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EXPERIMENTAL COMPARISON OF PU PROBES AND MICROPHONE ARRAYS USED IN IMPULSE ACOUSTIC HOLOGRAPHY

François Ollivier[1], Sylvie Le Moyne[1] and Christophe Picard[2]

[1]Institut d'Alembert- Université Pierre et Marie Curie – Paris 6, Paris, France
[2]PSA Peugeot Citroën - Aérodynamique Aéroacoustique Aérothermique, Vélizy, France
frol@ccr.jussieu.fr

Abstract

The aim of this work is to evaluate the gain of information provided by pressure-velocity probes as compared to microphones in near field acoustic holography (NAH). The acoustic field under study is the near acoustic impulse response of a thin plate submitted to a shock. Both a 4 PU probes array and a 120 microphones array are used to sweep the field of interest according to a fine grid. Finally, three different wide band acoustic near fields are obtained: the normal component of the acoustic velocity, and two different measures of the acoustic pressure. Near field acoustic holography is thereafter performed with the three measured quantities, each of which provide a reconstruction of the source normal velocity field. Along these processes, the fields and their transformations (K-space spectra and reconstructed vibration source fields) are compared. The normal velocity source distribution is also directly measured with a laser vibrometer. This distribution is considered as a reference for the evaluation of the different NAH processes by means of correlation coefficients.

1 INTRODUCTION

Acoustic sources can be characterised by means of near field acoustical holography (NAH). In classical methods one uses standard microphone arrays to measure the near field of the sources. Since particle velocity sensors are now available it is interesting to quantify the gain they can bring to the process of reconstruction of the sources. A numerical study [1] has shown that the direct knowledge of the particle velocity should produce better results in describing the normal velocity of the source itself. The work presented here is an experimental evaluation of the performance of PU sensors as compared to a classical microphones measurement in a (NAH) process [2]. The results provided by both ways are compared to the actual source velocity measured with a laser vibrometer. The source under study is a thin plate submitted to a shock excitation. In a previous work [3] it was shown that PU probes associated in a linear array can provide maps in pressure and normal velocity showing a good correlation with those obtained from a large array of electrets microphones. It has also been established [4] that such measurements associated with the near field acoustical holography technique could provide the vibration modal shapes of a radiating structure.

The experimental setup and the collected data sets are described in part 2. Part 3, gives a brief description of the different NAH processes used for the reconstruction of the normal velocity source distribution from both pressure and particle velocity measured fields.
In part 4, final and intermediate NAH results are presented and comparisons of the actual source distribution are led using correlation coefficients with the different distributions computed along the processes.

2 EXPERIMENTAL SETUP AND MEASUREMENTS

The structure under study is a 0.4 x 0.5 m x 4 mm aluminium plate (Figure 1). Its top face is localized in a plane referred to as the source plane and denoted $z_s = 0$. Each of the four corners of the plate is attached to a rubber silent block. The boundary conditions not being known precisely can be considered to approach free ends condition.
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. A point impulse excitation of the plate is provided by an automated hammer driven by an electromagnet that produces a reproducible shock. The position of the impact is chosen so as to mobilize significant flexural vibration modes of the plate. The resulting acoustic impulse response field is measured over a parallel plane at a distance $z_h = 25$ mm. This plane is hereafter referred to as the hologram plane. The field is sampled according to a thin grid with a 12.5 mm step and limited to a 0.6 x 0.5 m rectangle centred on the plate. The different sets of measurement finally count 1920 (48 x 40) point acoustic impulse responses.

Figure 1 : PU probes array (left) and electret microphones array (right) at a 25 mm distance of the 0.5x0.4 m aluminum plate

In the framework of this study, three different measurements are conducted.
First a 12 by 10 electret microphones array (Figure 1- left), with a 50 mm step, has been used to collect the pressure field here denoted $Ah(x,y,z_h,t)$. So as to fit the measurement grid, the array is moved according to 16 interleaved positions. The 120 impulse pressure responses for each position of the array are collected using a home made 128 channels synchronous digital recorder. The NAH process associated to this setup is fully described in a previous paper [3].
Secondly, four PU probes are assembled in a linear array with a 10 cm step (Figure 1 – right). The measurement grid is swept using a robot and 640 successive positions of the PU array and as many excitations of the plate. Since a PU-mini probe consists of an electret microphone associated with a single component particle velocity sensor, it provides the simultaneous measurement of the normal particle velocity field according to the normal

direction, denoted $Uh(t,x,y,z_h)$ and of a second pressure field denoted $Ph(t,x,y,z_h)$, both to be used in an NAH process.

