Acoustics radiation and modal analysis of a piano forte and its fac-simile

F. Ollivier[a], S. Le Moyne[a] and S. Leconte[b]

[a]UPMC - Institut Jean Le Rond d'Alembert, 2 place de la gare de ceinture, 78210 Saint Cyr L'Ecole, France
[b]Laboratoire de Recherche et Restauration du Musée de la musique, 221, avenue Jean-Jaurès, 75019 Paris, France
francois.ollivier@upmc.fr

The Music Museum in Paris keeps in its collection a piano forte made in 1802 by the famous piano maker Érard. At that time, Erard has just come back from England where another famous maker stays, his rival Broadwood. Historical literature shows that the spreading out of the Érard's instrument was very wide: indeed Erard has given this model to Haydn, Beethoven and to many French pianists and composers. As it is a unique witness of this type of process, it was decided to keep the instrument of the museum collection in its original state (not playable), and to build a facsimile.

In the objectives of increasing our knowledge of this instrument (organological and acoustical knowledge) and to compare the original and its facsimile, an experimental modal analysis of the soundboard was performed by processing its sound field.

A non intrusive method, the Impact Planar Nearfield Acoustic Holography, was used. This technique, developed by the authors, implements the well known inverse method NAH on the basis of the acoustic impulse response field and is well adapted to modal analysis.

The behaviour of the two specimens is compared. Moreover on this model, a second soundboard, called *fausse table* is added over the strings. The second objective of the measurement is then to understand the acoustical role of this *fausse table* comparing the sound field with and without this second soundboard.

1 Introduction

In Europe, a growing interest appeared in the second half of the 18th century for the pianoforte. In that period two types of action prevail in the grand piano: the Viennese push-button mechanism and the English simple escapement. In France, Sébastien Erard was inspired by the English technique, and particularly by Broadwood's production. Most of the pianoforte production of that period are square shaped instruments, but harpsichord shaped pianos represent about 10% of the production. The harpsichord shape is dedicated to concert representation. S. Erard produced his first model of harpsichord shape piano between 1797 and 1809 [1-2]. Many Pianists and composers of the period, including Haydn and Beethoven possessed this model [1-3].

The music museum of Paris keeps two of those instruments, from 1801 and 1802, but the 1801 one presents several interventions. As it is a unique witness of this type of process, it was decided to keep the 1802 instrument of the museum collection in its original state which is not playable, and to build a facsimile. The maker C. Clarke produced this facsimile in 2010 [2-3]. It was also decided to carry out a scientific accompaniment to the facsimile production [3]. The study of the vibroacoustic behaviour of the soundboard of the original and the facsimile is part of this scientific program.

Figure 1: Left: Original Erard piano (1802). Right: facsimile (2010)

A non intrusive method, the Impact Planar Nearfield Acoustical Holography, was used. This technique, developed by the authors, implements the well known inverse method NAH on the basis of the acoustic impulse response field and was previously improved on a 17th century harpsichord [4] and on a monochord model [5].

The experimental method is firstly presented. The experimental setup is then detailed, and finally results are presented for both original and facsimile instruments. In the case of the original 1802 piano it was possible to process measurements with and without an additional board, called "false soundboard".

2 Impulse Nearfield Acoustical holography

2.1 Principle

This technique is used here in the aim of achieving a structural modal analysis. The NAH process of planar harmonic pressure fields is exhaustively described in [6], its adaptation for impulse source excitation (IPNAH) was primary presented in [7].

The impulse response of the vibrating source is measured in terms of radiating acoustic field with a microphone array. The impulse response is obtained by a point shock excitation of the structure.

The vibration behaviour of the source is then deducted, in terms of normal vibration velocity, with the help of an inverse calculation method based on spatial 2D Fourier transforms.

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

- the vibration source is supposed to be planar
- the vibration source is reconstructed on a virtual planar rectangle of the same size as the microphones array.
- The source distribution is supposed to be continuous.
- Moreover measurements are performed in the near acoustic field, evanescent components are partially covered by noise and the information they contain is then lost with the noise filter NAH operation.

From the last two points results a lack of precision in the vibration field reconstruction in the vicinity of edges areas where sharp discontinuities are present. These defaults were shown to be minor.

IPNAH has some interesting advantages, especially in case of fragile structures like ancient musical instruments, compared to classical methods:

- except for the excitation process, it is a non contact method
- since an important number of grid points (120) can be measured at the same time, the number of shocks on the structure is strongly limited.

- The measurement time is comparatively very short In the present study it took about half a hour for recording the set of 3680 point impulse responses to be processed.

Following the measurement stage, a classical frequency analysis provides a set of harmonic hologram pressure fields (P$h(\omega,x,y,z_h)$) over the desired frequency band.

2.2 Nearfield Holography Process

The successive steps implemented for processing the harmonic acoustic fields obtained previously follow the description presented in [6]. 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 Ph(ω,k_x,k_y,z_h).

