First experiments with Real-Time Acoustic Holography (RT-NAH)

J.C. LE ROUX[1], V. GRULIER[1,2], J.H. THOMAS[2], J.C. PASCAL[2]

1: CTTM, 20, rue Thalès de Milet – F-72000 LE MANS
2: LAUM-ENSIM, Université du Maine, rue Aristote – F72085 LE MANS

Abstract:
The Near-field Acoustic Holography (NAH) techniques operate in the frequency-wavenumber domain to process differently the progressive and the evanescent waves. Instead of these techniques, the Real-Time Near-field Acoustic Holography (RT-NAH) works in the time-wavenumber domain. Each point of the instantaneous wavenumber spectrum is convolved by a numerical filter. Thus it is possible to continuously reconstruct the acoustic pressure field on the plane from which some non-stationary sources radiate. The starting point is the acquisition, in the near-field of the sources, of a pressure field which fluctuates in time. Then a spatial Fourier transform is applied to each temporal sample of the whole array of microphones. An analytic study of the problem shows that the pressure field can be propagated on a forward plane by filtering it in the time-wavenumber domain. In order to back-propagate the pressure field to the source plane, the inverse of the impulse response has to be used. After filtering, the fluctuating pressure signal is obtained by computing the inverse spatial Fourier transform of each time sample of the instantaneous wavenumber spectrum rebuilt on the source plane. Some experiments have been made to ensure the relevance of the technique. They are discussed in this paper.

Keywords: Acoustic holography, real time, experiments, time-wavenumber domain

1. Introduction

Acoustic holography is a measurement technique used to localize an acoustic source from measurements made with a microphone array located in the neighbourhood of the source plane. This technique, called Near-field Acoustical Holography (NAH), was introduced in the 80's [1], and is mainly dedicated to stationary sources. In order to study non-stationary sources, some derived methods have been developed: the Time Domain Holography [2], [3] and the Time Method [4]. These "Time domain" extensions of the standard NAH are used with fluctuating sources by carrying out a FFT on the time signals and by processing each spectral raw by NAH. A new formulation (RT-NAH) has been recently proposed [5], based on the reconstruction of the acoustic field using a time domain description of the problem. The measured pressure field is propagated using a convolution by an impulse response described in the time-wavenumber domain. The purpose of this article is to present some experimental results obtained with this new method.

2. Direct problem

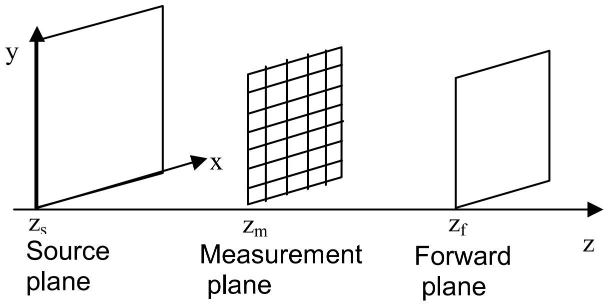

Figure 1: Geometry of the problem

The direct problem in acoustic holography consists in propagating the acoustic field $p(x,y,z_m,t)$ measured from the plane $z=z_m$ towards the forward plane at $z=z_f$ ($z_f > z_m$, see figure 1). It has been shown [6] that this propagation can be done by convolving each component of the instantaneous wavenumber spectrum $P(k_x,k_y,z_m,t)$ with a time domain impulse response h:

$$P(k_x,k_y,z_f,t) = P(k_x,k_y,z_m,t) \otimes h(k_x,k_y,\Delta z,t) \quad (1)$$

where $P(k_x,k_y,z_m,t)$ is obtained from the two-dimensional spatial Fourier transform of the pressure field $p(x,y,z_m,t)$ along x and y axis, k_x and k_y are the wavenumbers along x and y axis, and $\Delta z = z_f - z_m$.