Thirdly, a reference flexural vibration distribution of the plate is needed to which the different reconstructions should be compared. This distribution is measured by means of a sweeping laser vibrometer which measures point normal vibration impulse response of the plate according to a very fine grid of 4500 (75x60) positions, with a 6.8 mm step. The recording of the complete distribution needs as many shock excitations of the plate. Finally, in order to fit the acoustic grid, this vibration grid is afterwards to be interpolated. It is denoted $Vs(t,x,y,z_s)$.

In these three experiments, each measurement associated to one shock of the plate has to be phase referenced. Therefore an accelerometer has been positioned on the support of the plate and its constant impulse response is systematically recorded along with the acoustic or vibration signals.

Since the NAH technique processes harmonic fields, the measured time histories have to be frequency analyzed with respect of the reference accelerations. The phase referenced spectra resulting from this process have a 1 Hz frequency resolution and cover the band [0 - 4 kHz]. They are assembled into hologram matrices to be processed by NAH and denoted respectively $Ah(\omega,x,y,z_h)$, $Ph(\omega,x,y,z_h)$, $Uh(\omega,x,y,z_h)$, where $\omega = 2\pi f$ denotes the angular frequency. The same process is applied to the record of the normal velocity in the source plane to get $Vs(\omega,x,y,z_s)$.

3 HOLOGRAPHIC PROCESS DECOMPOSITION

The NAH process of planar harmonic pressure fields is exhaustively described in [2]. The steps implemented for the treatment of the previously measured fields follow this description. However in the case of the reconstruction from the particle velocity field simple adaptations have to be made as presented in [1]. Moreover, so as to establish clearly the influence of the different steps of the process, we have introduced a supplementary step decomposing the operation of back propagation in the k space into two operations.

The first step consists, by means of a 2D spatial Fourier transform, of converting the measured harmonic field $X_h(\omega,x,y,z_h)$ from the real space domain into its k-space representation $X_h(\omega,k_x,k_y,z_h)$. X being any of the physical measured quantities (pressures A and P or normal particle velocity U).

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 applying a low-pass Veronesi filter, with a cutoff wave number of k_c . The filtered spectrum is denoted $X_h^f(\omega, k_x,k_y,z_h)$.

In our case, the objective is to reconstruct the normal velocity of the structure V_s. Therefore the following operation, called the back propagation process, is modeled with an operator which takes two different expressions depending on the chosen measured quantity.

Let $G_{XV}(\omega,k_x,k_y,z_h\text{-}z_s)$ be the back propagator from X_h^f to V_s. It can be decomposed as follows: $G_{XV} = E_{XV}(\omega,k_x,k_y).H(\omega, k_x,k_y, z_h\text{-}z_s)$.

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.

This operator H is the same for the different combinations AV, PV or UV.

The operator $E_{PV} = E_{AV} = k_z/\rho ck$ is independent of the source-hologram distance and directly derives from Euler's equation. Its effect is to transform pressure into normal velocity for the couples AV and PV. For the case velocity to velocity, UV, we have $E_{UV} = 1$.

Regarding the gain brought by the particle velocity sensors, it will be shown in the following

that this decomposition of G into E and H is pertinent, and specifically that E_{PV} has a preponderant role in the reconstruction process.
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. We then get 3 reconstructed normal source velocities, respectively $VsA(\omega, x,y,z_s)$, $VsP(\omega, x,y,z_s)$, $VsU(\omega, x,y,z_s)$ which are to be compared to the true distribution $Vib(\omega, x,y,z_s)$. Figure 2 summarizes the different processes involved in the study.

