and detailed in the table 6. This figure shows that the mo-
268 dal overlap factor values and evolutions are similar for each soundboard, even
269 though these structures exhibit very different modal behaviour. The Selmer gui-
270 tar exhibits nevertheless a smaller modal overlap factor between 1250 and 2500
271 Hz. The mid frequency domain is reached for a frequency value comprised bet-
272 ween 800 and 1200 HZ, which is the limit of a modal point of view. The high
273 frequency domain is reached for frequencies comprised between 1600 and 2000
274 Hz. Above these values, modal analysis is no longer relevant since modes can no
275 longer be differentiated, and energy methods should be preferred [37].

276 *3.4. Stochastic results*

277 The results of the 1000 computations are shown using different formats : the
278 frequency dispersion of the first ten modes of the guitar soundboards, the statis-
279 tics and fuzzy-FRF of their admittance, and the correlation coefficient between
280 the parameters and the value of the FRF for each frequency step. The table 7
281 indicates the dispersion in the eigenfrequencies of a soundboard given the varia-
282 bility in its material parameters. The RSD of the eigenfrequencies of each cases
283 is close to $\pm 5.5 \%$, which means that up to 68 % of the computed eigenfre-
284 quencies are between this value. Hence, in order to ensure that a design leads to
285 different dynamics, the difference in the eigenfrequencies should be higher than
286 5.5 %.

287

288 All the bridge admittances are summed up in the figure 10 which displays
289 mean admittance and lower and upper limit for each brace pattern. Up to
290 350 Hz, the FRF shapes of each cases are very different. The A_{guitar} exhibits
291 the lowest eigenfrequency of the first mode and the lowest absolute dispersion
292 ([145;200], centered at 170 Hz). The C_{guitar} exhibits intermediate frequency
293 of the first mode and absolute dispersion ([180;250], centered at 215 Hz). The
294 S_{guitar} exhibits the highest frequency of the first mode, suggesting much higher
295 stiffness (also considering its higher mass) and absolute dispersion ([250;340]
296 Hz, centered at 290 Hz). The relative dispersion of each FRF upper and lower
297 limits are all close to 30 %. The difference between the mean FRFs decreases
298 above 400 Hz. The C_{guitar} and S_{guitar} bridge admittances are quite similar
299 between 400 and 800 Hz, in term of average level and lower and upper FRF
300 limits. Considering these features, between 600 and 750 Hz, the A_{guitar} levels
301 are very different from the two other configurations. Despite these observations,
302 above 400 Hz the bridge admittances seem to merge together.

303

304 These results have to be compared with those given by the fuzzy-FRFs,
305 displayed in the figure 11. In this figure, the dispersion in both amplitude and
306 frequency of the bridge admittance is given for the three bracing patterns. The
307 impact of the first mode on the low frequency admittance of the bridge is clearly
308 seen for each type of braces. The maximum corresponding admittances of each
309 case reach a similar value, close to 0.3, 0.5 and 0.2 mm/N for C_{guitar} , A_{guitar} and
310 S_{guitar} , respectively. Above the frequency of the first mode, it is shown that the
311 three bridge admittances are not superposed, even if the material properties and
312 the climate conditions may strongly vary. The amplitudes are not similar above
313 300 Hz, and each configuration exhibits complex responses, which is highlighted
314 by this probabilistic point of view.

315 In order to study the influence of the previous parameters with respect to
316 the frequency bands, the correlation coefficient is shown in figure 12. These
317 results show that, depending on the brace pattern, the correlation between each
318 material and climatic parameters and bridge admittance sampling varies. The

319 longitudinal stiffness of the soundboard and the bars is strongly correlated with
320 bridge admittance up to 220, 160 and 290 Hz for C_{guitar} , A_{guitar} and S_{guitar} ,
321 respectively. The RH is correlated with the FRF amplitude at 280 (which is
322 also the case for E_L of the bars) and 420 Hz especially, for C_{guitar} . For A_{guitar} ,
323 the RH is correlated with FRF magnitude especially in [220;340] (which is also
324 the case for E_L and E_R of the soundboard) and [600;650] Hz frequency bands.
325 Numerous other correlations with parameters can be observed for the different
326 braces patterns, as a function of the frequency bands. The results of the Morris
327 sensitivity analysis are correlated, that is to say, the properties of the soundboard
328 are most influential along with the relative humidity and the temperature. For
329 the S_{guitar} , the braces seem to have a higher impact on the overall response.
330 For this configuration the braces are larger and oriented perpendicular to the
331 grain direction, which is a direction where the soundboard is significantly less
332 stiff. Another output is observed where the figure shows some fringes. These
333 fringes highlight the fact that some frequencies admittances are not influenced
334 by any of the input parameters separately, as the coefficient correlation is equal
335 to zero for each parameter, which is associated with an eigenfrequency.