The expression of the impulse response h is reached by first considering the acoustic propagation described by the wave equation (2):

$$\Delta p(x,y,z,t) - \frac{1}{c^2}\frac{\partial^2 p(x,y,z,t)}{\partial t^2} = 0 \quad (2)$$

and secondly by solving the two-dimensional Fourier transform of this equation (3):

$$\frac{\partial^2 P(k_x,k_y,z,t)}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2 P(k_x,k_y,z,t)}{\partial t^2} -(k_x^2+k_y^2)P(k_x,k_y,z,t)=0 \quad (3)$$

where $P(k_x,k_y,z,t)$ is the instantaneous wavenumber spectrum obtained by spatial Fourier transformation of the signal on the microphone array at each discrete sample time, and c is the sound velocity in $m.s^{-1}$.

The expression of the impulse response h is then given by (4):

$$h(k_x,k_y,\Delta z,t)=h(\Omega_r,\tau,t)= \delta(t-\tau)-\tau\Omega_r^2\frac{J_1(\Omega_r\sqrt{t^2-\tau^2})}{\Omega_r\sqrt{t^2-\tau^2}}\Gamma(t-\tau) \quad (4)$$

where

$\tau=\Delta z/c$ is the delay corresponding to the propagation distance Δz,

$\Omega_r=2\pi f_r=ck_r=c\sqrt{k_x^2+k_y^2}$ is the transition pulsation,

J_1 is the first order Bessel function,

$\Gamma(t)$ is the heaviside function defined by

$$\Gamma(t)=\begin{cases}0 \ \ if \ \ t<0\\ 1 \ \ if \ \ t\geq 0\end{cases}$$

In (1), by replacing h with its expression from (4), the time dependent wavenumber spectrum in the forward plane $P(k_x,k_y,z_f,t)$ is obtained. Computing the two-dimensional inverse Fourier transform of this wavenumber spectrum yields the instantaneous spatial pressure in the forward plane $p(x,y,z_f,t)$.

For a practical implementation, several methods to sample the impulse response were investigated [6]. The method, which gives the best result, numerically computes the convolution of the impulse response by a Kaiser-Bessel window using the trapezoidal formula.

3. Inverse problem

In the context of real time holography, the objective is to calculate the pressure field on the source plane $p(x,y,z_s,t)$ from measurements made by the microphone array. In order to back-propagate this pressure field, it is therefore necessary to solve the inverse problem, that is to find the inverse impulse response h^{-1} operating in the time domain and fulfilling the following condition:

$$P(k_x,k_y,z_s,t)=P(k_x,k_y,z_m,t)\otimes h^{-1}(k_x,k_y,\Delta z_s,t) \quad (5)$$

where $\Delta z_s = z_m - z_s$.

The Fourier transform $H^{-1}(f)=TF[h^{-1}(k_x,k_x,\Delta z_s,t)]$ shown in figure 2 allows us to explain more clearly the reconstruction process for a given point $\{k_x,k_y\}$ of the wavenumber spectrum. The components with a frequency greater than the transition frequency f_r are propagative waves (their amplitude remains unchanged). The others components, which frequency is lower than f_r, correspond to the evanescent waves.

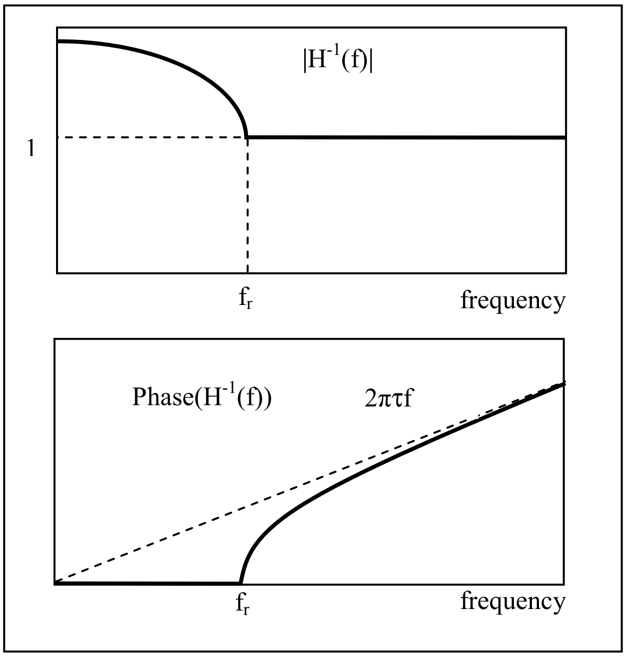

Figure 2: Amplitude and phase of TF $[h^{-1}]$

A critical point in the reconstruction process concerns the amplification of evanescent waves. To limit the distortion due to the presence of noise, some techniques of filtering and regularization in the wavenumber domain are used in the case of NAH [7]. Concerning RT-NAH, some studies are in progress on this topic [8]. For the experimental study presented here the impulse response given by (4) is inverted using Wiener filtering [5].

