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Restoration of a 17th-century harpsichord to playable condition: A numerical and experimental study

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The Music Museum in Paris recently acquired a harpsichord made by Ioannes Couchet in Antwerp in 1652. This instrument is considered to be a masterpiece and is protected as a "National Treasure." It was restored with the aim to be played again in concert. An experimental and numerical study of the vibraoacoustic behavior of this harpsichord is presented. A numerical modal analysis was performed with a finite element model. For the experimental part, impact nearfield acoustical holography was used. Experimental eigenmodes are compared to literature and to the finite element results. An application of the model for restoration studies is also proposed. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3651092]

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I. INTRODUCTION

In 2003, the Musée de la musique in Paris acquired a harpsichord made by I. Couchet. This instrument is a unique piece of musical heritage and French furniture. First, it is one of the rare examples of the work of Ioannes Couchet. Indeed, only six instruments in the world are listed as by the Couchet's descendants of the lineage of the famous Ruckers dynasty in Antwerp. Reworked in France, this harpsichord reflects the popularity of Flemish instruments in France and the influence they have exerted on the evolution of French music. The composer Jacques Champion Chambonnières (~1601/1602–1672), regarded as the founder of the first French school of harpsichord playing, was the owner of a Couchet instrument. Its painted and sculpted interior makes this instrument a particularly impressive piece of French furniture. Reworked in France in 1701 to expand its range, it was also redecorated with "grotesque" paintings on a gold background, all due to a talented decorator, which is supposed to be Claude Audran III, regarding the style of the decoration.[1] Case and table stand form a homogeneous whole, fortunately saved, and thus extremely rare. The harpsichord is a true testament of the taste in furniture at the end of the reign of Louis XIV (Fig. 1).

Built in 1652 this harpsichord initially had a single keyboard, a range of GG/BB–c^3 according to Clinkscale[2] notation (i.e., G1/B1–C6 according to U.S. standard notation), with 50 notes, and apparently three 8′ registers (but only two choirs of strings) actuated by a mechanical system from through the spine. An identical arrangement is found on an instrument built in 1679 by Ioseph Ioannes, a son of Ioannes Couchet. This instrument was stored at the Smithsonian Institution in Washington, D.C. until 2001 and then sold. In its original form, the 1652 Couchet harpsichord lacked the present 4′ choir of strings. This can be confirmed by the lack of the usual 4′ hitchpinrail under the middle of the soundboard, but the later structural addition of both a 4′ bridge and a thin 4′ hitchpinrail glued to the top of the soundboard and covering the original soundboard painting. Therefore, this extraordinary instrument represents the earliest harpsichord built in the Ruckers tradition with this disposition. The main objective for the museum was to restore this instrument to playable condition. However, in a museum, musical instruments are first regarded as cultural heritage objects kept for coming generations. For this harpsichord it was possible to also conserve the function of producing music thanks to the scientific method realized. This method consisted of a finite element model performed with a double objective: To predict the effect of structural modification resulting from restoration and from aging and to identify the influence of the different parts of the instrument on the soundboard behavior. Then an acoustical holography experiment was performed to validate the model and characterize the vibrational behavior.

When the museum acquired this harpsichord the soundboard was cracked in several places and the upper bellyrail was deformed by the string tension. It was first decided to reduce the tension of the strings and to remove them in order to repair the soundboard. This operation was realized slowly and allowed the measurement of the soundboard relaxation. The second step of the restoration was the reinforcement of

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FIG. 1. (Color online) Couchet harpsichord acquired in 2003 by the Musée de la musique in Paris (inventory number E. 2003.6.1).

the wrestplank to avoid future cracks in the soundboard and to decrease the displacement of the upper bellyrail (Fig. 2). It was decided to add some brass gap spacers (number and position determined by the model) (Fig. 3) and wooden blocks against spine and wrestplank (Fig. 2). The challenge of this restoration was to reduce the stress in the structure while modifying the dynamic response of the instrument as little as possible to allow the production of a sound nearest to the original one.

Well-conserved harpsichords of the 17th-century that have been restored to playing condition are rare. Thus, there are few scientific studies on the vibroacoustics behavior of such instruments in the literature. We can note the work of Tronchin *et al.*[3] on two Italian harpsichords of the 17th-century. In this experimental study, inspired by a similar work on pianos made by Giordano,[4] Tronchin *et al.*[3] compares the acoustical radiation of the two harpsichords. The higher frequency bandwidth of emission was indicated, as the modal density up to 800 Hz, the first modal shape and the loss factor distribution. As in the present paper, Tronchin *et al.*[3] chose to excite the soundboard with a punctual shock (hammer). Another possibility is to pluck the strings, as proposed by Beurmann *et al.*[5] and Bryanston-Cross and Gardner.[6] They measured the vibration response of the harpsichord soundboard to each string excitation, using a microphone array[5] or an optical holographic interferometry.[6] The interferometric method was also used by Suzuki[7] and Moore and Zietlow[8] for piano soundboards. Modal analyses were performed in 1985 by Kottick,[9] by means of the measurement of Chladni patterns on six antique and modern harpsichords. This technique could not be used in the present case, as it could damage the fragile soundboard decoration of the Couchet harpsichord. The very less intrusive method of nearfield acoustical holography (NAH) was therefore preferred. Savage *et al.*[10] completed a structural modes study of a modern harpsichord with an experimental and analytical study of air modes. Experimental modal analysis presented by Savage *et al.*[10] was performed with an impact hammer and accelerometers.