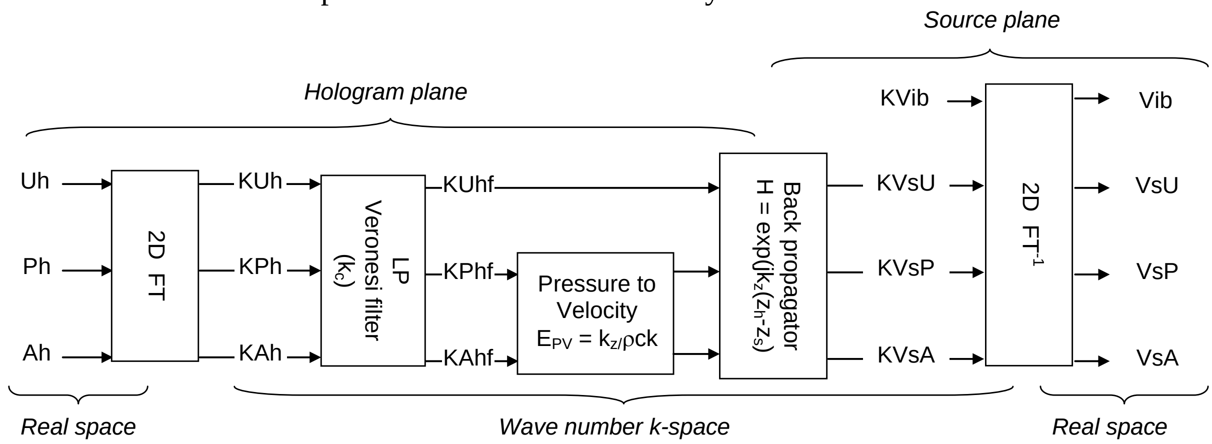

Figure 2: Sketch of the different NAH processes involved in the study

4 RESULTS AND ANALYSIS

4.1 Spectra and field distribution

The average spectra of the four measured fields (Figure 3) exhibit a good stability of the boundary conditions of the plate in time, as no variation of the resonant frequencies can be noticed. As the radiation efficiency of a thin plate is theoretically lower at low frequencies, level difference between source velocity (*Vib*) and acoustic pressure or velocity (*Uh*, *Ah*, *Ph*) is more important at high frequencies.

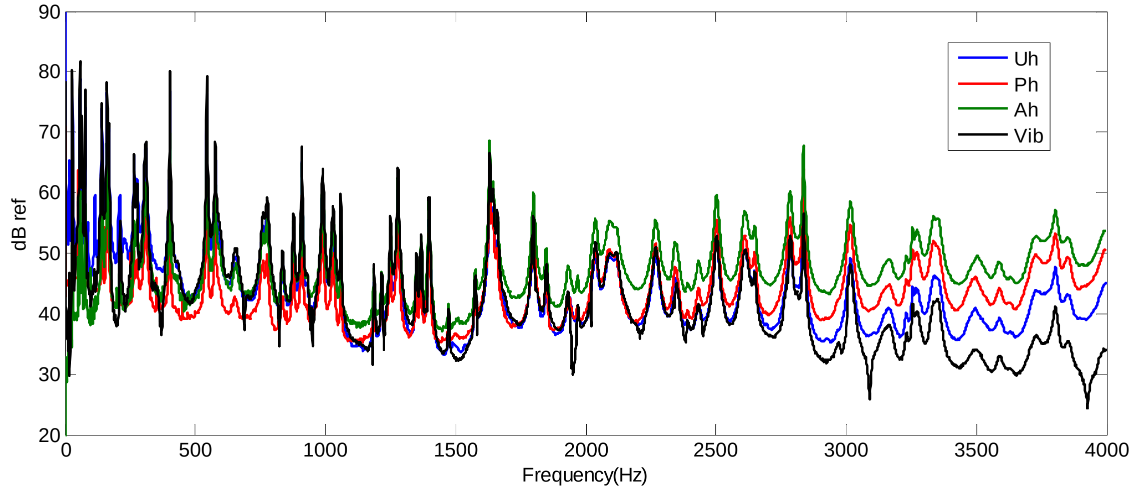

Figure 3 : Average spectra of the measured fields – Hologram plane :Uh -particle velocity
Ph- pressure from PU probes – Ah- pressure from the microphone array
Source plane : Vib - normal velocity of the plate from a laser vibrometer.

