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INVESTIGATION OF BRACINGS TRANSFORMATIONS ON VOBOAM GUITARS: WHAT CAN UNCALIBRATED FEM MODELS TELL US?

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ABSTRACT

The Baroque guitar was one of the most popular instruments among the French nobility, especially at the court of Louis XIV. The instrument makers of the Voboam family (1640-1731) helped to set the standard for Parisian Baroque guitars, particularly in terms of proportions and decorative features. Twenty-nine guitars of these makers are still extant, among which nine are preserved at the Musée de la musique, Paris. These instruments exhibit significant material transformations which are part of the instruments' material histories. Various modifications of the bracings glued underneath the soundboards are prone to have a strong impact on the vibrational behaviour of the instruments. This paper aims to provide answers to clarify the intention behind these transformations. Using 3D scan imaging, the dimensional differences of the eight soundboards are proved to be small enough to create one numerical model whose soundbox is representative of the corpus. The influence of two allegedly "typical" bracings on the vibration modes is then studied using X radiography and Finite Element Modeling (FEM) analysis. The dynamical analysis, coupled with uncertainties analyses, show that the lack of knowledge about material and geometrical parameters is too high to draw conclusive statements about bracings influence.

Keywords: *heritage science, FEM analysis, severe uncertainty, guitar, modal analysis.*

1. INTRODUCTION

The members of the Voboam family were the most important and probably the finest makers of French guitars during the 17th and 18th centuries. Twenty-nine instruments can be attributed to five members of the family, who were active over three generations [1]. All instruments share the characteristics of exceptionally fine decoration with rare and expensive materials such as ivory, ebony, and tortoiseshell, and nine of them are kept in the Musée de la musique, Paris. Some of the guitars are in an exceptional state of preservation, while others appear to have undergone important material transformations [1]. Indeed, the outstanding decoration of the Voboam guitars made them sought-after objects to adapt them to the new musical fashion among musical amateurs, often referred to as "guitar mania".

The material transformations, probably done to fit new Romantic sound aesthetics [2,3], are multiple and include interventions such as a reduction of the five double strings of the Baroque guitar to six single strings, and the replacement of the bridge [1]. The modification of the bracings of the soundboard is one important transformation which is likely to have a significant impact on the sound radiation of the instruments [4,5].

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Addressing the influence of makers' choice in cultural heritage objects by experimental modal analysis might not be the most relevant. Indeed, the "vibratory inauthenticity" of these objects can be questioned as their successive material transformation and their various state of conservation can impact the measurements and thus introduce intra-variability in the corpus. Numerical dynamic models can help to isolate the influence of a certain material transformation on the vibratory behaviour, and thus formulate hypotheses on the sound ideal intended by the maker.

In practice, however, numerical models require knowledge of the physical properties of the materials and the geometrical characteristics of the different elements. Obtaining this information can be difficult in the context of cultural heritage due to the deontological limitations concerning the analytic methods for objects. For this study, the parchment roses in the guitar sound hole could not be temporarily removed to examine the internal structures of the body such as the exact position and dimensions of the bracings. A Computed Tomography (CT) would have provided the required information but was not possible to execute.

This paper aims to investigate the relevance of uncalibrated finite elements models to evaluate the influence of the geometry and position of the bracings on the dynamical modal behaviour of baroque guitars. The study relies on two Voboam guitars (section 2.1), which have been chosen for their significant difference in their bracing configurations. The methodology, described in section 2, is based on the creation of a 3D model whose principal dimensions are representative of the whole Voboam corpus of the Musée de la musique. It relies on X-ray radiography and 3D structured light scanning, and *a priori* estimations of material mechanical characteristics coming from the literature. The impact of bracings modifications on the dynamical behaviour is evaluated by numerical modal analysis. The influence of geometrical and mechanical parameters uncertainties is included in sensitivity and robustness analyses described in section 2.3. Results are presented and discussed in section 3.