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

In our case, the objective is to reconstruct the normal velocity V_s of the structure Therefore the following operation, called the back propagation process, is modeled with an operator $G_{PV} = E_{PV}(\omega,k_x,k_y).H(\omega, k_x,k_y, z_h\text{-}z_s)$.

H stands for the exponential propagator $exp(jk_z(z_h\text{-}z_s))$, where $k_z = (k^2\text{-}(k_x^2+k_y^2))^{1/2}$ is purely imaginary for evanescent components of the field, and real for the propagating components.

The operator $E_{PV} = k_z/\rho ck$ is independent of the source-hologram distance and derives directly from Euler's equation. Its effect is to transform pressure into normal velocity.

After the back propagation process of the spatial spectra onto the source plane, the ultimate step brings back to the real space, consisting of an inverse 2D spatial Fourier transform.

3 Experimental setup

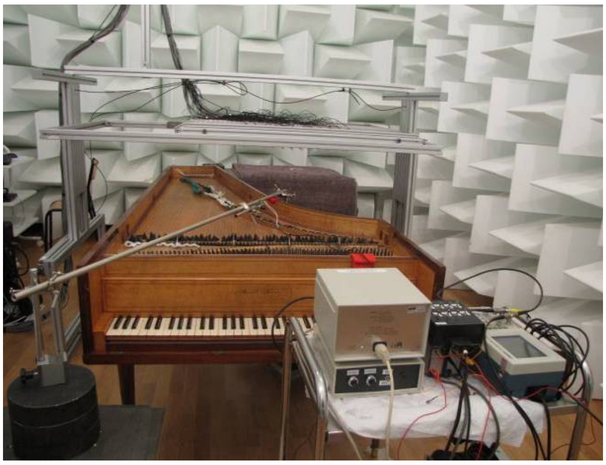


Figure 2: Experimental setup for the original piano.

The experimental setup used for the two instruments (original and fac-simile) was inspired by a precedent study on a Couchet harpsichord [4].

The impulse response of the piano soundboard is measured in the semi-anechoic room of the museum. Ambient temperature and hygrometry were controlled during the whole duration of the experiment.

The top was removed, for both instruments, original and facsimile. Also the keyboard and the mechanism were removed for the facsimile.

Figure 3: Experimental setup for the facsimile.

The strings were chosen not to be removed, on one hand for conservation reasons to avoid an additional stress cycle, and, on the other hand, in order to measure the acoustic radiation of the soundboard in its actual stress state [5-7]. In order to avoid their sound production, the strings were muffled (figure 4).

A point impulse excitation of the soundboard is provided by an automated hammer driven by an electromagnet that produces a reproducible shock. The excitation point is the same for both instruments and is chosen on the bridge in the treble area (figure 4) as it is usually done for modal analysis of soundboards [10-11]. In the case of the original instrument with the additional board ("false soundboard"), this point was not accessible therefore the soundboard was excited on its underside.

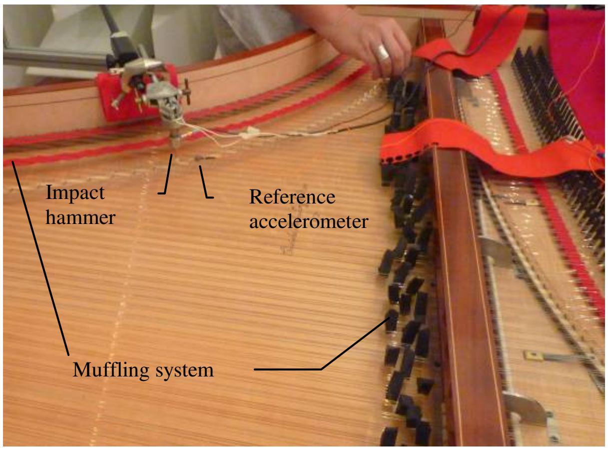


Figure 4: muffling system, excitation and reference accelerometer.

A 12 by 10 electret microphones array, with a 50 mm step, has been used to collect the pressure field. So as to fit the measurement grid, the array is moved according to 32 positions. The 120 impulse pressure responses for each position of the array are collected using a home made 128 channels synchronous digital recorder. Each measurement associated to one shock on the soundboard has to be phase referenced. Therefore an accelerometer has been positioned on the soundboard near the excitation point (figure 4), and its constant impulse response is systematically recorded along with the acoustic signals.

The resulting acoustic impulse response field is measured over a parallel plane at a distance z_h = 125 mm, the smaller possible here for technical reasons of accessibility. The field is finally sampled according to a thin grid with a 25 mm step and limited to a 1125x1975mm rectangle. The final set of measurements counts 3680 point acoustic impulse responses. It undergoes the NAH process summarized in the former paragraph.

4 Results

4.1 Original instrument

Figure 5 presents the average spectra on the microphones measurement grid. For the original instrument it was possible to choose an excitation point under the soundboard. The access was indeed possible through a drumming hole on the button of the instrument. It was then possible to measure the acoustic radiation of the piano with and without its additional soundboard. This board, called “false soundboard” is simply supported according to four points upon the soundboard.