A comparative study of the acoustics fields on the hologram plane has already been presented in a previous paper [3]. The present paper focuses on the study of the source velocity field at resonant frequencies from 0 to 3 kHz. For each of these particular harmonic fields, the comparison is led between the source velocity field directly measured by means of laser vibrometry (*Vib*), and the NAH reconstructed source velocity derived from:

- PU probes particle velocity measurements (*VsU*)
- PU probes pressure measurements (*VsP*)
- Microphones array pressure measurements (*VsA*)

Figure 4 presents the results obtained for the resonance at 545 Hz. This frequency as been chosen as it is well representative. Each column concerns one measurement type: *Vib, U, P, A*
On the first line, the source plane velocity fields are presented in the real space domain (x,y) in terms of magnitude. One can observe that the three NAH reconstructed fields seem well correlated. They are also quite similar to the vibrometer measured field, except at the limits corresponding to the free edges of the plate. This bias is due to the NAH treatment itself, which is not well fitted to discontinuities in the source velocity field.
The second line of Figure 4 presents the phase distribution of these velocity fields. One can observe that phase shapes are very similar in the four cases, but the phase distribution of *VsU* is of worse quality as it contains many values far from $\pm\pi/2$.
On the last line figures the velocity magnitude in the wave number space (k_x,k_y). One can observe that the NAH processes over estimate the low wavenumber components. This is particularly due to both the k-filtering and back-propagation operations. Parallely, as Euler operator $E_{PV} = k_z / \rho c k$ is zero on the radiation circle $(k^2 = k_x^2 + k_y^2)$, the velocity fields calculated from pressure distribution (*KVsP, KVsA*) present a very low value for planar wave numbers close to the radiation circle. This systematic under estimation is avoided when the source velocity is calculated from the particle velocity hologram *Uh*.