After a description of the finite element model of the Couchet harpsichord, static and vibration modal analyses are proposed. The experimental campaign is presented in III. The retained experimental method [impact nearfield acoustical holography (INAH)] is summarized and its choice is discussed. Experimental setup and conditions are presented. Experimental results are analyzed and, when possible,

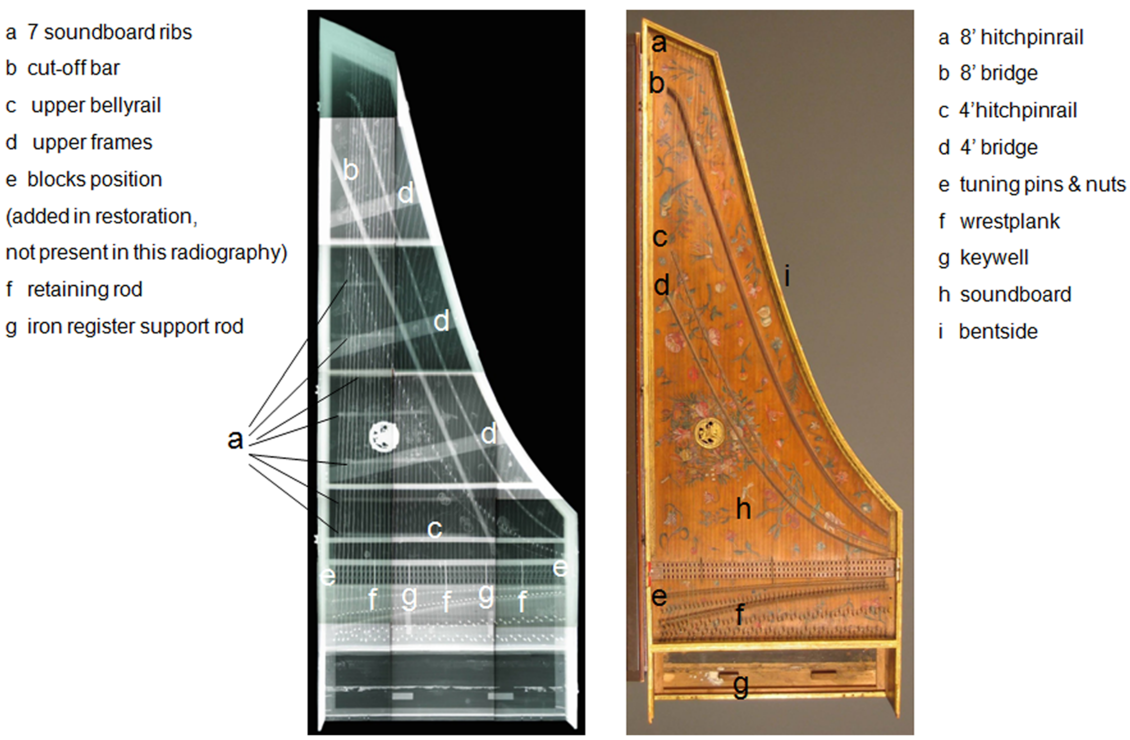

FIG. 2. (Color online) Couchet harpsichord in plan view. (Left) Internal structure, radiography before restoration; (right) visible structure.

FIG. 3. (Color online) Brass gap spacers added during restoration. (Left) Before addition; (right) after addition. Three identical spacers were added.

compared to the literature and to the finite element model. Finally an application of the model for restoration is proposed.

II. MECHANICAL SIMULATION

A. Finite element model

The finite element model (FEM) is based on the technical drawing of the Couchet harpsichord made by D. Ley in 1980 when the harpsichord belonged to a musician. The harpsichord model is made of the soundboard, the two bridges, the two hitchpin rails, the wrestplank with the two nuts and tuning pins, seven soundboard ribs, the upper bellyrail, the cutoff bar, the liners, three upper braces, and the bottom. The model considers precisely the geometry of these elements and their position, thanks to radiography of the whole instrument [Fig. 2 (left)]. During different restoration steps, some elements (three brass gap spacers and two limewood blocks) were added to the original construction. These elements are considered as beam and their mechanical properties are given in the Table I. Implemented with CAST3M software,[11] the mesh has 40 460 orthotropic shell elements for which the direction of the wood is taken into account, and 657 beam elements. The final model has 736 164 degrees of freedom. The wood species used have been identified and the material properties associated with these species have been found in the literature and are presented in the Table I.