2. MATERIAL & METHODS: GUITAR MODEL WITH UNCERTAINTIES

2.1 Corpus

Nine Voboam guitars are present in the collection of the Musée de la musique. One of the guitars (inv. E.28) has a non-conventional shape[1] and is removed from the study corpus. The dimensional metrology of the soundboxes and bracings is performed on the eight remaining guitars. Among this corpus, only two guitars are chosen for the FEM model and dynamical simulation. These guitars (inv. E.1411 and inv. E.2087), are from Jean Voboam and are dated 1687 and 1690 (see Fig. 1).

Figure 1. Two guitars from Jean Voboam used for the study. Top: guitar inv. E.1411 (Paris, 1687); bottom: guitar inv. E.2087 (Paris, 1690) (Photos: Jean-Marc Anglès © Cité de la musique – Philharmonie de Paris)

One of the two guitars (inv. E.2087) shows a major bracing transformation that could have been made with the intention of changing the sounding properties or reinforcing the strength of the soundboard due to the temporal addition of a

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[1] https://collectionsdumusee.philharmoniedeparis.fr/doc/MUSEE/0161567

sixth string [6]. Even though both guitars show typical bracings from the eighteenth century [7], written sources indicate that an oblique bar of guitar E.2087 could be considered a later addition [8]. All other material transformations include restorations [9] and the replacements of smaller parts such as pegs and bridges, which can be considered secondary to the vibratory behaviour of the guitar [10]. The two guitars have 5 double strings.

From now on, the inv. E.2087 will be referred to as guitar A, and the inv. E.1411 will be referred to as guitar B.

2.2 Dimensional metrology

The geometry of the 3D model is made using two complementary techniques: (i) a structured-light 3D scanner (EinScan HX Pro) is first used to acquire the contours of the eight Voboam guitars soundboards, in order to estimate the intra-variability of the soundboard shape within the corpus (resolution: 0.1mm); (ii) X-ray is then performed on the two guitars chosen for the study to evaluate their bracings positions and dimensions (X-ray source: Y.MG 165 / 2.25 160 kV, focal spot size: 0.4 mm, X-ray detector system: FILM Agfa Structurix D, resolution ca. 35 µm). The radiography images gave access to the internal position of the bracings, which were extracted using Gimp and ImageJ. The soundboard contours of the 8 Voboam guitars are displayed in Fig. 2.

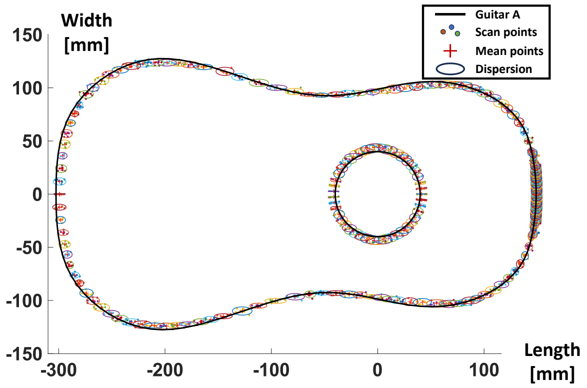

Figure 2. Point cloud of the eight Voboam guitars soundboards of the Musée de la Musique. The contour of guitar A is shown with a black line.

The contours, aligned in a plane taking its origin at the sound hole centre, define a point cloud representative of the dimensional dispersion of the corpus. The error along both axes can be then computed with a confidence of 95%. The mean x-axis error reaches 3.15 mm, and the mean y-axis error reaches 1.60 mm. The guitar A has a contour included in the point cloud. Therefore, it is possible to create a unique soundboard model with a mean curve representative of the corpus.

The X-ray radiographies showing the bracings geometry and position of the guitars A and the B are displayed in Fig. 3. Note the oblique bar of the guitar A as expected from written sources mentioned in section 2.1.