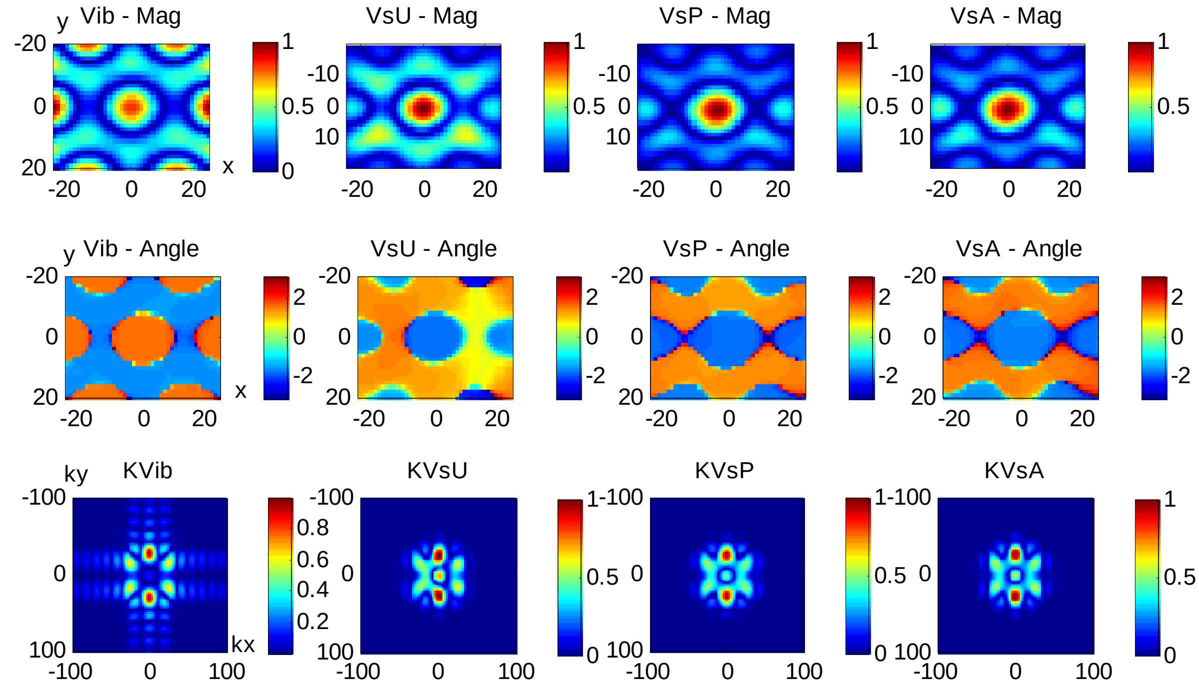

Figure 4 : Results for the 545 Hz resonant frequency
Laser vibrometer measured vibration of the plate (Vib)
and 3 differents NAH reconstructions (VsU from Uh, VsP from Ph and VsA from Ah)

4.2 Correlation coefficients

In order to evaluate the accuracy of the different NAH processes, the previous results are compared to the measured (actual) source velocity field. The comparison is quantified by computing a correlation coefficient of the images of the harmonic fields for each of the resonant frequencies in the band [0-3 kHz].

4.2.1 Velocity distributions in the source plane

In a first evaluation step, correlation coefficients are calculated between the true source velocity field *Vib* and the NAH reconstructed source fields *VsU*, *VsP* and *VsA*, for the entire source plate surface and also for this same surface being truncated of a 5 cm wide band at the edges. From these correlations presented on Figure 5 one can notice that:

- The correlation is far better when areas near edges are not taken into account. This bears out that NAH provides a good estimation of the source velocity field, except in the areas near free edges.

- In terms of magnitude, the velocity fields obtained from the three different measured acoustic quantities are quite similar (*VsP*, *VsU* and *VsA*). Nevertheless, one can notice better results for the source velocity field reconstructed from the microphone array pressure (*VsA*) and poorer results for the source velocity field reconstructed from the PU probes pressure (*VsP*) particularly at frequencies over 1300 Hz.

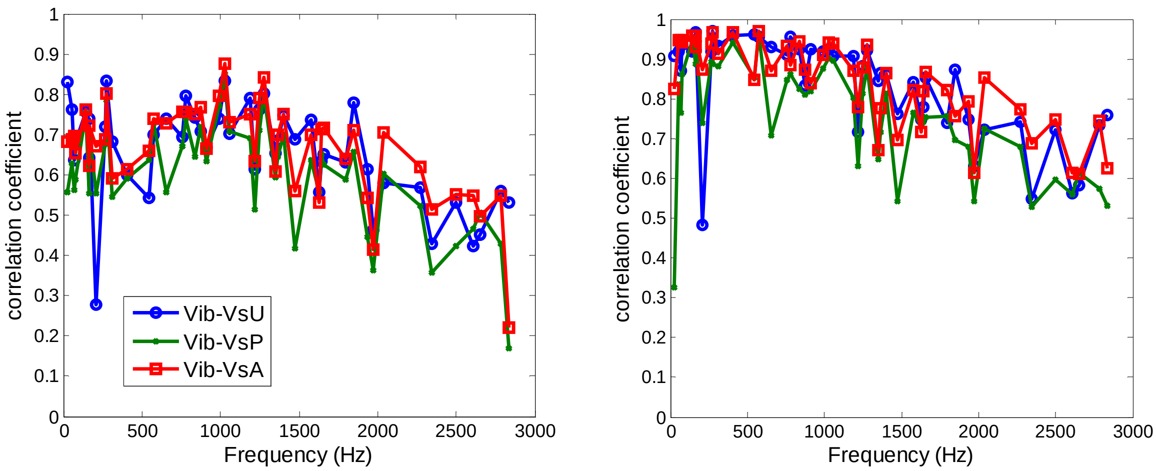

Figure 5 : Correlations of the reference source velocity (Vib) with the different NAH reconstructed velocity fields (VsU, VsP, VsA) (left : untruncated-right:edges truncated)

4.2.2 Accuracy of the NAH processes

In order to evaluate the influence of the successive steps of the NAH processes, for both cases of source velocity calculated from hologram pressure and hologram velocity, the field computed at each step is compared (in terms of correlation coefficient) to the reference source velocity field *Vib*.

