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# **Aeroacoustic sources localization by means of nearfield acoustic holography adapted to wind tunnel conditions**

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## **ABSTRACT**

Nowadays, several acoustic imaging methods exist but only beamforming can be used for aeroacoustic sources localization in wind tunnels. This method is based on farfield acoustic pressure measurements with a microphone antenna. That is the reason why it would be interesting to develop another method that would allow the localization and quantification of aeroacoustic sources by means of nearfield acoustic measurements. This can be made possible by coupling LDV measurements, that provide acoustic and aerodynamic velocity fields, with Nearfield Acoustic Holography based on velocity-pressure propagator, in order to obtain backward and forward pressure fields around the measurement plane. Although Nearfield Acoustic Holography is a powerful acoustic imaging method, its application to aeroacoustic sources localization in wind tunnels has never, to the authors knowledge, been studied yet. This paper describes an investigation of a new method based on Nearfield Acoustic Holography that allows sources localization in the presence of flow. In order to take into account the flow effect, the spatial propagator used in the real space is the convected Green's function dependent on Mach number. The discrete Fourier transform of this new propagator is then used for reconstruction based on the convected Kirchhoff-Helmholtz integral theorem. In this paper, we first present the methodology, especially the use of the real-velocity-to-pressure propagator, the convected Green's function and the convected Kirchhoff-Helmholtz integral formula. We will then proceed with the simulations, performed to assess the feasibility of this method in the case of a uniform flow with a simple acoustic source (monopole).

Keywords: Aeroacoustics, Wind Tunnel, NAH

## **1 INTRODUCTION**

With the great development of transports, aeroacoustics studies take an important place in acoustic research, especially in aeroacoustic sources localization. That is why research on noise measurements in wind tunnels is still relevant today. Application of directional microphone array measurements, also called beamforming, in wind tunnel began in the end of the 1970s [1]. This imaging method allows acoustic sources localization based on farfield microphone antenna measurements and monopole sources hypothesis. Since, beamforming has seen large improvements due to the availability of better data acquisition and recent software developments. This enabled the introduction of data reduction methods [2] in frequency or time domains. Nevertheless, some specific problems linked to wind tunnel applications had to be studied: disturbances by the shear layers for free-jet facilities, and disturbances by the boundary layers and the wall reflections in closed test sections. High background noise levels and convection of the sound waves by the tunnel flow are also relevant in both cases. One problem in open jet wind tunnels is the phase distortion introduced when the sound waves pass the free shear layer. To correct the phase shift of the signal several approaches were studied. Humphreys and Brooks [3] use a geometrical correction based on Snell and Amiet theory. More recently Koop and Ehrenfried [4] have proposed the use of a test source of known location in the open jet. Special problems and developments of beamforming in acoustic testing are addressed by Dougherty [5]. One important procedure is the elimination of flow noise by removing the diagonal elements of the crossspectral matrix. The influence of reflections on the wind-tunnel walls and the convection of the sound waves by the tunnel flow, considered in the data reduction by means of the convected Green's function, are also discussed in this work. With these different improvements, beamforming could provide a performant localization of acoustic sources in wind tunnel conditions. The main problem of beamforming remains that amplitudes of sound sources are very difficult to derive from beamforming maps. This could be avoided by the development of inverse methods based on deconvolution algorithms. This is the case of CLEAN [6] or DAMAS [7]. Recently, a different kind

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of inverse method has emerged based on time-reversal techniques [8, 9]. These approaches provide an accurate acoustic sources localization in the presence of scattering effects, but the assessment of sources magnitude is greatly dependent on boundary conditions used for the time-reversal simulation.

Thus, the purpose of this paper is to study numerically the feasibility of another method, which would be able to avoid problems linked to shears and boundary layers, monopole sources hypothesis and wall reflections (minimisation of image sources). The idea is to couple non-intrusive in-flow acoustic measurements with a new method based on Nearfield Acoustic Holography (NAH) [10, 11] which could allow the localization and quantification of aeroacoustic sources. For wind tunnel application, optical methods as LDV [12] linked with signal processing could be used to extract acoustic velocity field.