336 3.5. Discussion

337 A screening analysis has demonstrated that longitudinal specific moduli and
338 densities of soundboard and braces have the main impact on eigenfrequencies of
339 the clamped soundboards, followed by the relative humidity, which is consistent
340 with wood selection habits of guitar makers. The results show that material
341 variability affect the dynamic features of guitars, such as eigenfrequencies, ei-
342 genmodes shapes and bridge admittances shape. Moreover, it is observed that
343 the relative humidity also has a strong impact on the same features.
344 Nevertheless, it has been shown that the guitar maker design choices have a
345 stronger impact on the dynamics of the soundboards. Indeed, the few matched
346 eigenfrequencies are shifted in a more important way than with material and
347 climatic changes. This highlights the dominant impact of braces on the low fre-
348 quencies, in particular on the matched eigenmodes. For higher frequencies, the

349 mode shapes are too different and they can no longer be matched between the
350 different brace configurations. Moreover, it has been highlighted that for the
351 perception of a sound and timbre, the damping and frequency of the modes
352 may be less important than the effective mass and the zones of the considered
353 modes [8]. This result is confirmed by the stochastic analyses results, especially
354 fuzzy-FRF of each brace pattern configuration. There is no compensation effect
355 due to the material variability that can lead to a similar vibratory behaviour
356 of the structure. Hence, the design choices of the guitar makers can be consid-
357 ered as more influential than the wood choices and climatic changes, considering
358 dynamic features such as eigenfrequencies, eigenmode shapes and bridge admit-
359 tances. An important perspective to consolidate these findings is to perform
360 perceptive tests, with sounds synthesized with the modal bases using a string
361 model and verify that, whatever wood or climate variability, listeners would
362 still clearly differentiate each type of brace. The correlation coefficient proposed
363 here for material and climatic parameters is a key tool to highlight the link
364 between the admittance amplitudes and the input parameters as a function of
365 frequency. This post-processing tool, associated with the geometrical input pa-
366 rameters, may be used for further tuning of the guitar soundboard to reach a
367 desired response in a reduced frequency band. The relative humidity appears
368 to be important, but it has to be pointed out that the evolution of the mate-
369 rial parameters of the wood when undergoing climatic changes are considered
370 for a hygroscopic equilibrium state of the wood. In reality, these effects are not
371 immediate and it is assumed that the wood stiffness is not fully modified by
372 a climatic change. One of the main perspective of this work is to study small
373 differences for each given brace pattern, by changing geometrical parameters of
374 each brace one by one. Also, the impact of the different materials for the braces
375 and soundboards (like other species or composites) with similar geometry needs
376 to be investigated.

377 **4. Conclusion**

378 In this paper, a physics-based model has been used to perform stochastic
379 analyses on guitar soundboards with different brace patterns, corresponding to
380 classical, steel-string and Selmer guitars. The comparison of the influence of
381 material and climatic variability and guitar maker design choices has been per-
382 formed in the dynamic domain. The results have shown that brace patterns
383 have a higher impact on the dynamic features of a soundboard than material
384 and climatic variability. The choice of a brace pattern family leads to dynamic
385 behaviours that are not comparable with those of another family. This effect is
386 not clearly apparent when considering the average and upper and lower bounds
387 of the bridge admittances, but the fuzzy-FRF representation proposed gives
388 more interesting insight. The main conclusion of this paper is that the design
389 choices of brace shapes have a dominant impact on soundboard dynamics and
390 that variations in wood density and stiffness is a second order effect. From an or-
391 ganological point of view, this provides a partial explanation for the existence of
392 different guitars subcategories. Theses results and the methods proposed herein
393 can provide decision support tools for instrument making, taking into account
394 both geometrical and material changes. Futhermore, this approach can provide a
395 basis for the robust optimisation of the guitar bracing patterns in order to deve-
396 lop designs that reproduce specific dynamic behaviours, for example of a specific
397 appreciated instrument, even though the material and climate conditions may
398 vary.

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FIGURE 1 – Computer aided designs of : (a) top view, (b) C_{guitar} , (c) A_{guitar} , (d) S_{guitar} .