Particle velocity Hologram to source velocity (*Uh to VsU)*

Figure 6 shows the correlation coefficients between the reference source velocity field and respectively:

- the measured hologram particle velocity field *Uh*,
- the k-filtered hologram particle velocity field *Uhf* (*KUhf* Fourier inverted)

- the NAH calculated source velocity field *VsU* (*KUhf* back propagated and Fourier inverted). This shows that the measured field exhibits a notably better correlation with the reference when truncated. Indeed as the acoustic field is continuous, while the source velocity distribution is not, a free edges bias appears when comparing acoustic field and source vibration field.

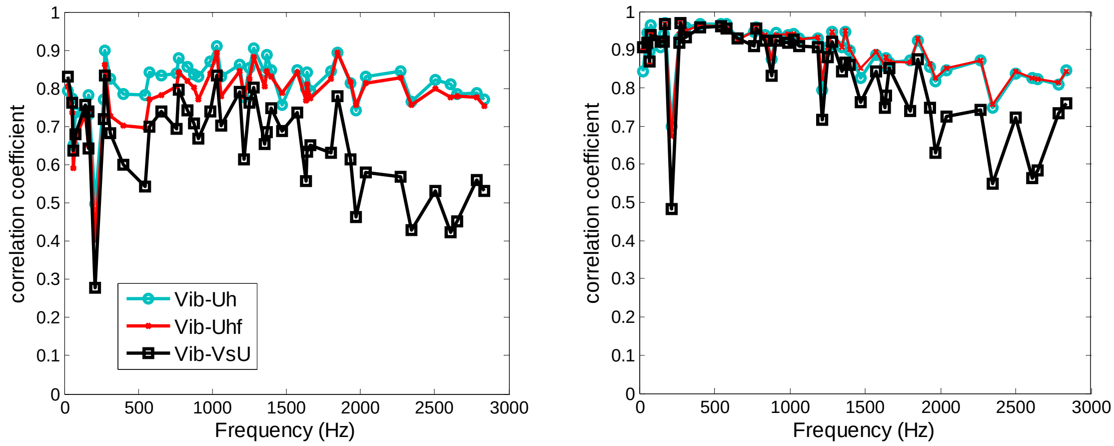

Figure 6 : Correlation of the reference source velocity (Vib) with fields obtained at successive steps of the particle velocity NAH process (left : untruncated-right:edges truncated)

Note that when the low-pass k-space filtering is not well suited (wrong cutoff wave number k_c), the correlation decreases especially on areas near the free edges (comparison between *Vib-Uh* and *Vib-Uhf*). It is the case here in the 300-1000 Hz band.

Back-propagation (comparison of *Vib-Uhf* and *Vib-VsU*) does not seem to modify the results at low frequencies (below 1300Hz) except in the areas near the free edges. At higher frequencies, correlations are surprisingly worse after the back-propagation operation for the whole plate surface. This is illustrated, for example (Figure 7), for the resonant mode at 2502 Hz. The measured hologram velocity field *Uh* is indeed much more similar to the measured source velocity field *Vib* than the NAH reconstructed source velocity distribution *VsU*.