The soundboard is assumed to be a uniform 3 mm thick, although its thickness can, in reality, vary from 2 to 3.5 mm (but is close to 3 mm on most of the surface). For simplification it is considered as a unique piece of wood, although formed from separate flitches. The finite element model thus obtained is presented in Fig. 4.

Mamou-Mani *et al.*[12,13] have shown that prestress can have an influence on the modal behavior of instrument soundboards. Therefore, we have included the effect of static forces due to string tension (downbearing) in the model. The downbearing was calculated from the string tension (according to a 17th-century French pitch standard A392, i.e., 392 Hz) and from the angles between nut pins, hitchpins, tuning pins, and bridge. A local force with three components is then added at each node of the bridges, nots, hitchpins, and tuning pins. Simply supported boundary conditions on the whole surface of the bottom of the instrument are considered.

B. Results

1. Static analysis

The results presented in Fig. 5 consist of the representation of the shear stress in the soundboard when this element is included in the whole instrument. It can be seen that the maximum shear stress is observed in the extreme treble (bottom right corner) and in the extreme bass (upper left corner). This result has been compared to the observation of several other harpsichords and it appears that these are the two most fragile regions of a soundboard as many harpsichord soundboards are cracked here. The sudden change in stiffness of the soundboard at the end of the 8′ bridge can contribute to this shear stress concentration.

2. Dynamic analysis

Modal frequencies and mode shapes have been calculated from 1 to 500 Hz. The modal density is relatively important as 60 modes were found in this frequency band. Some examples of mode shapes are shown in Fig. 6.

The soundboard appears to be the most flexible part of the harpsichord. It was however observed that, for some modal shapes, the sides (bentside, spine) also present a significant level of flexibility. If we focus on the soundboard

TABLE I. Mechanical properties of the harpsichord components.

Component	Species	kg/m^3	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xy}
Soundboard, soundboard ribs, cutoff bar	Spruce	440	14	1.1	1.36	0.37
Bridges, hitchpin rails	Maple	500	10			0.43
Wrestplank	Oak	610	12.5	1.9	1.1	0.35
Liners, bottom, upper bellyrail, upper frames	Poplar	410	9	1	5.5	0.2
Blocks	Limewood	410	9			0.2
Gap spacers	Brass	7 000	100			0.35

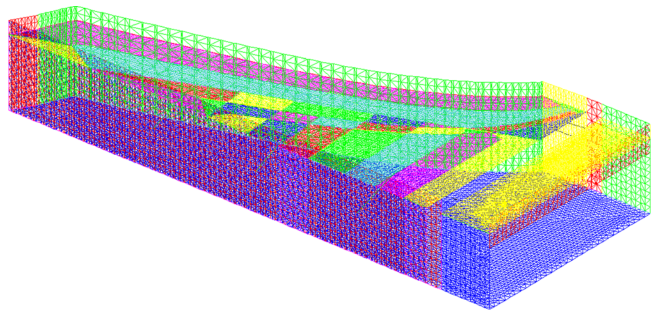

FIG. 4. (Color online) Finite element model. The model is composed of 40 460 orthotropic shell elements and 657 beam elements. Static forces due to string tension are included in the model.

modal shapes, we can observe that the very first modes are global movement of the soundboard. The influence of ribs on the modal shapes is significant from the seventh mode. From this mode one can distinguish two distinct flexible areas on the soundboard, separated by the cutoff bar.

III. EXPERIMENTS

A. Measurement method

The INAH is an adaptation of the NAH process for an impulse source excitation, was primary presented by Ollivier *et al.* [14] The NAH process of planar harmonic pressure fields was introduced by Williams *et al.*,[15] Maynard *et al.*,[16] and Veronesi and Maynard[17] and it is exhaustively described by Williams.[18] The response of the vibrating source is measured in terms of radiating acoustic field with a microphone array located at a distance z_h, when the plane source is at z_s.

The vibration behavior of the source is then deduced, in terms of normal vibration velocity, with the help of an inverse calculation method based on spatial two-dimensional (2D) Fourier transforms.