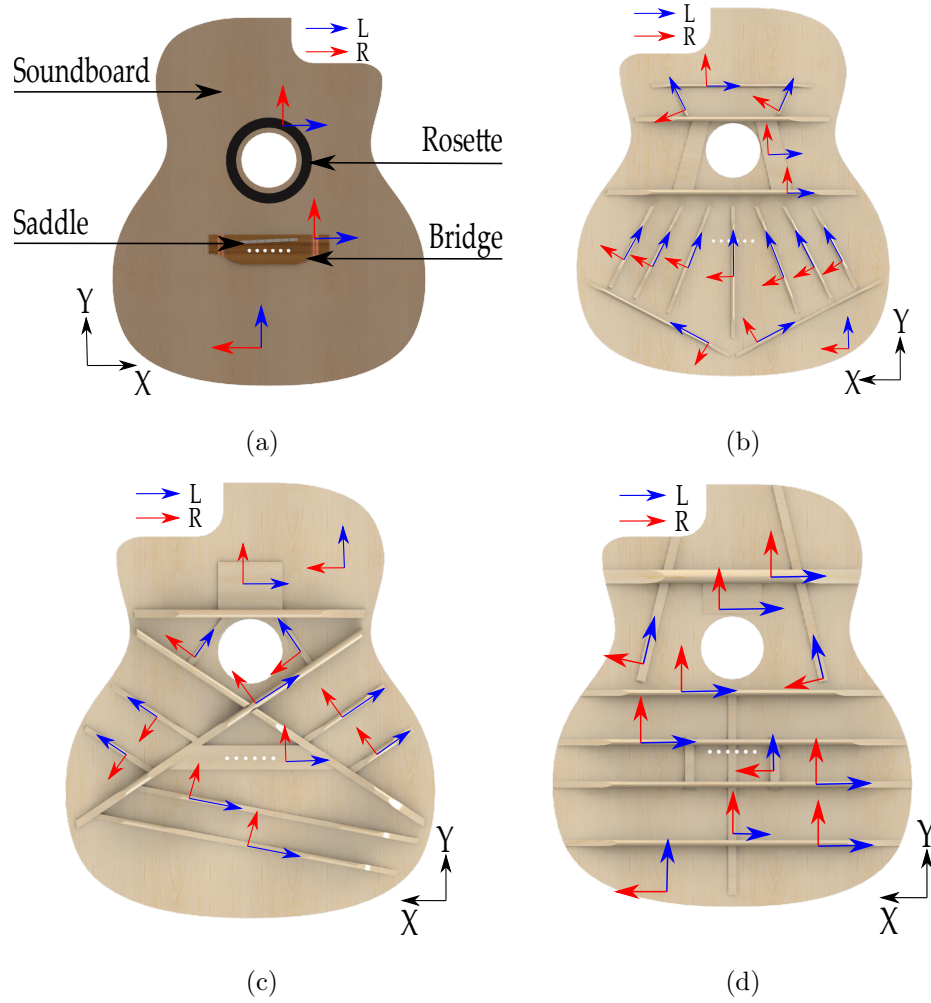


TABLE 1 – Material properties of indian rosewood for bridge and rosette[29, 30, 31].

Rosewood (<i>Dalbergia</i>)	
Material parameter	Value
E_L (GPa)	13.3
E_R (GPa)	1.7
E_T (GPa)	1.0
ν_{LR}	0.38
ν_{RT}	0.49
ν_{TL}	0.02
G_{LR} (GPa)	0.93
G_{RT} (GPa)	0.2
G_{TL} (GPa)	0.8
d (-)	0.79

TABLE 2 – Material properties of spruce implemented in the models, italic from [28] at $MC = 10\%$. Remaining values from [30] and [38].

Parameter	Spruce	Min. value	Max. value
$\frac{E_L}{\rho}$ (MPa g ⁻¹ cm ⁻³)	<i>29000</i>	<i>20590</i>	<i>35380</i>
$\frac{E_R}{\rho}$ (MPa g ⁻¹ cm ⁻³)	<i>2280</i>	<i>1460</i>	<i>3810</i>
$\frac{E_T}{\rho}$ (MPa g ⁻¹ cm ⁻³)	1480	1300	1660
ν_{LR} (-)	0.37	-	-
ν_{RT} (-)	0.48	-	-
ν_{TL} (-)	0.02	-	-
$\frac{G_{LR}}{\rho}$ (MPa g ⁻¹ cm ⁻³)	<i>1850</i>	<i>1295</i>	<i>2442</i>
$\frac{G_{RT}}{\rho}$ (MPa g ⁻¹ cm ⁻³)	<i>100</i>	<i>74</i>	<i>150</i>
$\frac{G_{TL}}{\rho}$ (MPa g ⁻¹ cm ⁻³)	<i>1910</i>	<i>1070</i>	<i>2750</i>
Density (g cm ⁻³)	<i>0.44</i>	<i>0.39</i>	<i>0.51</i>
Relative humidity (%)	<i>50</i>	<i>20</i>	<i>85</i>
Temperature (°C)	<i>21</i>	<i>15</i>	<i>35</i>

TABLE 3 – Physical properties of the soundboard models.

Parameter	C_{guitar}	A_{guitar}	S_{guitar}
Mass (g)	237	244	295
Volume (cm ³)	516	571	647

FIGURE 2 – (a), dimensions of the soundboard; (b), dimensions of the rosette; (c), dimensions of the bridge.

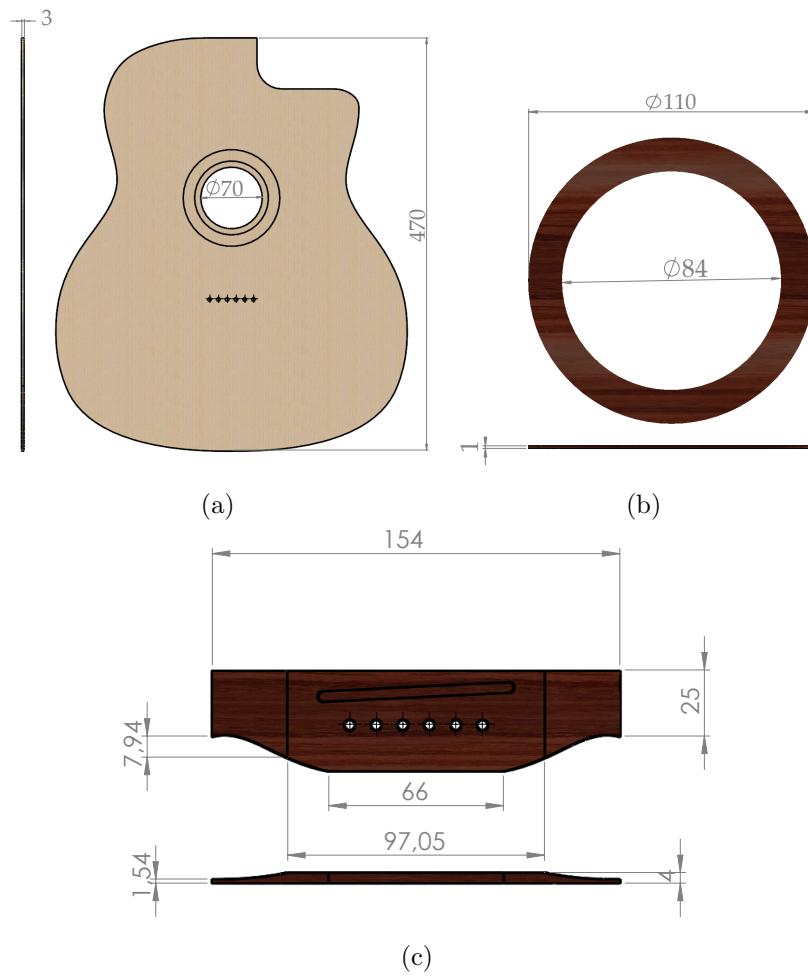


TABLE 4 – Name and description of the parameters considered for the analysis.