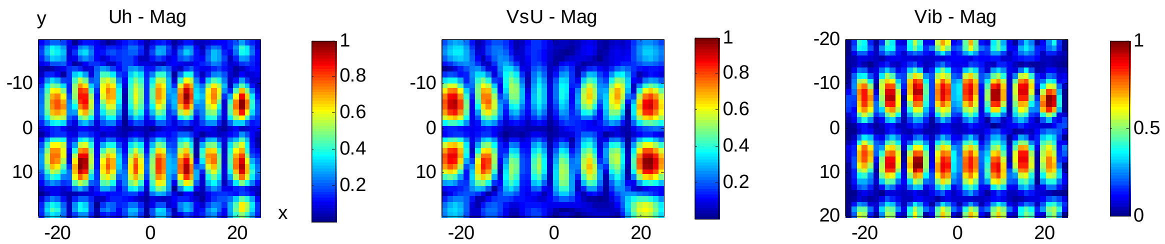

Figure 7 : Particle velocity hologram (Uh) at 2502 Hz – NAH reconstructed source velocity (VsU) compared to reference (Vib)

Pressure hologram to source velocity (*Ah to VsA)*:

On Figure 8 the correlation coefficients compare the reference source velocity field (*Vib*) to:

- the measured hologram pressure field *Ah*
- the k-filtered hologram pressure field *Ahf* (*KAhf* Fourier inverted)
- the hologram velocity field *VhA* calculated from *Ahf* with the Euler operator,
- the NAH calculated source velocity field *VsA* (*VhA* back-propagated).

The Euler operator, transforming the hologram pressure to a hologram velocity, exhibits an actual gain of accuracy (comparison between *Vib-Ahf* and *Vib-Vhf*), especially in the area close to the free edges and at low frequencies. Besides, as for the NAH process from the particle velocity hologram to the source velocity, the back-propagated field *VsA* appears to be of poorer correlation to the actual source velocity than the velocity hologram $VhA = E_{PV}.Ah$.

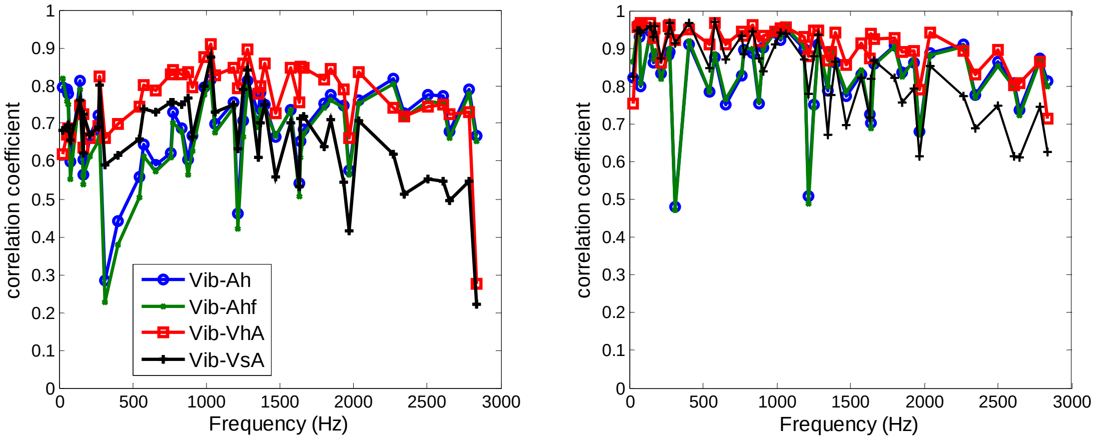

Figure 8 : Correlation of the reference source velocity (Vib)with different fields at successive steps of the pressure NAH process. (left : untruncated-right:edges truncated)

5 CONCLUSIONS

This experimental study has compared planar near field acoustic holography based on a classical measurement of the sound pressure and planar NAH based on measurement of the normal component of particle velocity. It has been possible to evaluate the accuracy of both NAH processes with the use of an experimental reference by means of the source normal component velocity measured with a laser vibrometer.

It reveals that, in the case of as sufficiently short distance measurements, normal component velocity field measured with PU probes gives a good estimation of the source velocity distribution, except near free edges of the vibration source. Such a measurement gives a good estimation to the true source velocity field without any NAH calculation process.

In the case of a very near field acoustic measurement (25 mm in our case), it has been found that the back-propagation operator does not appear to be accurate.

For both near field pressure and velocity measurement based methods, normal component velocity fields obtained are sufficiently consistent for a modal analysis of the vibration source: resonant frequencies and the associated operational shapes can be clearly identified.

6 REFERENCES

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