The steps implemented for the processing of the previously measured fields follow the description presented by Williams.[18] The first step consists, by means of a 2D spatial Fourier transform, in converting the measured harmonic pressure field $P_h(\omega, x, y, z_h)$ from the real space domain into its k-space representation $P_h(\omega, k_x, k_y, z_h)$:

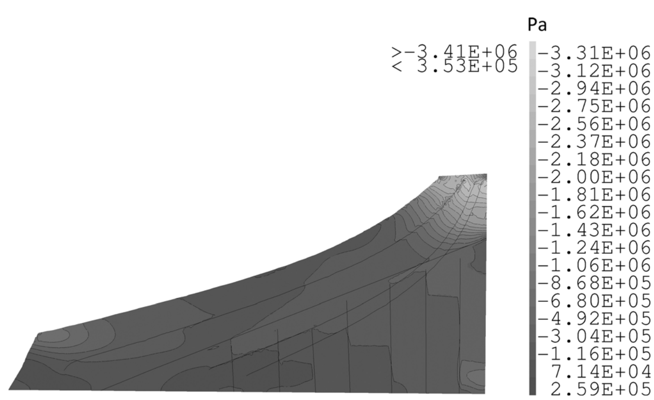

FIG. 5. Shear stress distribution on the soundboard. Calculated with the complete model, with downbearing and restoration added elements. Shear stress range is (-3.41×10^6 Pa; 3.53×10^5 Pa).

$$KP_h(\omega, k_x, k_y, z_h) = \mathbf{F}_{xy}[P_h(\omega, x, y, z_h)]. \quad (1)$$

The second step consists of conditioning the obtained spatial spectrum in order to eliminate the high spatial frequency noise brought by the measurement process. This is done by applying a low-pass exponential (Veronesi) filter, with a cutoff wave number of k_c. The filtered k-spectrum is denoted $KP_{hf}(\omega, k_x, k_y, z_h)$:

$$KP_{hf}(\omega, k_x, k_y, z_h) = W(k_x, k_y, k_c) KP_h(\omega, k_x, k_y, z_h). \quad (2)$$

The normal velocity of the structure, V_s, is then calculated with the following backpropagation process:

$$KV_s(\omega, k_x, k_y, z_s) = \frac{k_z}{\rho c k} \exp[j k_z (z_h - z_s)] \times KP_{hf}(\omega, k_x, k_y, z_h). \quad (3)$$

where k_z is purely imaginary for evanescent components of the field, and real for the propagating components:

$$k_z = \left[k^2 - \left(k_x^2 + k_y^2\right)\right]^{1/2}. \quad (4)$$

After the backpropagation process of the spatial spectra onto the source plane, the last step brings back to the real space, consists of an inverse 2D spatial Fourier transform:

$$V_s(\omega, x, y, z_s) = F_{xy}^{-1}\left[KV_s(\omega, k_x, k_y, z_s)\right]. \quad (5)$$

This technique is used here to achieve a structural modal analysis. The impulse response is obtained by a point shock excitation of the structure.

Among different possible techniques to perform experimental modal analysis, INAH was here chosen for its advantages specially adapted for the case of fragile structures like antique musical instruments:

(1) except for the excitation system, it is a noncontact method and
(2) as an important number of measurement points can be measured at the same time (120 in the present case), the number of shocks on the structure is much fewer, consequently the measurement time is very short (less than 120 mm for 15 360 measurement points).

Compared to more classical experimental modal analysis methods (laser vibrometry, piezoelectric accelerometers) that measure directly the vibration behavior of the structure, one must keep in mind the inverse calculation hypothesis used in NAH:

(1) the vibration source is supposed to be planar,
(2) the vibration source is reconstructed on a virtual planar rectangle of the same size as the microphone array,
(3) the source distribution is supposed to be continuous, and
(4) although measurement is performed in the near acoustic field, evanescent components are partially covered by noise and the information they contain is then lost with NAH low pass filtering process.

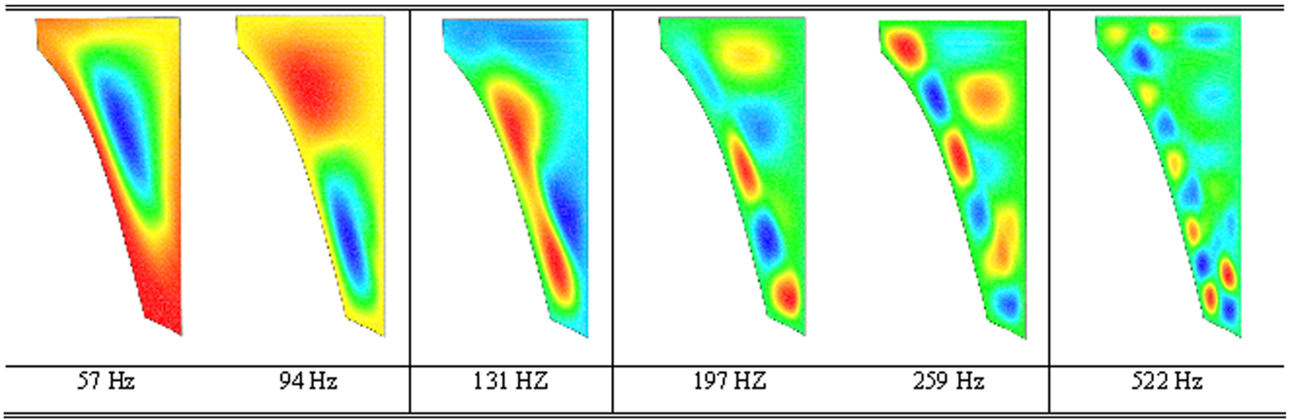

FIG. 6. (Color online) Example of six representative modal shapes and frequencies calculated.