Name	Description
Sb_{E_L}	Soundboard E_L (MPa)
Sb_{E_R}	Soundboard E_R (MPa)
$Sb_{G_{LR}}$	Soundboard G_{LR} (MPa)
$Sb_{G_{RT}}$	Soundboard G_{RT} (MPa)
$Sb_{G_{TL}}$	Soundboard G_{TL} (MPa)
Sb_{ρ}	Soundboard density (gcm^{-3})
$Bars_{E_L}$	Bars E_L (MPa)
$Bars_{E_R}$	Bars E_R (MPa)
$Bars_{G_{LR}}$	Bars G_{LR} (MPa)
$Bars_{G_{RT}}$	Bars G_{RT} (MPa)
$Bars_{G_{TL}}$	Bars G_{TL} (MPa)
$Bars_{\rho}$	Bars density (gcm^{-3})
T	Temperature ($^{\circ}\text{C}$)
RH	Relative humidity (%)

FIGURE 3 – Bridge admittance evaluation and input force position and direction.

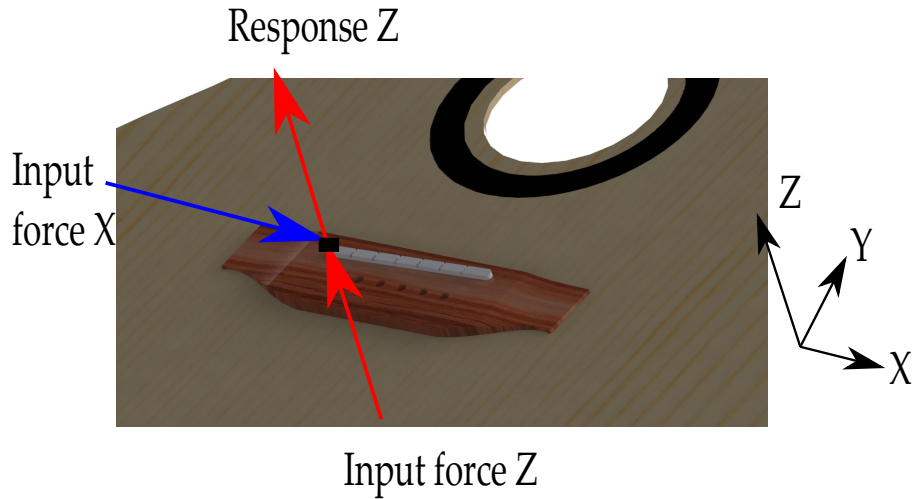


FIGURE 4 – Computed modes of the classical braces guitar soundboard, C_{guitar} .

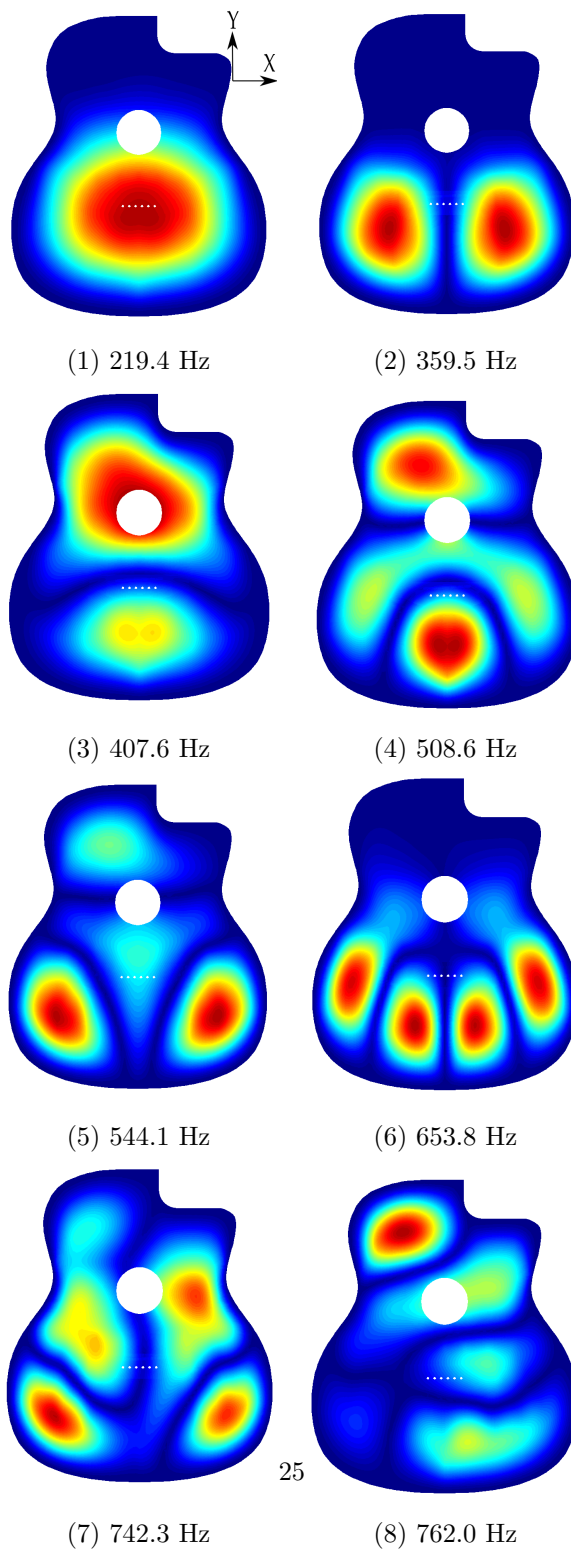


FIGURE 5 – Computed modes of the string-steel braces guitar soundboard, A_{guitar} .