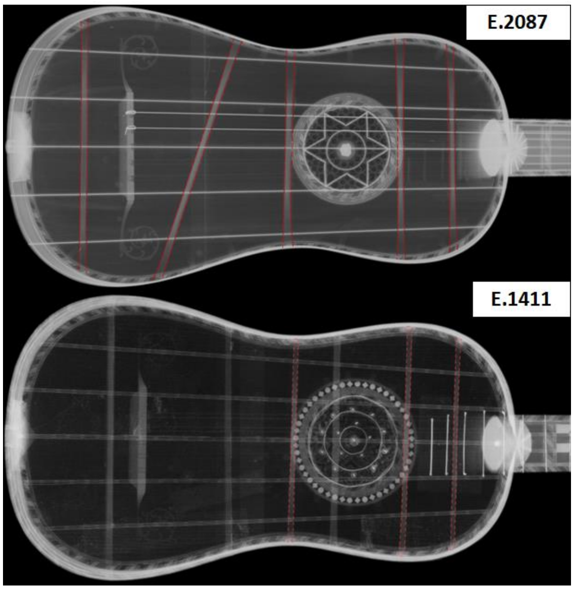

Figure 3. Guitars A (top) and B (bottom) bracings, obtained from X-ray radiography.

2.3 Numerical model

Because of the small dispersion of the point cloud, it has been decided to model one generic guitar. In this model, two geometrical configurations of the bracing are tested with the same material parameters.

The guitar A is used as a reference for the geometrical modelling. The computer-aided design (CAD) model is built with *SolidWorks*. The different parts of the model are illustrated in Fig. 4. It must be highlighted that the model of the parchment rose has been simplified to reduce the calculation time of the dynamical analysis.

The FEM model is designed with *Abaqus*. Strings tension and varnish are not considered, whereas the air cavity is modelled with fluid-structure interactions [11,12]. A local coordinate system is assigned to each part with a material anisotropic behaviour. Spruce is used for the soundboard, the neck, and the rose, while the bridge, the backboard and the guitar sides are made of rosewood.

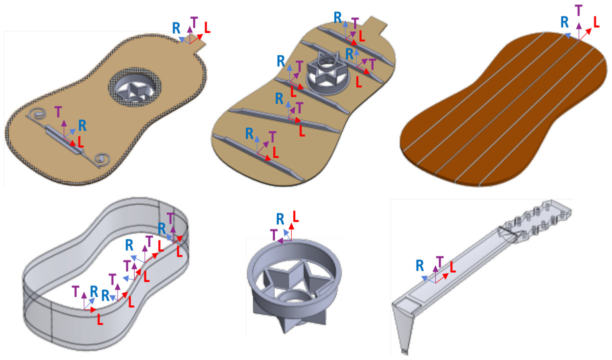

Figure 4. Coordinate systems for the FEM model. “L” stands for “longitudinal”, R for “radial” and T for “transverse” directions.

The mechanical properties of those materials are extracted from literature [13,14]. The neck-soundbox junction is constrained with a rigid joint. C3D15 and C3D10 elements are mostly used for structural parts, with typical sizes ranging from 1.8 mm (sides) to 8 mm (soundboard) preventing element distortion. The air cavity is modelled with 3D elements inside the sound box, and with a skin composed of semi-infinite acoustic elements at the sound hole interface. AC3D10 and ACIN3D6 elements are used for the acoustic medium with a typical size of 3mm around the rose and 10mm otherwise. The link between structural and acoustic elements is made with node-tied constraints. The first 30 vibration modes are extracted with a “natural frequency extraction” step over [50 – 2000 Hz].

2.4 Sensitivity and robustness analyses

Sensitivity analyses were performed to quantify the effects of the numerical model input parameters on the identified eigenfrequencies of interest. Thus, the input parameters which have a critical impact on the model behaviour can be identified. Finite Difference [15] and Morris’s sensitivity [16] analyses are used.

Finite Difference is a local method that helps to screen roughly the whole input domain (or parameters space). The nine elastic constants and the density of each element of the guitar have been selected for the material parameters. In addition, the thicknesses of the soundboard, the sides, and the back as well as 4 parameters related to the bracing bars (Fig. 5) have been selected for the geometrical parameters. In total, 133 input parameters were studied for guitar A and 105 for guitar B.

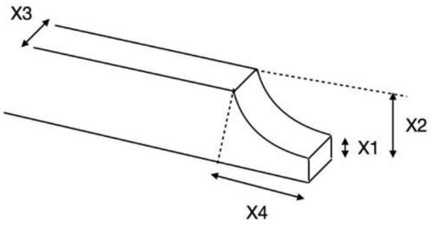

Figure 5. Parameters related to the bars of the bracing.