The main consequence of the last two points is a lack of accuracy in the vibration field reconstruction of the free edges. These faults were shown to be minor in a recent study,[19] and could be neglected for the present study as the soundboard is glued to the case and to the upper bellyrail.

B. Experimental setup

The impulse response of the harpsichord soundboard was measured in the semi-anechoic room of the museum (Fig. 7) after the restoration process. In such a room, the noise level is consequently lowered. This condition allows to minimize the soundboard excitation level and also to optimize the signal-to-noise ratio for evanescent waves. The first point is of particular importance in the case of such a fragile object as this antique musical instrument (decoration conservation).

Ambient temperature and humidity were controlled in the test room during the whole duration of the experiments, to obviate additional stress caused by climate variations.

Strings were chosen not to be removed, on one hand for conservation reasons to avoid a new stress cycle, and, on the other hand, in order to measure the acoustic radiation of the soundboard in its actual stress state. Indeed, in recent studies Mamou-Mani *et al.*[12,13] have shown that prestress due to strings can modify the modal behavior of string instrument soundboards. Finally the strings were muted in order not to radiate sound [Fig. 8 (left)].

FIG. 7. (Color online) Experimental setup. Harpsichord in the anechoic room with holographic microphone array.

The point impulse excitation of the soundboard was provided by an automated hammer driven by an electromagnet that produces a repeatable shock. In the double objective of accessibility and decoration conservation, the excitation position was chosen on the underside of the soundboard. Therefore the keyboard was removed. The position of the impact was chosen so as to mobilize significant bending vibration modes of the soundboard [Fig. 8 (right)]. It was located 220 mm from the bentside and 45 mm from the front end of the soundboard.

A 12 by 10 electret microphone array, with a 50 mm step, was used to collect the impulse response pressure field (Fig. 7). So as to fit the measurement grid, the array was moved to eight positions. For each of these positions the array was also moved according to 16 interleaved positions so as to refine the measurement step grid to 12.5 mm. The 120 impulse pressure responses for each position of the array were collected using a homemade 128 channels synchronous digital recorder. Each measurement associated to one shock on the soundboard had to be phase referenced. Therefore, an accelerometer was positioned on the soundboard and its constant impulse response was systematically recorded along with the acoustic signals.

The resulting acoustic impulse response field was measured over a parallel plane at a distance $z_h = 72$ mm from the soundboard. This distance was the smallest possible here for technical reasons of accessibility.

The field was finally sampled according to a thin grid with a 12.5 mm step and limited to a 1162.5×1762.5 mm rectangle. The different sets of measurement finally count 13 348 point acoustic impulse responses (Fig. 9). The NAH process associated with this setup is summarized in the previous paragraph

C. Results

In Fig. 10, we present the sound pressure level, averaged on the whole measurement plane, from 0 up to 4000 Hz. Figure 10 shows a significant radiation level for frequencies between 140 and 2000 Hz. An important modal density in

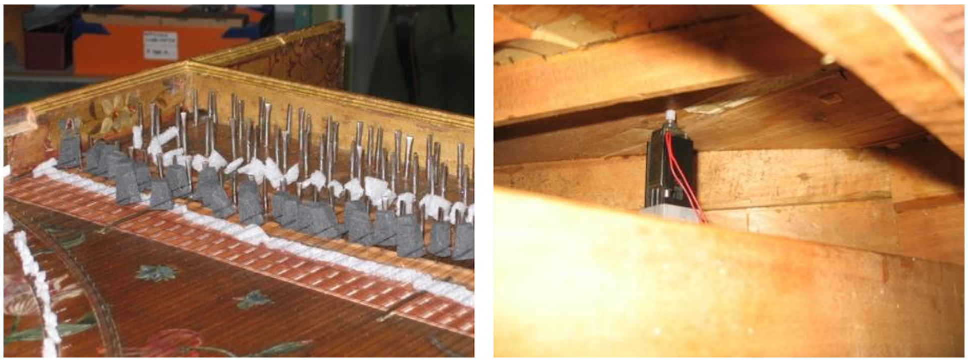

FIG. 8. (Color online) Experimental setup. (Left) String muting system. The soundboard is maintained in its actual stress state. (Right) Point impulse excitation. The impact automated hammer was placed on the underside of the soundboard.

the exploitable band [0–2000 Hz] can be observed. The frequency band of maximum radiation can be considered to be about [160—900 Hz]. Compared to the measurements made on two Italian harpsichords by L. Tronchin *et al.*,[3] the modal density and maximum radiation frequency band of the Couchet harpsichord are a little wider but quite comparable. These results confirm the statements of Tronchin *et al.*[3] that Italian harpsichords were known as being sharper than other national school of instruments. This difference can be explained by the fact that Italian harpsichords dimensions are tighter than Flemish harpsichords and that Italian frequency range of strings is sharper. The radiated sound pressure spectrum can indeed be confronted to the strings fundamental frequencies (Fig. 10). One can then observe the particularly good concordance of the maximum radiation band and the band covered by both registers and more particularly by the 4′ register.

