Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Couchet Harpsichord soundboard vibroacoustics behaviour: An application of the Impact Nearfield Acoustical Holography (IPNAH)

Sylvie Le Moyne[a], Sandie Le Conte[b] and François Ollivier[a]

[a]UPMC Univ Paris 06, CNRS UMR 7190 Institut Jean Le Rond D'Alembert, 2 Place de la Gare de Ceinture, 78210 Saint Cyr l'Ecole, France
[b]Musée de la Musique, 221 avenue Jean Jaures, 75019 Paris, France
slemoyne@ccr.jussieu.fr

The Music Museum in Paris recently acquired a harpsichord made by Ioannes Couchet in 1652 in Anvers. As a masterpiece this instrument is considered as a "National Treasure" and therefore protected. A challenging problematic has risen when its restoration was decided since the aim was to play this instrument again in concert. In the objectives of increasing our understanding of the harpsichord ageing, improve a numerical model currently in process and develop a diagnostic method for conservation, 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.

NAH is performed in the anechoic room of the museum, on the soundboard with strings on their functional stress but muffled. Eigen modes are extracted for the [30-1500Hz] bandwidth, results are confronted with literature and an energetic analysis is proposed.

1 Impulse Nearfield Acoustical Holography

1.1 Principle

This technique is here used in the aim of achieving a structural modal analysis. The NAH process of planar harmonic pressure fields is exhaustively described in [1], its adaptation for impulse source excitation (IPNAH) was primary presented in [2].

The impulse response of the vibrating source is measured in term of radiating acoustic field with a microphones 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 measurement is 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 in a recent study ([3])

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 less than 120mn for recording the set of 15360 point impulse responses to be processed.

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

1.2 Nearfield Holography Process

The successive steps implemented for processing the harmonic acoustic fields obtained previously follow the description presented in [1] (figure 1). The first step consists, by means of a 2D spatial Fourier transform, in converting the measured harmonic pressure field $Ph(\omega,x,y,z_h)$ from the real space domain into its k-space representation $Ph(\omega,k_x,k_y,z_h)$.

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 Veronesi filter, with a cutoff wave number of k_c. The filtered k-spectrum is denoted $KPhf(\omega, k_x,k_y,z_h)$.

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.

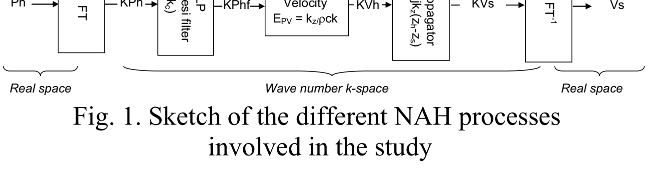

Fig. 1. Sketch of the different NAH processes involved in the study

2 Experimental setup

The impulse response of the harpsichord soundboard is measured in the semi-anechoic room of the Musée de la musique (figure 2). In such a room, noise level is seriously diminished. This condition allows to minimize the soundboard excitation level and also to optimise the signal to noise ratio for evanescent waves.

Fig.2. Couchet harpsichord in the anechoïc room
with string muffling system
and holographic microphone array

As strings should not be removed, so as to preserve the stress state of the board, they are muffled in order to avoid their sound production (figures 2 and 3).

Fig. 4. String muffling set-up

A harmonic acoustic nearfield is to be measured in order to be used in an NAH reconstruction process. This field is to be derived from an impulse response, which allows performing measurements in an ill conditioned acoustic environment ([2]). A point impulse excitation of the soundboard is provided by an automated hammer driven by an electromagnet that produces a reproducible shock. In the double objective of accessibility and painting conservation, the excitation position is chosen on the underside of the soundboard. The keyboard is therefore removed. The position of the impact is chosen so as to mobilize significant flexural vibration modes of the soundboard (figure 4).

Fig. 4. Impact hammer on position in the harpsichord
underside of the soundboard.

A 12 by 10 electret microphones array, with a 50 mm step, has been used to collect the pressure field (figure 5). So as to fit the measurement grid, the array is moved according to 8 positions. For each of these positions the array is 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 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 and its constant impulse response is systematically recorded along with the acoustic signals.