Morris’ sensitivity analysis is a global method and helps to confirm the results of the finite difference method and identifies potential couplings between the parameters. The 10 most influential material parameters and the 10 most influential geometrical parameters per eigenmode have been selected from the finite difference method. In total, 34 parameters were studied for guitar A, while 29 were for guitar B, with variations of +/- 25 % of their nominal value, over four random trajectories in the parameters space.

From these sensitivity analyses, robustness analyses inspired by the info-gap method [17] can be performed. Several horizons of increasing uncertainty are applied to the model to find the "worst” uncertainty horizon for which the variation of modal frequencies will be the most important. Eqn. (1) and Eqn. (2) describe the parametric models used for the robustness analyses.

$$U_{geo}\left(Inc^{max}, u_{geo}^{(0)}\right) = u_{geo}^{(0)} \pm s * Inc^{max} \tag{1}$$

$$U_{mat}\left(\alpha, u_{mat}^{(0)}\right) = u_{mat}^{(0)} \pm s * u_{mat}^{(0)} * \alpha \tag{2}$$

with, $u^{(0)}_{geo}$ the initial value of the geometric parameters, $u^{(0)}_{mat}$ the initial value of the material parameters, s the sign vector, Inc^{max} the maximum geometric uncertainty, α the uncertainty horizon, $u_{geo}(Inc^{max}, u^{(0)}_{geo})$ the parametric model of the geometric parameters and $u_{mat}(\alpha, u^{(0)}_{mat})$ the parametric model of the material parameters.

3. RESULTS AND DISCUSSION

3.1 Numerical modal analysis

The extraction of the modal frequencies is performed for the two guitars. To compare the modal bases, the usual modal assurance criterion (MAC) is computed on the whole numerical model [18]. The MAC matrix is given in Fig. 6.

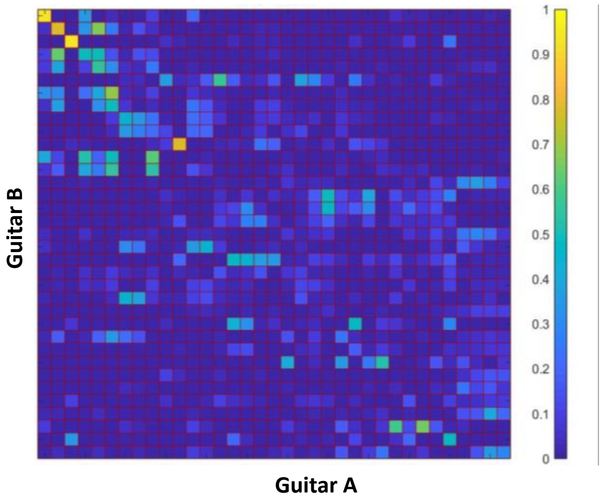

Figure 6. MAC matrix for guitars A Vs. B.

The relevant modes are chosen so that they combine a soundboard strain energy level superior to 80 % and a MAC matching criterion over 80 %. The fourth mode of the two guitars have been added as the soundboard modal shapes are visually correlated. These modes and their associated frequencies are summarised in Tab. 1. The corresponding modal shapes are displayed in Fig. 7.

Table 1. Matched modes between the guitar A and the guitar B (soundboard strain energy level and MAC matching criterion over 80%).

Guitar A		Guitar B		Frequency shift (%)
n°	**Frequency (Hz)**	**n°**	**Frequency (Hz)**	
2	155.27	2	136.86	-11.86
4	306.06	4	266.69	-12.86
6	350.08	7	420.01	19.97

The first air cavity mode, also referred to as the pseudo-Helmholtz (mode 2; Fig. 7a), as well as the first soundboard mode (mode 4; Fig. 7b) are well matched regarding their modal shapes. However, there is a frequency shift of, at least, 10 % on these modes, which is significant. These results indicate that the oblique bar of the guitar A bracing seems to have a significant influence even on the low-frequency behaviour. This low-frequency behaviour has a strong impact on the radiated sound [19]. Thus, it is possible to categorize and discriminate between original and modified bracings.