## 2 VELOCITY-BASED NAH

### 2.1 Nearfield Acoustic Holography

Planar Nearfield Acoustic Holography [10, 11] is a powerful experimental technique for extrapolating sound fields from measurements in a plane and especially toward sources in order to characterize them. This method is based on Kirchhoff-Helmholtz integral theorem which links pressure field  $p$  at  $\mathbf{r} = (x, y, z)$  to measured pressure field at  $\mathbf{r}' = (x', y', z')$  using free-space Green's function  $G$  without hypothesis sources:

$$p(\mathbf{r}, \omega) = \int_S (p(\mathbf{r}', \omega) \partial G(\mathbf{r} | \mathbf{r}', \omega) / \partial \mathbf{n} - G(\mathbf{r} | \mathbf{r}', \omega) \partial p(\mathbf{r}', \omega) / \partial \mathbf{n}) dS \quad \forall \mathbf{r} > \mathbf{r}' \quad (1)$$

where  $\mathbf{n}$  is the pointing out normal of the surface  $S$  into the external volume,  $G(\mathbf{r} | \mathbf{r}', \omega) = e^{ikR} / 4\pi R$  with  $R = |\mathbf{r} - \mathbf{r}'| = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$ , and  $k$  is the wavenumber. The convention used here is  $e^{-i\omega t}$  where  $\omega$  is the angular frequency and  $i = \sqrt{-1}$ .

Using the Neumann  $G_N$  and Dirichlet  $G_D$  Green's functions, one can derive the Rayleigh's integrals:

$$p(\mathbf{r}, \omega) = - \int_S G_N(\mathbf{r} | \mathbf{r}', \omega) \partial p(\mathbf{r}', \omega) / \partial \mathbf{n} dS \rightarrow \text{Rayleigh's first integral formula} \quad (2)$$

$$p(\mathbf{r}, \omega) = \int_S p(\mathbf{r}', \omega) \partial G_D(\mathbf{r} | \mathbf{r}', \omega) / \partial \mathbf{n} dS \rightarrow \text{Rayleigh's second integral formula} \quad (3)$$

where  $G_N(\mathbf{r} | \mathbf{r}', \omega) = e^{ikR} / 2\pi R$  and  $\partial G_D(\mathbf{r} | \mathbf{r}', \omega) / \partial \mathbf{n} = (\mathbf{r} - \mathbf{r}') \cdot \mathbf{n} (1 - ikR) e^{ikR} / 2\pi R^3$ .

These formulas allow the extrapolation of the pressure  $p$  at  $\mathbf{r}$  based on the pressure or velocity measurements at  $\mathbf{r}'$  by means of two-dimensional convolution integrals. Since a convolution is more readily evaluated in spectral space, NAH uses Fourier transforms of these equations:

$$p(\mathbf{r}, \omega) = \mathcal{F}^{-1} [ -i\rho c k \mathcal{F}[v_n(\mathbf{r}', \omega)] \mathcal{F}[G_N(\mathbf{r} | \mathbf{r}', \omega)] ] \quad (4)$$

$$p(\mathbf{r}, \omega) = \mathcal{F}^{-1} [ \mathcal{F}[p(\mathbf{r}', \omega)] \mathcal{F}[\partial G_D(\mathbf{r} | \mathbf{r}', \omega) / \partial \mathbf{n}] ] \quad (5)$$

where  $\mathcal{F}$  and  $\mathcal{F}^{-1}$  are, respectively, the direct and the inverse Fourier transform in the spatial domain and  $c$  denotes the speed of sound.

So, the convolution product is replaced by a simple multiplication, and the Fourier transforms of the Green's functions are spatial propagators that allow pressure field evaluation in every plane parallel to the measurements plane, also called the hologram plane. This evaluation is called *propagation* when  $p(\mathbf{r}, \omega)$  is determined from  $p(\mathbf{r}', \omega)$  or  $v_n(\mathbf{r}', \omega)$ , or *reconstruction* when  $p(\mathbf{r}', \omega)$  or  $v_n(\mathbf{r}', \omega)$  are determined from  $p(\mathbf{r}, \omega)$  taking the inverse of propagators. The advantage of NAH is that it provides a solution to the inverse problem, whereas Rayleigh's integral formulas can only provide the pressure radiated from the sources. Its major attraction is its solution to the inverse problem, that allows the reconstruction of sound field from the hologram plane to the source plane, giving localization and quantification of sources.