4. Experimental setup

Industrial real-time holography measurements would require a large array with 64 or 100 microphones to acquire simultaneously the temporal acoustic signals. However, for this experimental study, a reduced number of microphones are used. The sources are reproducible and the acquisition is triggered. The acoustic pressure field is acquired by using a 36 (6 x 6) microphone array in four steps, leading to a virtual 144 (12 x 12) microphone matrix. The distance between adjacent microphones is 4cm, so that the total size is 44cm x 44cm. The position of the array is 6 cm from the source plane.

The first experimental setup involves two small speakers S1 and S2 mounted on a screen and spaced from 11 cm. The second one is a small bass reflex enclosure with two vents (see figures 3 and 4). The measurements are carried out in the CTTM's semi-anechoic room.

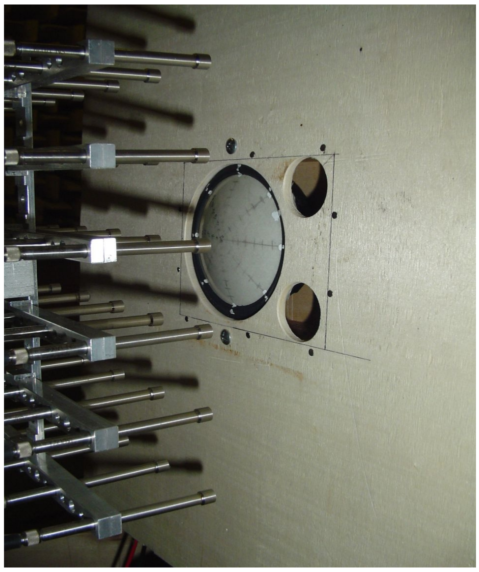

Figure 4: view of experimental setup n°2

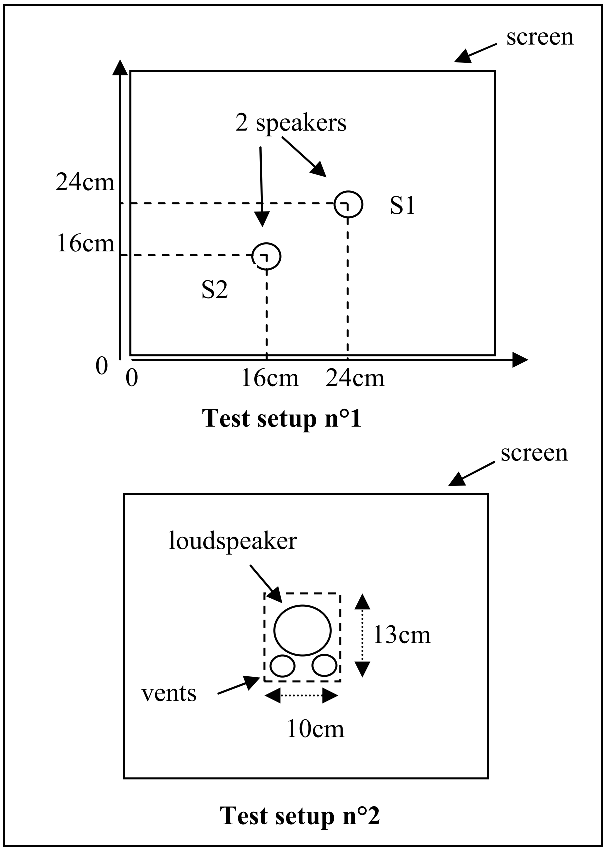

Figure 3: Schemes of experimental setups

5. Results

5.1 Tests with setup n°1

The speaker S2 is excited by an 800Hz sinusoidal signal starting at t≈0.01s. The speaker S1 is excited by a chirp signal from 1kHz to 1.5kHz, starting at t≈0.015s. Both excitation signals have the same amplitude. Measurements are made at a 16 kHz sampling frequency.