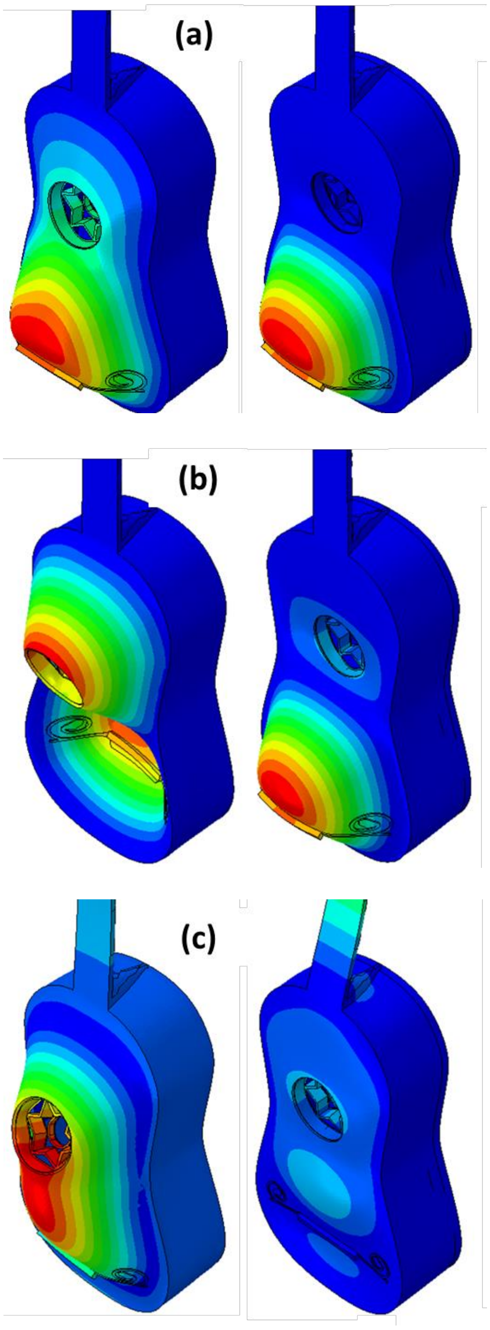

Figure 7. Modal shapes of matched modes (MAC > 80 %) of the guitar A (left) and guitar B (right). (a) Mode n°2 (air-cavity mode) (b) Mode n°4 (soundboard mode) (c) Left: mode n°6; right: mode n°7 (soundboard mode).

3.2 What about severe uncertainties?

Because of the severe uncertainty relative to the patrimonial aspects, previous results must be nuanced. The sensitivity analyses, performed with the finite difference method and the Morris's analysis, highlight that the most influent parameters involve both materials as well as geometrical parameters. The most influential parameters are detailed in Tab. 2. Guitar A is mostly subject to bracing height uncertainty while guitar B is mostly influenced by material parameters uncertainty. This can be explained by the presence of the oblique bar in guitar A bracing. This bar affects the global stiffness of the soundboard. As it is not present in guitar B, the latter is mostly affected by stiffness properties of the material, i.e. the Young's moduli.

From this sensitivity analysis, a robustness analysis is performed over the matched modes frequencies to evaluate the (dis)similarity between the models. For example, the mode n°2 frequency (air cavity mode) is given in Fig. 6. Three uncertainty horizons for the geometrical parameters are evaluated: the horizon used in this study (constrained by the use of X-ray radiography, Tab. 2), an uncertainty horizon reachable with a better metrology system like a CT-scan (resolution up to 0.5mm), and a theoretical level making it possible to separate the two models. In addition, three uncertainty horizons (α) for material parameters are evaluated: 10 %, 20 % and 30 %.

Table 2. Uncertainty horizon of the most influential parameters obtained from sensitivity analyses for guitar A and guitar B. ρ is the density, E_l and E_r stand for the longitudinal and the radial Young's moduli, t is the thickness of the part, and X_2 is the height of the associated bar.