### 2.2 The real-space velocity-to-pressure propagator

Since it is usually easier to measure the sound pressure than the particle velocity, conventional applications of NAH are based on the forward and inverse pressure-to-pressure propagators ( $\mathcal{F}[\partial G_D / \partial \mathbf{n}]$  et  $1/\mathcal{F}[\partial G_D / \partial \mathbf{n}]$ ) and the inverse velocity-to-pressure propagator ( $1/\mathcal{F}[G_N]$ ). However, with the recent developpment of an acoustic particle velocity transducer called "Microflow", the potentiality of NAH based on particle velocity measurements using the forward velocity-to-pressure propagator ( $\mathcal{F}[G_N]$ ) has been tested [13]. This study shows that NAH based on particle velocity measurements can give accurate predictions of the sound field. Nevertheless, in some applications, it is necessary to use a "smooth" version of the wave number spectra [14] to avoid the influence of the singularity of the velocity-to-pressure propagator. As microphones or particle velocity transducers may be too

intrusive to measure acoustic field near sources in wind tunnel, the idea is to apply the forward velocity-to-pressure propagator at LDV measurements in the nearfield, since it has been shown possible to measure acoustic velocity field by LDV [12].

Usually, the spectral form of propagators is used directly in NAH calculations because the Fourier transforms of the Green's functions  $G_D$  and  $G_N$  may be found analytically [10, 11]. However, the spectral form of propagators taking into account a uniform flow is still not known, to the authors' knowledge. This is the reason why, in what follows, the Fourier transform of real-space propagators is used, and research was conducted on the rewriting of the Green's functions to have a description of acoustic wave propagation in presence of flow.

### 3 NAH IN UNIFORM FLOW

#### 3.1 The convected Green's function

In the case of a uniform flow  $\mathbf{U}$ , usual equations for mass and momentum balance written in the laboratory system become:

$$D\rho(\mathbf{r}, t)/Dt + \rho_0 \sum_i \partial u_i(\mathbf{r}, t)/\partial x_i = 0 \quad (6)$$

$$\rho_0 Du_i(\mathbf{r}, t)/Dt = -\partial p(\mathbf{r}, t)/\partial x_i \quad (7)$$

where  $p(\mathbf{r}, t) = \rho(\mathbf{r}, t)c^2$  and  $D/Dt = \partial/\partial t + \mathbf{U} \cdot \nabla$ . From these equations, one can derive the expression of the wave equation in uniform flow, also called the convected wave equation [15]:

$$\nabla^2 p(\mathbf{r}, t) - 1/c^2 D^2 p(\mathbf{r}, t)/Dt^2 = 0 \quad (8)$$

The convected Green's function  $G_\beta$  is obtained by solving the adjoint of the previous equation with an harmonic unit point impulsive source as a second member:

$$\nabla^2 G_\beta(\mathbf{r} | \mathbf{r}', \omega) + k^2 G_\beta(\mathbf{r} | \mathbf{r}', \omega) - 2ikM \partial G_\beta(\mathbf{r} | \mathbf{r}', \omega)/\partial z - M^2 \partial^2 G_\beta(\mathbf{r} | \mathbf{r}', \omega)/\partial z^2 = -\delta(\mathbf{r} - \mathbf{r}') \quad (9)$$

where  $\delta$  is the Dirac function, and  $M$  the Mach number of the flow assumed to be uniform in the positive  $z$  direction.

Using the Prandtl-Glauert transformation:  $\tilde{x} = x$ ,  $\tilde{y} = y$ ,  $\tilde{z} = z/\beta$ ,  $\tilde{k} = k/\beta$ ,  $\tilde{f} = f e^{i\tilde{k}M\tilde{z}}$ , where  $\beta = \sqrt{1 - M^2}$ , one can achieve the Helmholtz equation in transformed coordinates and then derive the expression of the convected Green's function [16]:

$$G_\beta(\mathbf{r} | \mathbf{r}', \omega) = e^{ik(r_\beta - M(z - z'))/\beta^2} / 4\pi r_\beta \quad (10)$$

where  $r_\beta = \sqrt{\beta^2[(x - x')^2 + (y - y')^2] + (z - z')^2}$ .

#### 3.2 The convected Kirchhoff-Helmholtz integral theorem

Applying the weighted residual method to (8) written at  $\mathbf{r}'$  and using  $G_\beta$  as a weighting function, the weighted residual statement is:

$$\int_V G_\beta(\mathbf{r} | \mathbf{r}', \omega) (\nabla^2 p(\mathbf{r}', \omega) + k^2 p(\mathbf{r}', \omega) + 2ikM \partial p(\mathbf{r}', \omega)/\partial z - M^2 \partial^2 p(\mathbf{r}', \omega)/\partial z^2) dV = 0 \quad (11)$$

where  $V$  is the domain of interest.