In addition to the measurements done at 6cm, an acquisition is performed at 1cm from the source plane. The purpose is to compare the backpropagated field to the measured one. The diffraction effect of the array was checked to be negligible below 3kHz.

Some results in the time domain are given below. In front of the speakers (figure 5a), the comparison between back-propagated and measured pressure fields shows a good agreement in terms of signal shape. However, the amplitudes corresponding to the signal provided by the nearest speaker are significantly greater than the reconstructed one. At other locations in the source plane (figure 5b) the comparison between the back-propagated and measured signals are better, for both the shape and the magnitude.

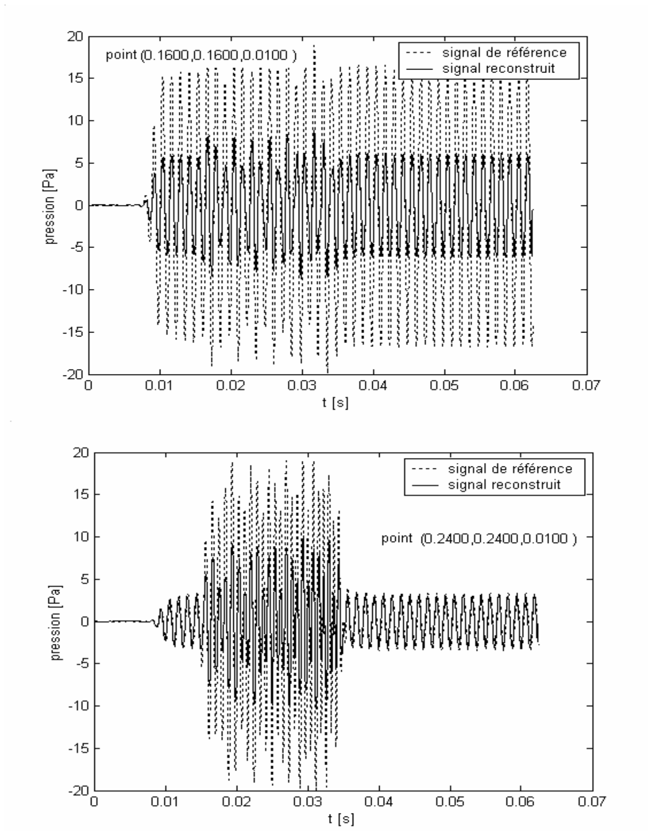

Figure 5a: results at points facing speakers

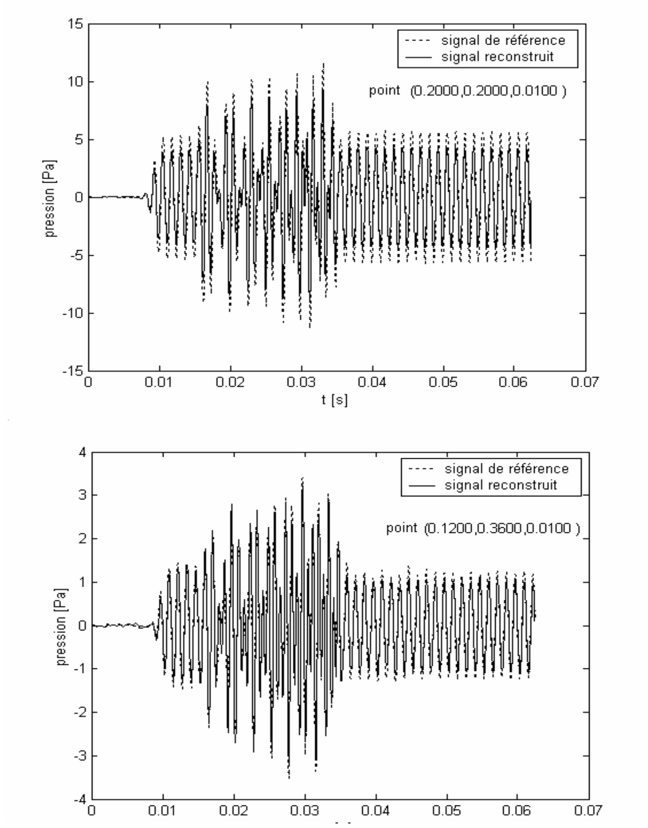

Figure 5b: results at two other points

5.2 Tests with setup n°2

The bass reflex enclosure was designed in order to have a resonant frequency of the Helmholtz resonator at about 600Hz. Figure 6 shows the frequency response of the speaker and that of the vents: below 700Hz the pressure radiated by the vents is greater than that generated by the speaker. The opposite is true above 800Hz.

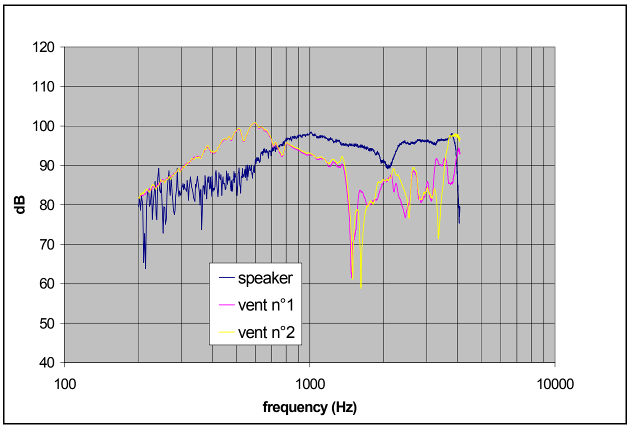