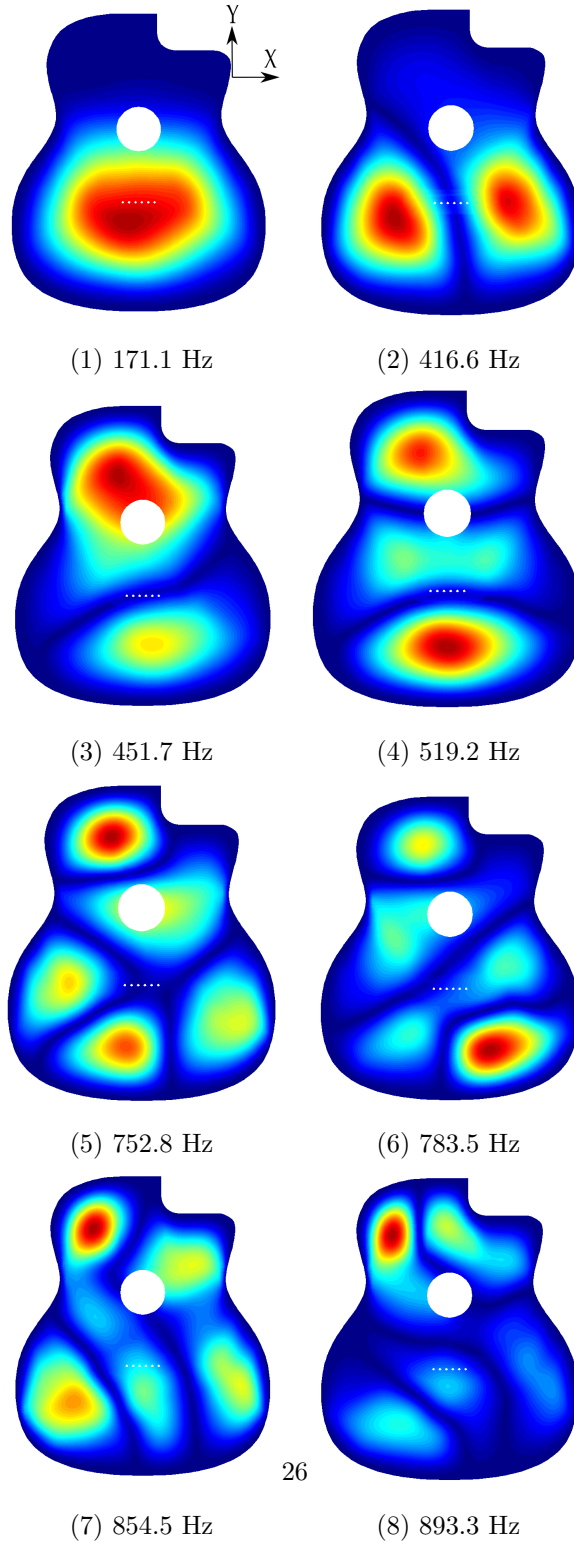


FIGURE 6 – Computed modes of the selmer braces guitar soundboard, S_{guitar} .