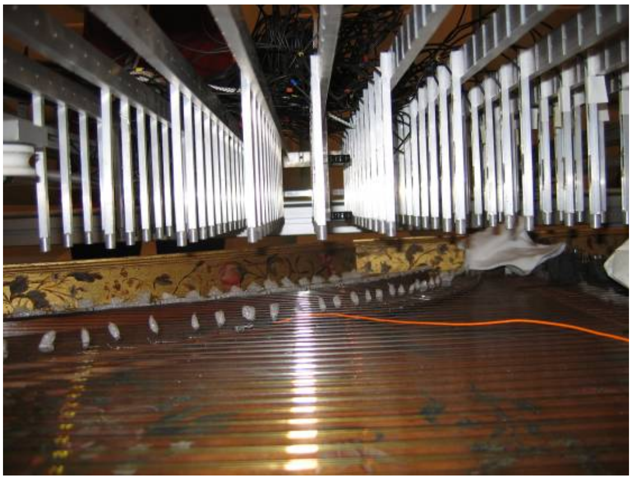

Fig. 5. Microphone array

The resulting acoustic impulse response field is measured over a parallel plane at a distance $z_h = 72$ mm, the smaller possible here for technical reasons of accessibility. It remains however an unusually large distance for NAH.

The field is finally sampled according to a thin grid with a 12.5 mm step and limited to a 1162.5x1762.5 mm rectangle. The final set of measurements counts 13348 point acoustic impulse responses. It undergoes the NAH process summarized in the former paragraph.

3 Results

3.1 Radiated sound pressure

On figure 6, we present the pressure level, averaged on the whole measurement plane, from 0 to 4000Hz. This graphic shows a significant radiation level for frequencies between 140 Hz and 2000 Hz. An important modal density in the exploitable [0 2000Hz] bandwidth can be observed.

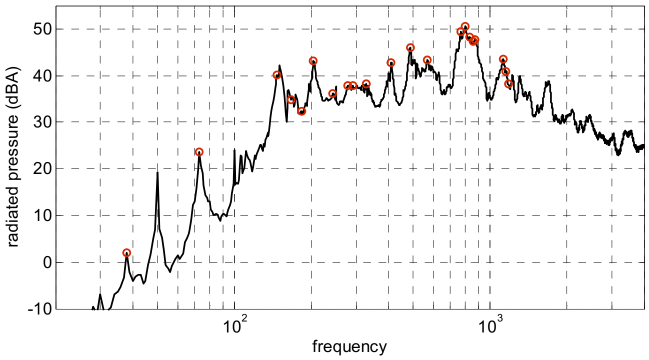

Fig. 6. Radiated pressure dBA spectrum with modal frequencies retained.

3.2 Modal analysis

A more particular attention was focused on the modal behaviour of the soundboard for the [0-1200 Hz] bandwidth. In this bandwidth 21 radiating modes were found (figure 6). Frequency and mode shape of six of them are presented on figure 7. Mode shapes are presented in terms of normal vibration velocity distribution. The velocity distribution is obtained by NAH inverse calculation on a virtual rectangular plane that contains the soundboard and has the same dimensions as the measurement plane.

The boundary conditions and the ribs distribution under the soundboard (presented on figure 8) can be of good help for the understanding of those operating mode shape. Indeed, the soundboard edges can be considered as clamped except for the one in front of the keyboard that can be considered as free. This can in particular explain the shape of the first operating mode. The shape of this first eigen mode is very similar to the one measured on an other harpsichord by [4].

The ribs distribution can also explain that for most modes the deformation energy is particularly concentrated on the area zone a, that is more flexible.

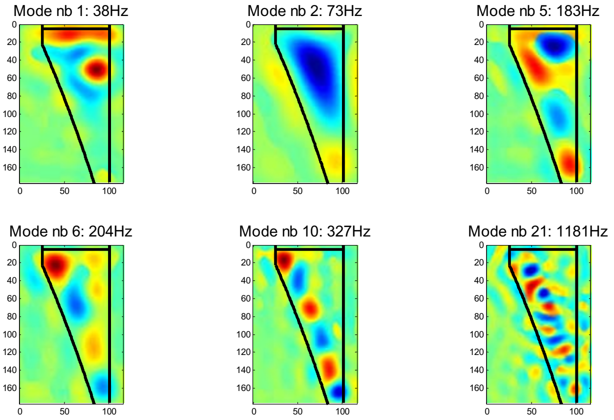

Fig. 7. Operating mode shapes reconstructed for six frequencies.