Particular attention was paid to the modal behavior of the soundboard in the [0–1200 Hz] band. In this band more than 50 radiating modes were clearly identified (frequency and mode shape). Frequency and NAH identified modal shapes for six of them are presented in Fig. 11, where modal shapes are presented in terms of normal vibration velocity distribution obtained by NAH inverse calculation.

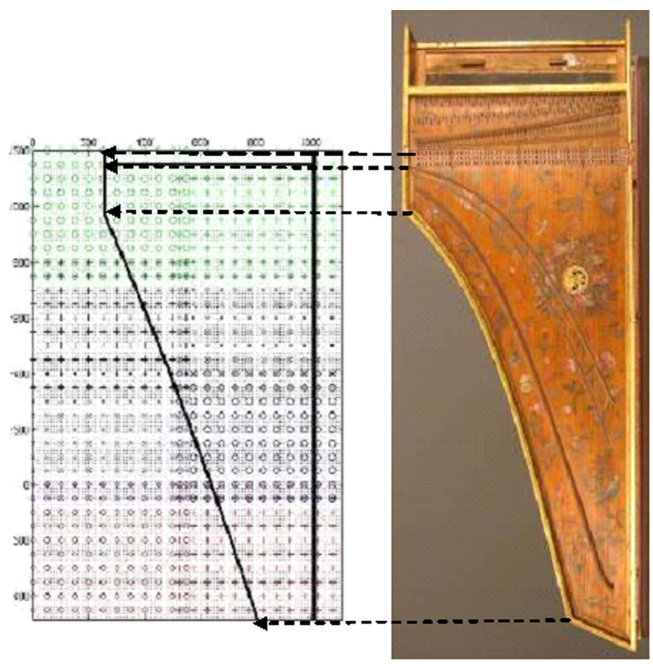

FIG. 9. (Color online) Measurement grid. The field was sampled according to a 12.5 mm step and 1162.5×1762.5 mm^2, which count 13 348 point acoustic impulse responses.

The boundary conditions and the distribution of ribs under the soundboard (presented in Fig. 2) can help the understanding of those operating mode shapes. Indeed, except the frontend the soundboard edges can be considered to be clamped as they are glued to the case. The frontend is glued to the upper bellyrail but not to the case and may be a little more flexible than the other sides of the soundboard. This can in particular explain the shape of the first operating mode. The shape of this first eigenmode is very similar to the one measured on another harpsichord by Tronchin *et al.*[3] Frequencies of the first modes are in accordance with Kottick[9] results on Northern instruments: indeed, the first mode is found between 70 and 100 Hz (73 Hz) and the second one is well around 100–110 Hz (106 Hz). The pattern of these two modes are also relatively similar to the one measured by Kottick[9] on his modern Flemish instrument.

The rib distribution can also explain that for most modes the deformation energy is particularly concentrated on the area between the cutoff bar and the bentside, as it is more flexible. A similar deformation distribution was observed by Bryanston-Cross and Gardner,[6] where the soundboard was excited by playing a single string.

IV. EXPERIMENTAL/CALCULATION COMPARISON

Experimental and finite element modal analyses have been compared. In both cases the modal density is quite similar. Comparison of six significant modes is presented in Fig. 11. Regarding both experimental and numerical limitations, the conformity of results is very satisfactory.

Indeed the numerical model is partly inaccurate as

(1) the material properties come from theoretical tables, the actual ones being unknown,
(2) the boundary conditions (especially between different parts) are considered ideal, and
(3) the only prestress taken into account is the one produced by the strings tension.