The radiated pressure spectra (figure 5) and the modal behaviour are more comparable to the one obtained on harpsichords [4] than for modern pianos [10-11]. This result is not surprising regarding the shape and thickness of the soundboard. The energy distribution is very similar to the radiation of a harpsichord and the frequency and mode shape of the first mode (around 70Hz, table 1) is also similar. The rib distribution being quite different between this piano and harpsichords, modes shape are more “global” here than for a harpsichord. An important modal density can be observed in the [50 2000] Hz bandwidth.

The effect of the additional soundboard is soft on the average acoustical pressure radiated (figure 5). Some resonant frequencies are slightly decreased. The energy and the peak emergence is decreased in low frequencies, which is in accordance with some subjective sensations.

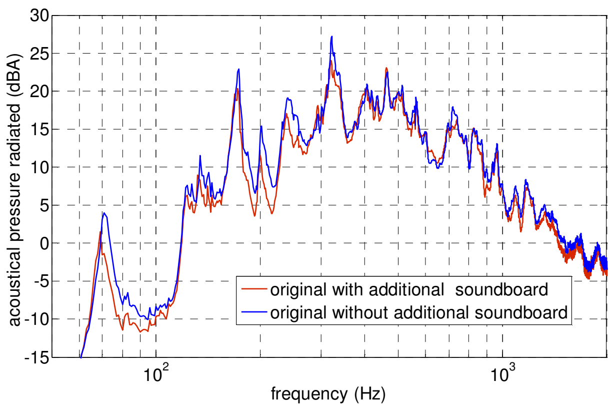


Figure 5: Original piano. Effect of the “false soundboard” on the average acoustical pressure spectra.

4.2 Facsimile

Since the facsimile does not have a drumming hole, the excitation of the soundboard is performed on the bridge. A measurement with the same excitation point was done on the original instrument. On figure 6, the average acoustical spectra of the original and facsimile instruments can be compared. The energy distribution is relatively similar for both instruments. It can be observed that resonance frequencies are very similar. Some resonant frequencies difference are less than 2Hz, some others are more different. One possible explanation of those differences can be the slight difference of string tension on both instruments. It was effectively shown that the string tension can have a different effect on the modal frequencies (some frequencies are unchanged, others are modified) [5-7].

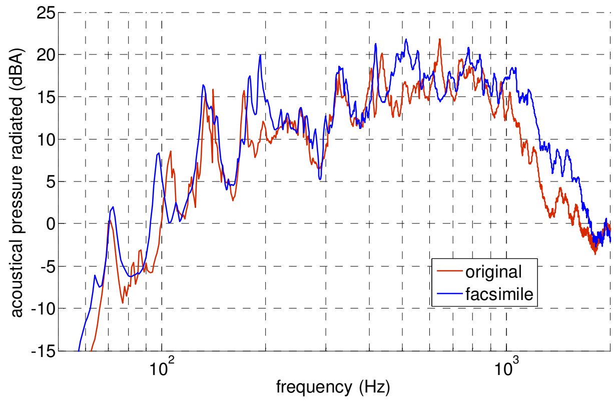
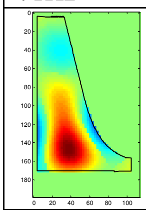
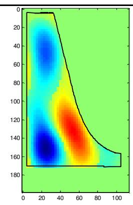
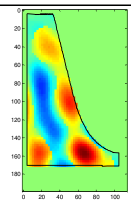
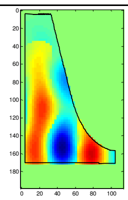
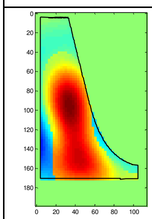
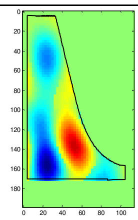
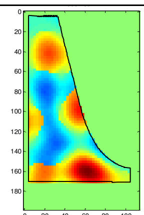
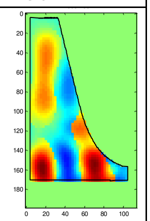


Figure 6: Original / facsimile comparison. Average acoustical pressure radiated.

A good concordance was observed considering the operational mode shapes. A few examples are shown on table 1. Operational mode shapes represented on table 1 are the result of the holographic reconstruction of a virtual vibrating source on the soundboard plane.

Table 1: Holographic reconstruction for five operational modes

Original			
71Hz	105 Hz	141 Hz	173 Hz
			
Facsimile			
72 Hz	98 Hz	139 Hz	180 Hz
			

5 Conclusion

An experimental study was conducted on a Erard 1802 piano and its facsimile. Acoustical holography was used to access to the vibraoacoustic behavior of both instruments. Acoustic radiation and modal behavior or both instruments was shown to be very similar in the experimental conditions. The effect of the addition of a "false soundboard" was also examined for the original instrument.

Acknowledgments

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