Figure 6: frequency responses of the bass-reflex enclosure components

For the experiments, we use a chirp signal from 400Hz to 1kHz. The shape of the far-field pressure generated by the source is described in figure 7. At the beginning (t < 0.1s and then frequency < 650Hz), the enclosure radiates mainly by its two vents. Later the acoustic pressure generated by the speaker increases, leading to a third acoustic source (at t = 0.16ms, the excitation frequency is about 800Hz and both the pressure generated by the vents and the speaker have the same magnitude). At t=0.2s (the frequency is close to 900Hz) the acoustic signal is mainly created by the speaker.

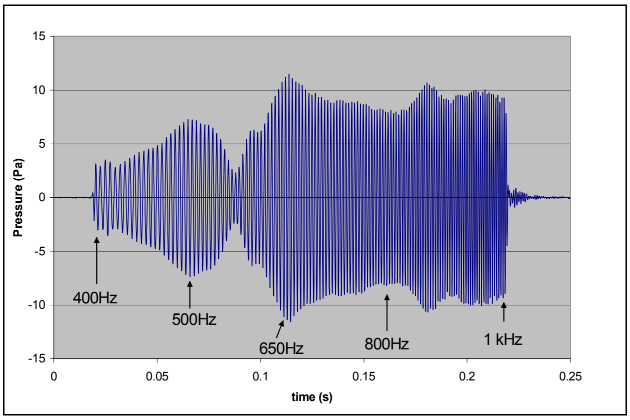

Figure 7: far-field pressure signal generated by the source of the 2nd setup

Measurements are carried out using an 8 kHz sampling frequency. The position of the array is 6 cm from the source plane. Figure 8 shows three views of the instantaneous pressure reconstructed on the source plane, shared on a quarter of the time period (figure 9). The sources positions (speaker and vents) are indicated by the “×” symbol. The microphone lines and columns are represented by the dotted lines. It clearly appears that the time fluctuation of the reconstructed pressure is well described.