Guitar A			
Material		**Geometrical**	
Parameter	Uncertainty horizons	Parameter	Uncertainty horizons
$\rho_{soundboard}$	0, 10, 20, 30 %	$t_{soundboard}$	± 1 mm, ± 0.5 mm, ± 0.1 mm
ρ_{sides}		t_{sides}	
$\rho_{backboard}$		$t_{backboard}$	
$E_{l\text{-}backboard}$		$X_{2\text{-}B2}$	± 3 mm, ± 0.5 mm, ± 0.1 mm
		$X_{2\text{-}B3}$	
		$X_{2\text{-}B4}$	

Guitar B			
Material		**Geometrical**	
Parameter	Uncertainty horizon	Parameter	Uncertainty horizon
$\rho_{soundboard}$	0, 10, 20, 30 %	$t_{soundboard}$	± 1 mm, ± 0.5 mm, ± 0.1 mm
ρ_{neck}		t_{sides}	
$E_{l\text{-}soundboard}$		$t_{backboard}$	
$E_{r\text{-}soundboard}$			
$E_{l\text{-}backboard}$			
$E_{r\text{-}backboard}$			
$E_{l\text{-}neck}$			

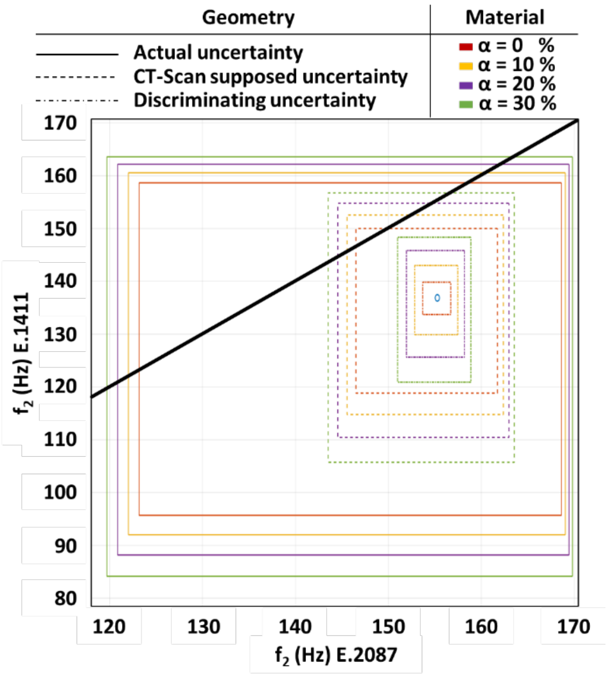

Figure 8. Evolution of the frequency of mode n°2 of guitar A (horizontal) and guitar B (vertical) according to increasing uncertainty horizons for geometrical (plain, dotted and dot-dash lines) and material parameters (see the different colours for alpha values). The line f_2(guitar A) = f_2(guitar B), which bounds the discrimination of the two models for f_2, is displayed in thick black line.

With the actual level of geometrical uncertainty (see the rectangles in plain line in Fig. 8), it is not possible to discriminate the two bracings configurations for the air cavity mode frequency - the rectangles cross the line f_2(guitar A) = f_2(guitar B). Increasing the resolution of the metrology could increase the robustness of the conclusions. Note that the robustness has been evaluated on the modal frequencies only, and not on the modal shapes, which could also change and influence the total sound behaviour.

4. CONCLUSIONS

The research presented in this paper proposed to address the ability of non-calibrated FEM models to discriminate the influence of bracings on guitar dynamical behaviour, hence clarifying the intention behind transformations of historical guitars. The bracings geometry and configurations of two Voboam baroque guitars from the Musée de la musique have been extracted and included in a complete 3D guitar model. FEM modal base extraction allows discriminating original bracing from lately modified bracing. However, when severe uncertainties on material and geometry are considered, this conclusion does not remain valid, mostly because of the geometrical parameters.

A better dimensional extraction would benefit to the proposed methodology. For example, a CT-scan would provide more precise dimensional information than 2D radiography. In addition, a better knowledge of the mechanical parameters of materials would help. Instead of using literature values, the resort to a non-destructive and in-situ technique [20] to properly measure the mechanical properties of the soundboard and the backboard could be used considering the ageing of the instruments.

Finally, modal base matching used for the comparison of the instrument might be too specific to the structure: two instruments with slightly different structural modal bases could still have a similar perceived acoustic radiation. More global mechanical and acoustical descriptors, such as Complex-Frequency Domain Assurance Criterion (CFDAC) matrix and fuzzy-FRF [21] or sound radiation could be considered in future work.

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