Integrating the first and second terms of this equation by parts twice and the convective term once, and using (9) yields the convected Kirchhoff-Helmholtz integral formula [16] for a uniform flow in the positive  $z$  direction:

$$\begin{aligned} p(\mathbf{r}, \omega) = - \int_S [ & (G_\beta(\mathbf{r} | \mathbf{r}', \omega) \partial p(\mathbf{r}', \omega)/\partial \mathbf{n} - p(\mathbf{r}', \omega) \partial G_\beta(\mathbf{r} | \mathbf{r}', \omega)/\partial \mathbf{n}) \\ & - M^2 (G_\beta(\mathbf{r} | \mathbf{r}', \omega) \partial p(\mathbf{r}', \omega)/\partial z - p(\mathbf{r}', \omega) \partial G_\beta(\mathbf{r} | \mathbf{r}', \omega)/\partial z) n_z \\ & + 2ikM G_\beta(\mathbf{r} | \mathbf{r}', \omega) p(\mathbf{r}', \omega) n_z ] dS \end{aligned} \quad (12)$$

where  $n_z$  is the  $z$  component of  $\mathbf{n}$ .

#### 3.3 Application to NAH

One can notice that (12) can be simplified when  $\mathbf{n}$  is perpendicular to the flow direction  $z$  (ie. for  $n_z = 0$ ):

$$p(\mathbf{r}, \omega) = - \int_S (G_\beta(\mathbf{r} | \mathbf{r}', \omega) \partial p(\mathbf{r}', \omega)/\partial \mathbf{n} - p(\mathbf{r}', \omega) \partial G_\beta(\mathbf{r} | \mathbf{r}', \omega)/\partial \mathbf{n}) dS \quad (13)$$

This equation is the same as (1) with  $G_\beta$  defined by (10). By introducing the convected Neumann and Dirichlet Green's function  $G_{N_\beta}$  and  $G_{D_\beta}$ :

$$G_{N_\beta}(\mathbf{r} | \mathbf{r}', \omega) = e^{ik(r_\beta - M(z-z'))/\beta^2} / 2\pi r_\beta \quad (14)$$

$$\partial G_{D_\beta}(\mathbf{r} | \mathbf{r}', \omega) / \partial \mathbf{n} = e^{ik(r_\beta - M(z-z'))/\beta^2} / 2\pi r_\beta (\beta^2 / r_\beta^2 - ik / r_\beta) (\mathbf{r} - \mathbf{r}') \cdot \mathbf{n} \quad \text{if } \mathbf{n} \perp \mathbf{z} \quad (15)$$

we obtain formulas similar to (2) and (3) :

$$p(\mathbf{r}, \omega) = - \int_S G_{N_\beta}(\mathbf{r} | \mathbf{r}', \omega) \partial p(\mathbf{r}', \omega) / \partial \mathbf{n} dS \quad (\text{Neumann's condition}) \quad (16)$$

$$p(\mathbf{r}, \omega) = \int_S p(\mathbf{r}', \omega) \partial G_{D_\beta}(\mathbf{r} | \mathbf{r}', \omega) / \partial \mathbf{n} dS \quad (\text{Dirichlet's condition}) \quad (17)$$

Pressure gradient can be obtained from acoustic and aerodynamic velocity fields using the Euler's equation (7) projected on axis  $\mathbf{n}$ :

$$\rho_0 (\partial / \partial t + U \partial / \partial z) u_n(\mathbf{r}', t) = - \partial p(\mathbf{r}', t) / \partial \mathbf{n} \quad (18)$$

In the case of *propagation*, pressure can be obtained by (16) from hologram plane  $\mathbf{r}_h$ :

$$p(\mathbf{r}, \omega) = - \mathcal{F}^{-1} [ \mathcal{F} [\partial p(\mathbf{r}_h, \omega) / \partial \mathbf{n}] \mathcal{F} [G_{N_\beta}(\mathbf{r} | \mathbf{r}_h, \omega)] ] \quad \forall \mathbf{r} \leq \mathbf{r}_h \quad (19)$$

In the case of *reconstruction*, as discussed in section 2.1, knowledge of pressure in hologram plane coupled with (17) is needed to reconstruct pressure towards the sources. One solution is to use (19) to transform pressure gradient into pressure in the hologram plane  $\mathbf{r}_h$ , then, use the Fourier transform of (17) to reconstruct pressure towards the source:

$$p(\mathbf{r}, \omega) = \mathcal{F}^{-1} [ (- \mathcal{F} [\partial p(\mathbf{r}_h, \omega) / \partial \mathbf{n}] \mathcal{F} [G_{N_\beta}(\mathbf{r}_h | \mathbf{r}_h, \omega)]) \mathcal{F} [1 / \partial G_{D_\beta}(\mathbf{r} | \mathbf{r}_h, \omega) / \partial \mathbf{n}] ] \quad \forall \mathbf{r} < \mathbf{r}_h \quad (20)$$