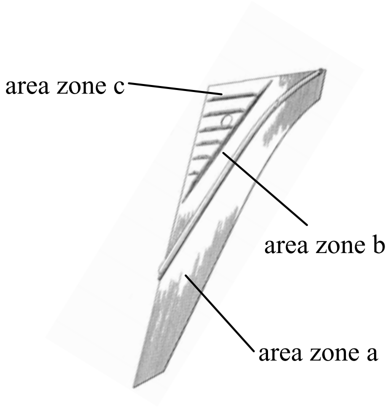

Fig. 8. Ribs distribution on the under face of the harpsichord soundboard

4 Energetic considerations

In the objective of evaluating the radiation efficiency of the soundboard, we first can compare the radiated pressure level (averaged at a 72mm distance from the soundboard) to the vibrating acceleration level measured with the reference accelerometer (figure 9). We can first observe a good concordance of resonance frequencies between both acoustics and vibration fields. It also appears that the global level ratio between acoustics and vibrating energies seems to change at around 600Hz, upon this frequency the radiation efficiency σ should then be more important as it is defined by:

$$\sigma = \frac{W_{ac}}{\rho_0 c_0 S \langle V_n^2 \rangle}$$

Where W_a is the radiated acoustic power, S the radiating surface, and V_n the normal vibration velocity.

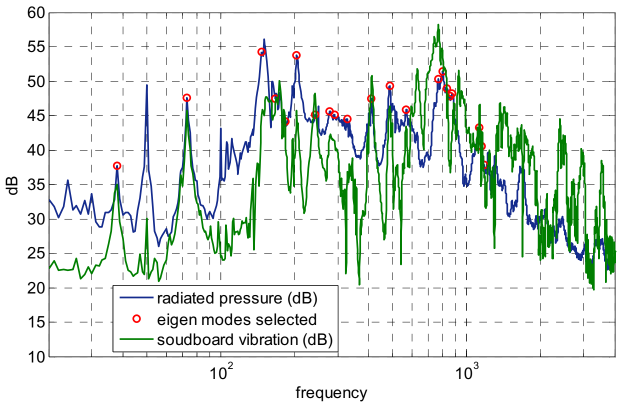

Fig. 9. Radiated pressure and soundboard vibration spectra.

In order to confirm this observation, an energetic analysis of the radiated pressure field was performed. For two different distances (the original 72mm from soundboard and an additional measure at 122mm), proportion of evanescent and propagating waves were compared (figure 10). Evanescent waves are preponderant below 150 Hz, and propagating waves are preponderant up to 600 Hz. This is confirmed by the additional measure at 122mm since the evanescent wave proportion is lower from 200 Hz

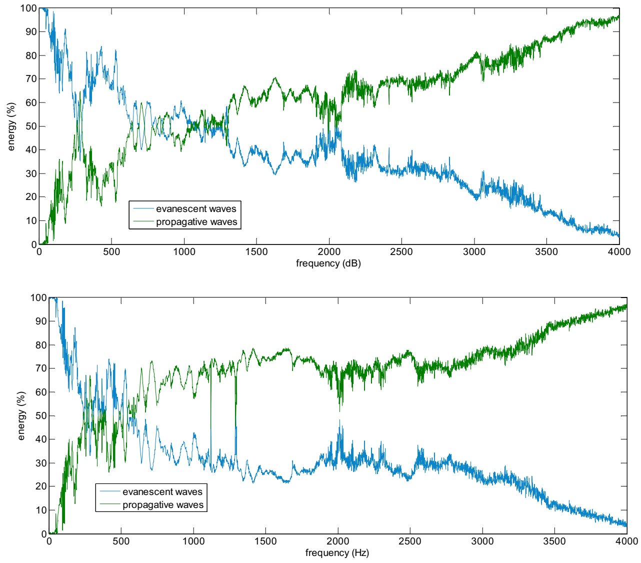

Fig. 10. Evanescent and propagating energetical ratio at zh=72mm and 122 mm .

5 Conclusion

NAH has been performed here in unusual conditions compared to literature, as they are far from the ideal: unbaffled source, low sound pressure level, unusually large measurement distance, preponderance of evanescent waves. An additional challenge was to muffle strings, as they should not be removed nor slackened. However, a very satisfying modal decomposition for [30-1500Hz] bandwidth is obtained. Comparison with literature has shown similar results for the first mode, whose shape is an indication of correct restoration.

Results here obtained will be soon be compared with numerical results (finite elements) and the experimental method will be performed again in an objective of conservation diagnostic. (especially when the harpsichord is in playable state).

References

[1] E.G. Williams, *Fourier Acoustics. Sound Radiation and Nearfield Acoustical Holography*, Academic Press, 1999.

[2] F. Ollivier, P. Alais, A. Karkaletsis "*Fast modal analysis by means of impulse acoustical holography*", Proceedings of the 11th ICSV 2004, pp 2395-2402.

[3] Ollivier F., Le Moyne S., Picard C., "*Experimental comparison of PU probes and microphones arrays for use in Impulse Acoustical Holography"*, ICSV14, Cairns, Australia, July 9-12 2007.

[4] L. Tronchin, A. Cocchi, C. Consani. Vibrational and acoustical radiation in two harpsichords of XVII century", ISMA2001, 2001.