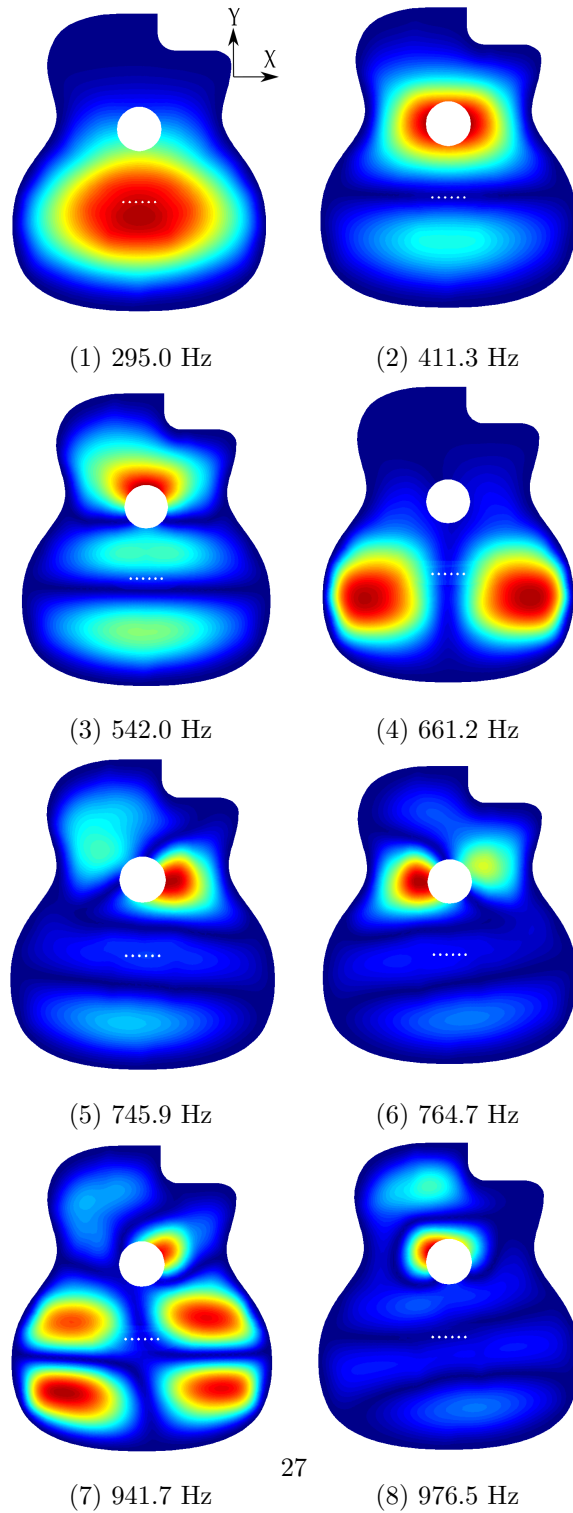


FIGURE 7 – Nominal FRF with initial material and climatic parameters.

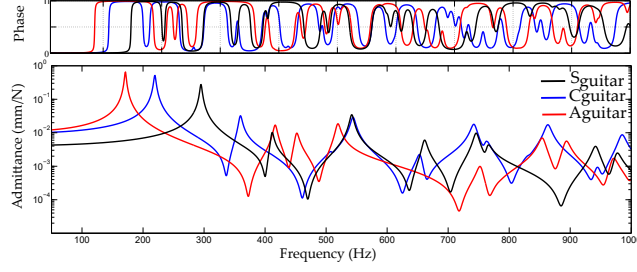
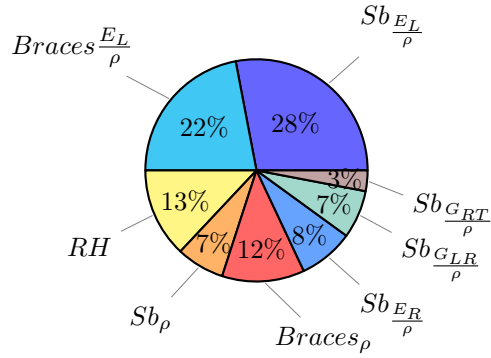


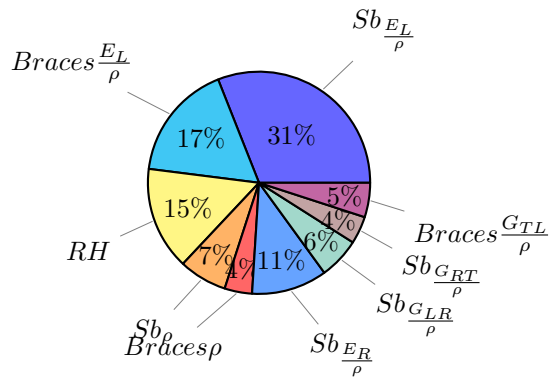
TABLE 5 – Matched eigenfrequencies error (MEE) and MAC value of the three cases with nominal values of the parameters.

	C_{guitar}		S_{guitar}			
Mode	Frequency (Hz)	Mode	Frequency (Hz)	MEE (%)	MAC (%)	
1	214.6	1	288.7	34.5	98.9	
2	353.5	4	645.0	82.5	88.1	
3	400.3	2	403.5	0.8	89.9	
	C_{guitar}		A_{guitar}			
Mode	Frequency (Hz)	Mode	Frequency (Hz)	MEE. (%)	MAC (%)	
1	214.6	1	167.5	-22.0	99.5	
2	353.5	2	407.4	15.3	87.7	
3	400.3	3	442.7	10.6	88.3	
4	501.0	4	512.3	2.3	65.0	
8	750.8	6	770.6	2.6	55.4	
10	844.6	8	873.5	3.4	52.5	
12	965.5	9	953.5	-1.2	58.7	
	S_{guitar}		A_{guitar}			
Mode	Frequency (Hz)	Mode	Frequency (Hz)	MEE (%)	MAC (%)	
1	288.7	1	167.5	-42.0	99.2	
2	403.5	3	442.7	9.7	73.0	
3	532.7	4	512.3	-3.8	76.9	
4	645.0	2	407.4	-36.8	84.2	

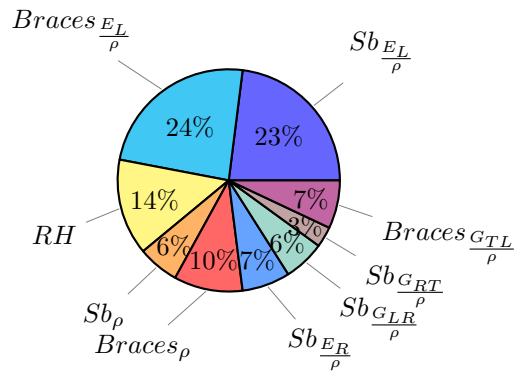
FIGURE 8 – Material screening analysis on matched eigenfrequencies of : (a) C_{guitar} , (b) A_{guitar} , (c) S_{guitar} .