## 4 SIMULATIONS

### 4.1 In-flow monopole source

In order to validate numerically the method developed in the previous sections, the simple case of a monopolar potential radiating in a uniform flow in positive  $z$  direction is tested. The velocity potential of such a monopole [16] is given by:

$$\Phi(\mathbf{r}, \omega) = A e^{ik(r_\beta - M(z-z'))/\beta^2} / 4\pi r_\beta \quad (21)$$

where  $A$  is a constant. The velocity potential  $\Phi$  is linked to acoustic pressure and velocity by these relations:

$$p(\mathbf{r}, \omega) = -\rho D\Phi(\mathbf{r}, \omega) / Dt \quad (22)$$

$$u_i(\mathbf{r}, \omega) = \partial \Phi(\mathbf{r}, \omega) / \partial x_i \quad (23)$$

The effect of uniform flow on acoustic propagation is shown in Figure 1. The monopole's wavelength is reduced upstream and increased downstream, and magnitude is modified by the mean flow.

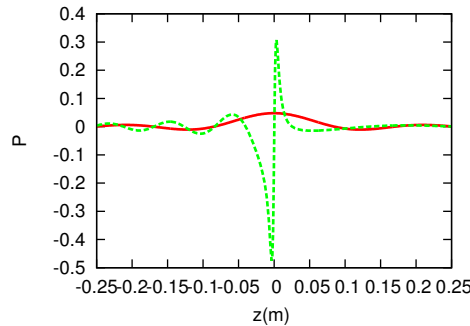


Figure 1:  $\text{Re}(p)$  at  $x = 0.005$ ,  $y = 0$  for a monopole at  $\mathbf{r} = 0$  without flow (red) and in a uniform flow at  $M_z = 0.5$  (green)

## 4.2 Reconstruction for a monopole source

In this section the capacity of developed method to characterize a monopole source in uniform flow is tested. The studied case is the following: a monopolar potential situated at  $\mathbf{r} = 0$  radiates in a uniform subsonic flow in the positive  $z$  direction at  $2000\text{Hz}$  for  $A = 10^{-3}$  (Figure 2). For NAH computation, the corresponding pressure gradient is computed from (18) in a virtual measurements grid  $(x, z)$  of  $0.45 \times 0.45\text{m}^2$  with  $16 \times 16$  points at  $y_h = -0.05\text{m}$ . Acoustic pressure can then be determined in any plane parallel to this grid using (19) and (20). To reduce the influence of the spatial sampling, zero padding is applied before the discrete spatial Fourier transform is computed. Numerical results are compared to theoretical pressure field (22).

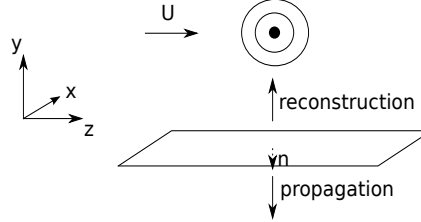


Figure 2: Numerical setup

As can be seen in Figure 3, reconstructed pressure in the source plane is in good agreement with theoretical results for every studied Mach number ( $M = 0, 0.25, 0.5, 0.75$ ). Similar results have been found at other tested frequencies ( $1000 - 5000\text{Hz}$ ). One can notice that even if the maximal magnitude of the potential is at  $\mathbf{r} = 0$ , the maximal pressure magnitude is moved upstream by the flow (21, 22). The developed method seems to be relevant to localize and quantify the maximum of pressure of simple potential sources in uniform flow.

## 5 CONCLUSIONS

Since there exists only one way to study aeroacoustic sources in wind tunnel (beamforming), this paper presents research on a new method to characterize acoustic sources in presence of flow. This method is based on rewriting NAH using convected Kirchhoff-Helmholtz integral formulas. In this way, one can obtain, in some configurations, an integral formulation similar to classical NAH with real-space propagators built on the convected Green function. Thus acoustic field can be reconstructed towards sources combining velocity-to pressure and inverse pressure-to-pressure propagators applied at velocity measurements in a plane parallel to the flow.