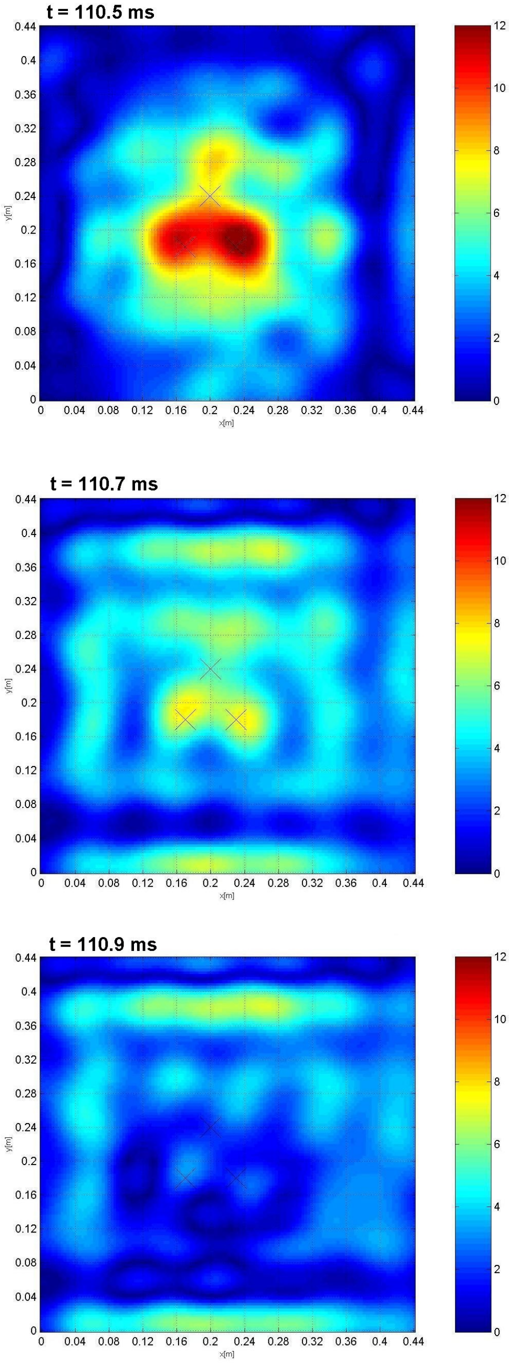

Figure 8: view of the reconstructed pressure fields at three consecutive instants

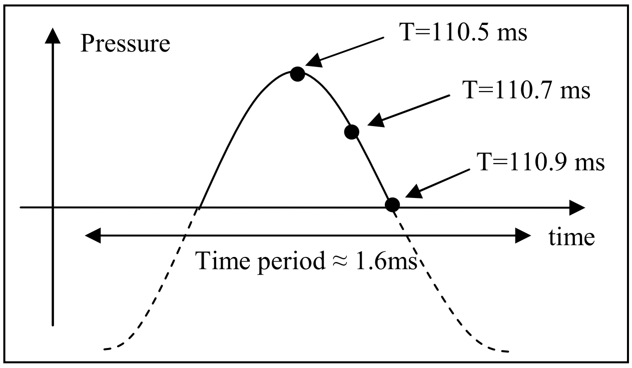

Figure 9: instantaneous pressure at f ≈ 600Hz

Figures 10 to 12 show the comparison between the reconstructed pressure on the source plane and the recorded pressure on the measurement plane at three instants, corresponding to different behaviours of the source (see figure 6). At t=110.5ms (f≈ 600Hz) only the vents radiate. At t=145.5ms (f≈ 700Hz) both the vents and the speaker radiate. Later, at t= 218.4ms (f≈1kHz) the acoustic field is mainly generated by the speaker. The reconstructed pressure at these three instants allows us to localize the sources positions whereas the measurements in the array plane cannot separate them.