(a)



(b)



(c)

TABLE 6 – Values of modal overlap factor (%) for corresponding third octaves bands for different cases of guitar bars and frequency domain.

Third octave band (Hz)	C_{guitar} (%)	A_{guitar} (%)	S_{guitar} (%)	Domain
160	0	9	0	L.F.
200	7	0	0	L.F.
250	2	0	3	L.F.
315	7	0	3	L.F.
400	14	14	2	L.F.
500	18	16	9	L.F.
630	16	9	14	L.F.
800	37	32	21	M.F./L.F.
1000	39	34	28	M.F./L.F.
1250	48	46	46	M.F.
1600	83	96	70	H.F./M.F.
2000	101	97	87	H.F.
2500	152	143	124	H.F.

FIGURE 9 – Modal overlap factor as a function of the third octave bands, for three different cases of guitar bars

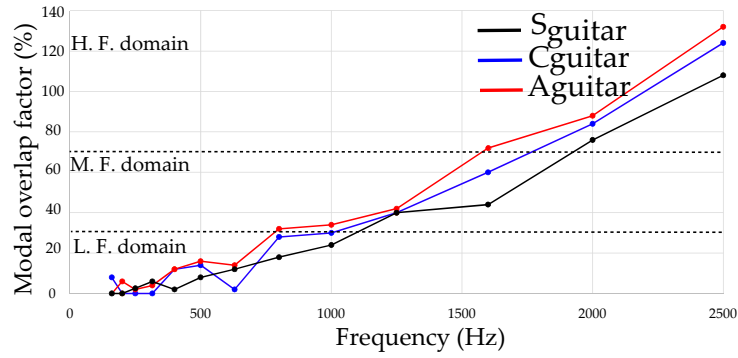


TABLE 7 – Frequency mean values and absolute and relative standard deviation (RSD) of the three cases for a normal distribution of the frequencies.

Mode	C_{guitar}		A_{guitar}		S_{guitar}	
	μ and SD (Hz)	RSD (%)	μ and SD (Hz)	RSD (%)	μ and SD (Hz)	RSD (%)
Mode 1	215.9 \pm 11.3	\pm 5.1	168.9 \pm 9.2	\pm 5.5	291.1 \pm 16.5	\pm 5.6
Mode 2	355.9 \pm 19.5	\pm 5.4	413.9 \pm 23.8	\pm 5.7	406.1 \pm 22.3	\pm 5.4
Mode 3	403.4 \pm 21.3	\pm 5.2	448 \pm 24.6	\pm 5.5	534 \pm 28.8	\pm 5.3
Mode 4	502.5 \pm 27.3	\pm 5.4	511.1 \pm 29.2	\pm 5.7	658.1 \pm 40.0	\pm 6.0
Mode 5	541.5 \pm 29.1	\pm 5.3	743.5 \pm 40.1	\pm 5.4	731.9 \pm 40.6	\pm 5.2
Mode 6	653.9 \pm 37.8	\pm 5.8	774.4 \pm 42.6	\pm 5.5	757.7 \pm 42.3	\pm 5.3
Mode 7	737.1 \pm 40.0	\pm 5.4	848.7 \pm 46.5	\pm 5.5	930 \pm 51.1	\pm 5.3
Mode 8	750.8 \pm 42.8	\pm 5.7	888.5 \pm 49.6	\pm 5.6	960.9 \pm 55.2	\pm 5.6
Mode 9	832.9 \pm 49.6	\pm 5.6	959.4 \pm 54.8	\pm 5.7	1101 \pm 60.8	\pm 5.4
Mode 10	858.4 \pm 45.9	\pm 5.3	1006 \pm 57.6	\pm 5.7	1159 \pm 64.8	\pm 5.5
Avg :	-	\pm 5.4	-	\pm 5.6	-	\pm 5.5

FIGURE 10 – Mean and upper and lower limits for each case of braces.

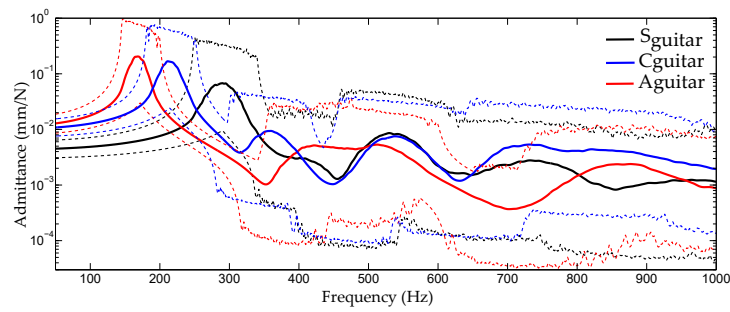
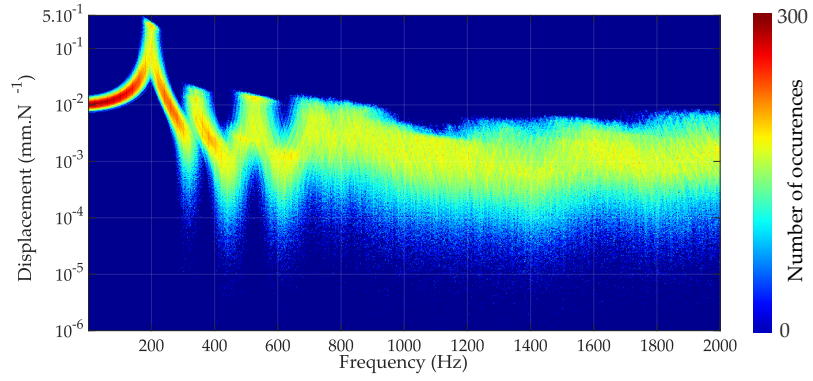
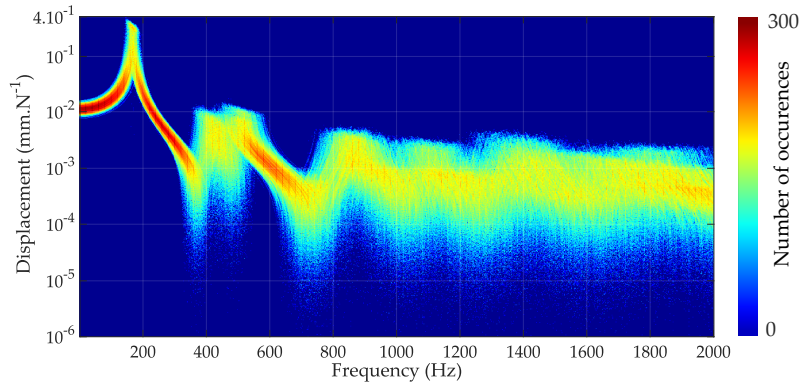