A preliminary numerical study shows that this method is pertinent in the case of simple sources in uniform flow for various Mach numbers and frequencies. Indeed, reconstructed acoustic fields allow a good quantification of maximal pressure magnitude without any additional inverse method like in beamforming. However, further simulations will have to be performed to study the method's performances for more complex sources. It could be also useful to create 3D acoustic cartography of the field radiated below tested sources by reconstructing and propagating the acoustic field at several  $y$  abscissas. As the aim would be to use this method in wind tunnel, future research will, therefore, concentrate on the integration of effects of acoustic wall reflections in the reconstruction procedure. After that, experiments will be performed in wind tunnel to confirm the effectiveness of the method.

Although this study is based on a very simple application, it could become an interesting and promising tool for aeroacoustic measurements.

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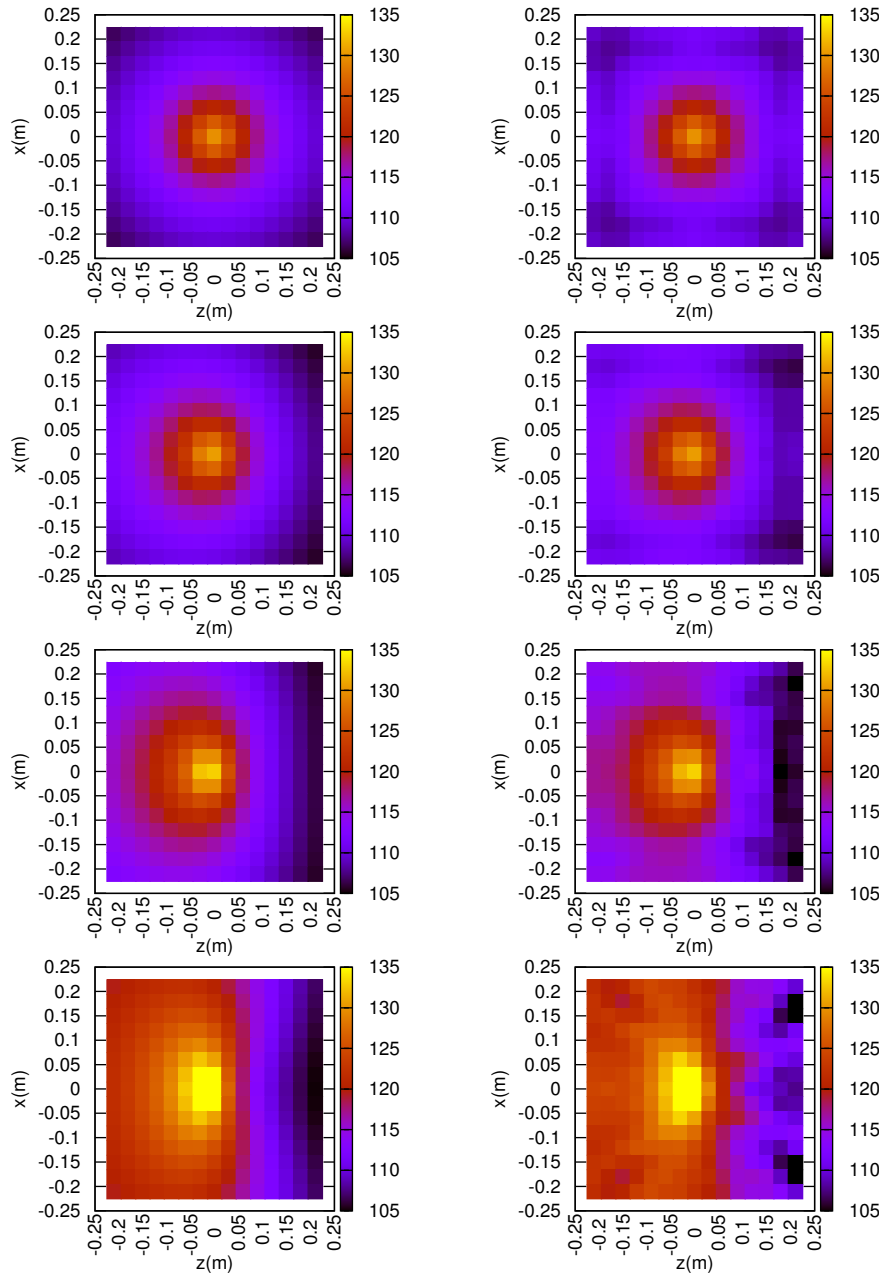


Figure 3: Reconstructed pressure (dB) in the source plane obtained by the theory (left) and NAH (right) for various Mach number: 0, 0.25, 0.5, 0.75