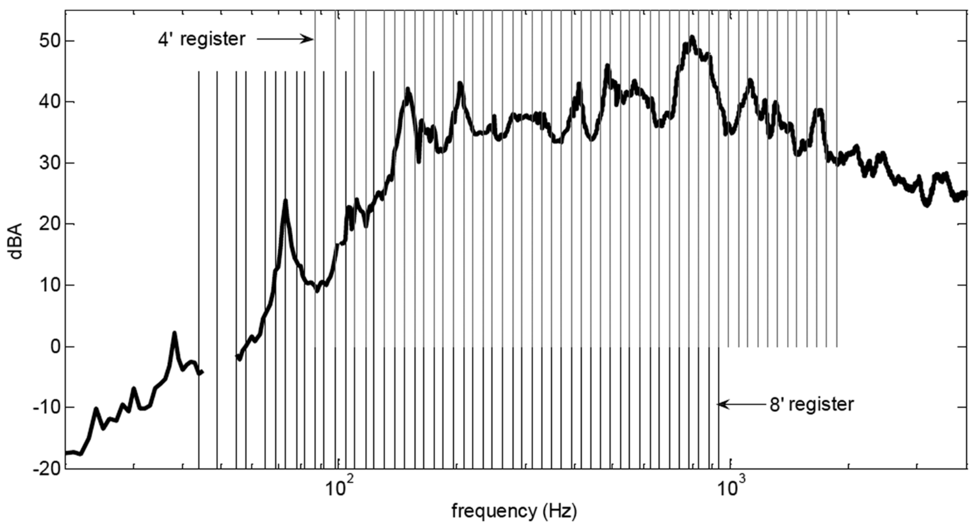

FIG. 10. Radiated pressure spectra and string frequencies. The sound pressure level is averaged on the whole measurement plane, positioned at 72 mm from the soundboard plane.

For the experimental results, we must keep in mind the specifications of the NAH process. For example, the sides contribute to the vibration state of the harpsichord, as it has been found with the FEM simulation and consequently to the measured radiation, which can distort the source identification with the NAH process.

However, one can consider that in this state the finite element model is sufficiently accurate to be used as a predictive model. This model will be used to estimate the effects of ambient conditions or structural modifications.

V. APPLICATION TO RESTORATION

The static results presented in Sec. II B 1 (Fig. 5), compared to the experiment, take into account the added blocks and the brass gap spacers. But prior to validating this choice,

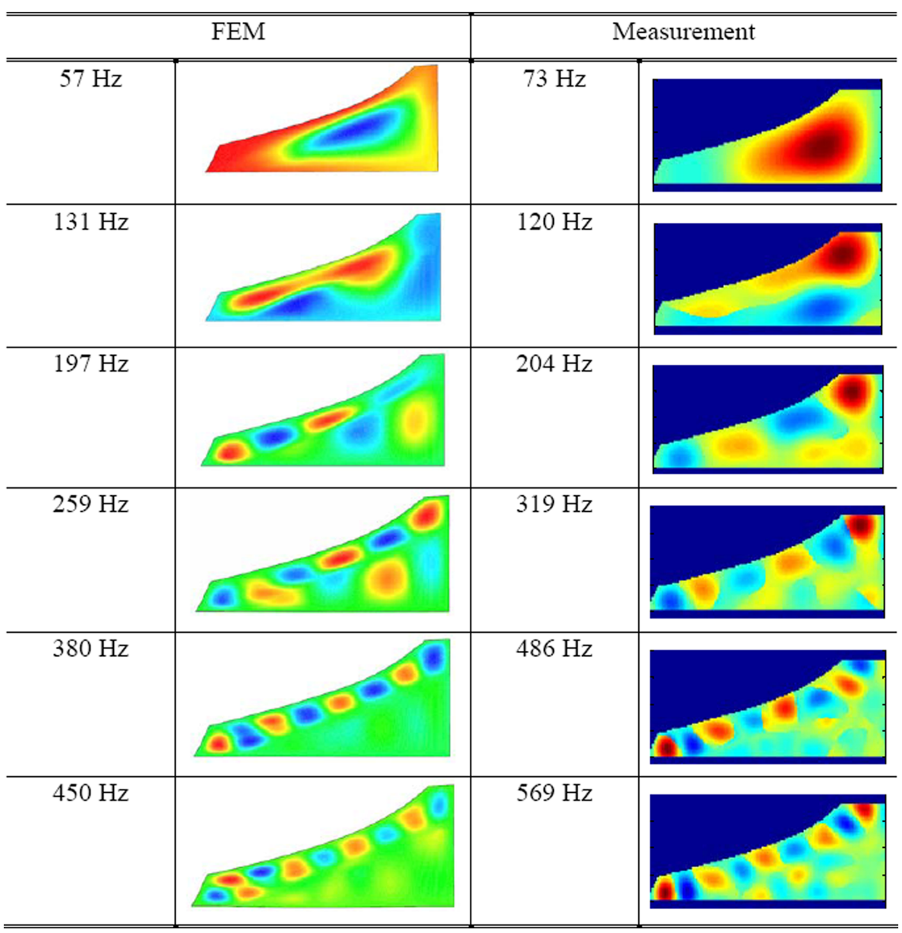

FIG. 11. (Color online) Mode shapes. Numerical/experimental comparison.