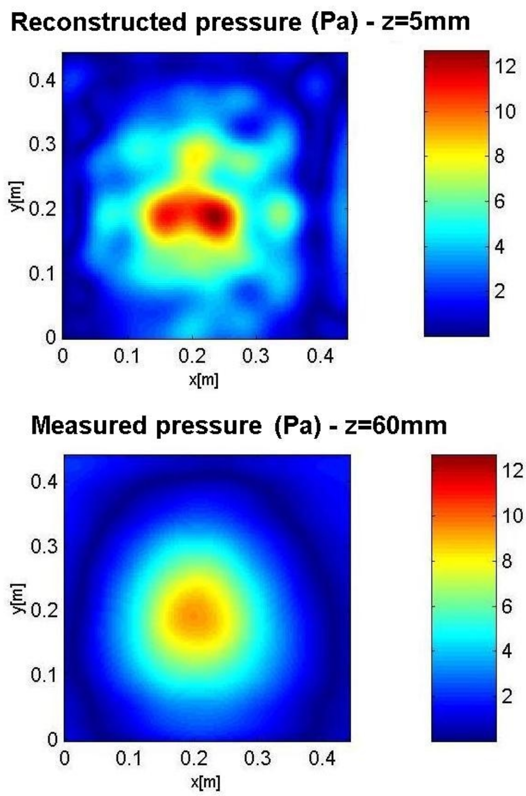

Figure 9: measured and reconstructed pressure fields at t=110.5ms

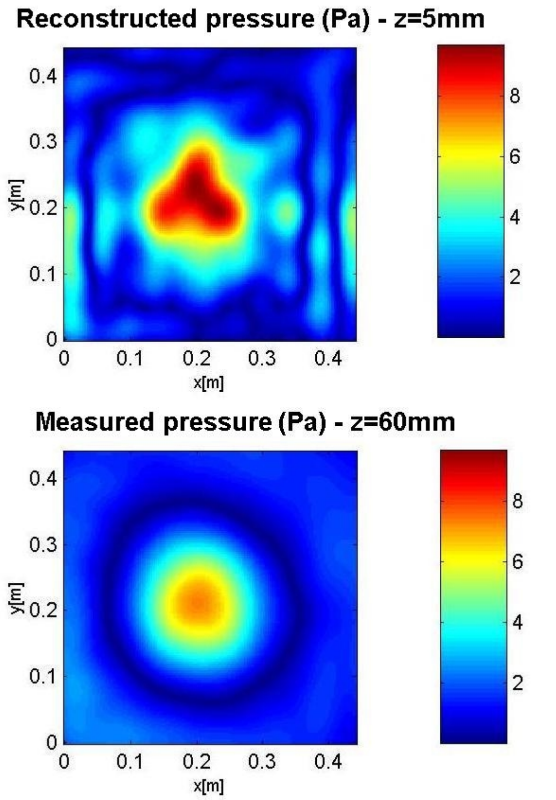

Figure 10: measured and reconstructed pressure fields at t=145.5ms

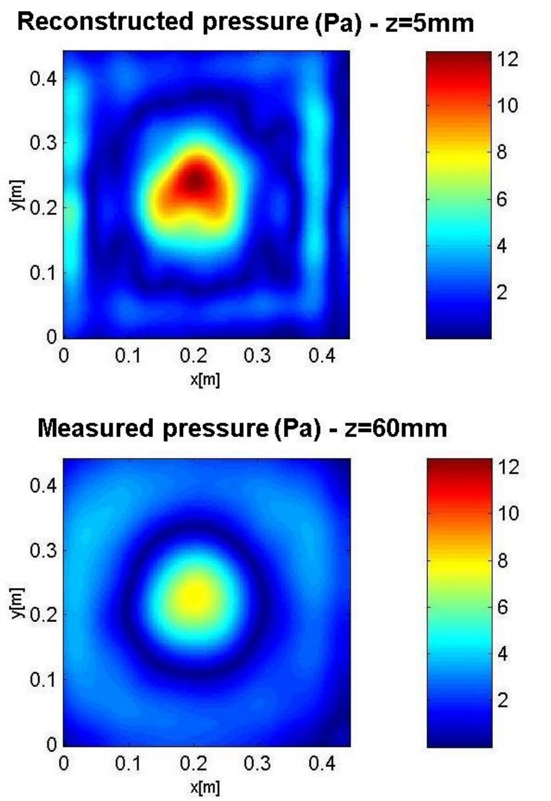

Figure 11: measured and reconstructed pressure fields at t=218.4ms

5. Conclusion

Experimental results have been presented concerning a new real time acoustic holography measurement method, called RT-NAH. From the instantaneous acoustic near-field as an input, this method provides a continuous reconstructed time signal on the source plane. The approach seems promising even though additional work is needed. In particular, experiments on industrial non stationary systems will be performed during the following months. Additional works are also in progress concerning more effective regularization methods.

6. References

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