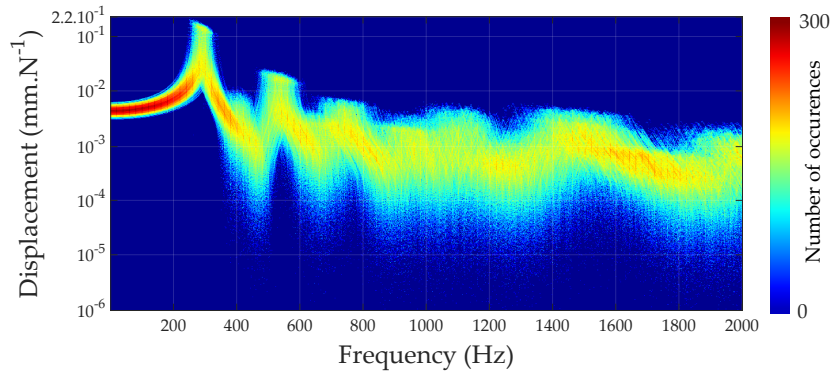
FIGURE 11 – Fuzzy FRF of the bridge admittance for : (a) C_{guitar} , (b) A_{guitar} , (c) S_{guitar} .



(a)



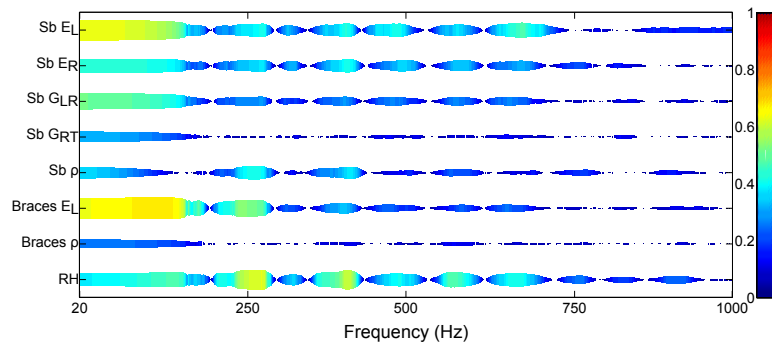
(b)



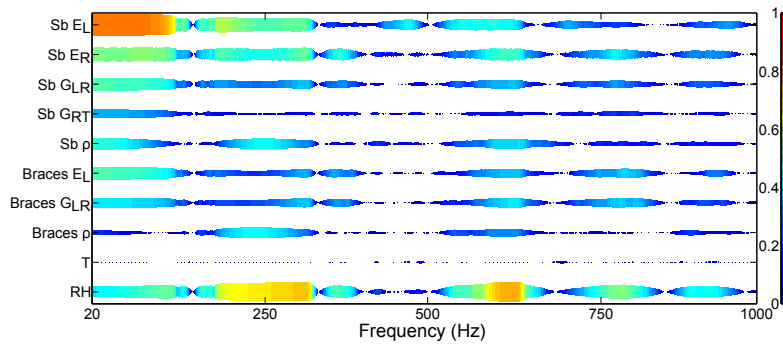
(c)

FIGURE 12 – Coefficient of correlation between bridge admittance and material parameters :

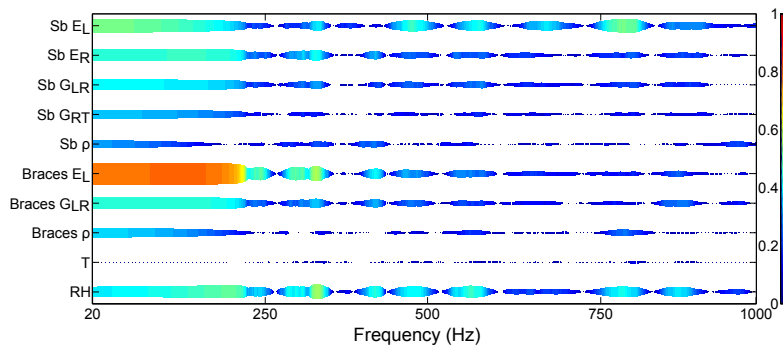
(a) C_{guitar} , (b) A_{guitar} , (c) S_{guitar} .



(a)



(b)



(c)