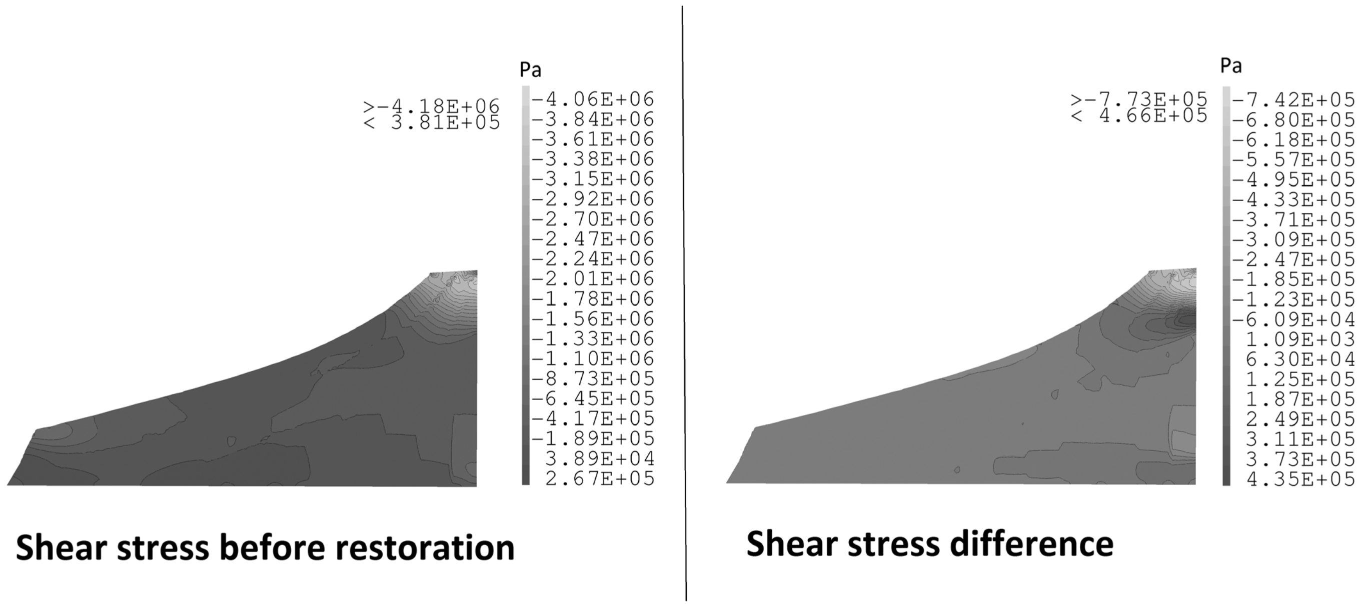

FIG. 12. Shear stress distribution on the soundboard. Effects of restoration (addition of three brass gap spacers and two wooden blocks). Shear stress range is (-4.18×10^6 Pa; 3.81×10^5 Pa) before restoration.

the effects of these elements have been simulated. The results presented in Fig. 12, show that the addition of the spacers and the blocks decrease the shear stress gradient observed in the bottom right corner. Indeed, Fig. 12 (left) represents the shear stress in the soundboard without these elements, and Fig. 12 (right) represents the shear stress difference with and without these elements.

The influence of the restoration additions was studied using a finite element modal analysis. The first 30 vibrational modes without and with restoration additions were compared. As presented in Table II for the first 10 modes, a negligible shift of the frequencies is observed. Modal shapes are identical, except for small discrepancies for 4 of the 30 calculated modes.

The main objective of the restoration was achieved. Indeed, the addition of the blocks and brass spacers has decreased the shear stress gradient in the fragile area of the soundboard without modifying the dynamic response of the vibrating part of the instrument too much.

TABLE II. Effect of restoration on dynamic behavior.

	Modal frequency (Hz)	
Mode number	Without restoration elements	With restoration elements
1	57.15	57.12
2	64.37	64.30
3	65.23	65.15
4	94.12	93.87
5	108.99	109.02
6	112.92	112.65
7	115.63	115.64
8	131.03	131.10
9	152.91	152.52
10	158.46	158.55 Hz

VI. CONCLUSION

The harpsichord studied in this paper is a unique piece, being a rare example of I. Couchet's work that was restored to be played. A finite element model was built and used for the evaluation of its static and dynamic behavior. This model was used also to assist decisions regarding the instrument restoration. The number and position of additional brass spacers were optimized considering their effect on the shear stress gradient on the soundboard. The effects of the structural elements added during the restoration were shown to be negligible with respect to the dynamic behavior of the soundboard.

An experiment was also made. The acoustic radiation and modal behavior of the soundboard were measured with impact nearfield acoustical holography (INAH) technique. This nonintrusive and fast method is particularly well suited for the study of such a fragile and large structure. The experimental results were in good agreement with the existing literature on modern and antique harpsichords and bring complementary information.

The numerical/experimental comparison of the modal behavior was quite satisfactory, considering the limitations of both the numerical and experimental results. The model is thus considered to be sufficiently accurate and usable for predictive purposes (ambient conditions and structural modifications). The experimental trial is to be renewed for diagnosis of conservation effects (especially when the harpsichord is in playable state).

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