

# Localization of stationary sound sources in flows by using a time-reversal method

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## ABSTRACT

The time-reversal (TR) technique has been extensively developed over the two last decades, but very few applications have concerned the field of aeroacoustics. The possibility of using the TR technique in the context of wind-tunnel measurements is then investigated in this study, in order to localize a sound source in a flow. The chosen strategy is the following: in a first experimental step, the pressure fluctuations are recorded in the far field over a linear array of microphones, located outside the flow; in a second simulation step, the experimental signals are time-reversed and used as input data. The time-reversed linearized Euler equations are then solved numerically in order to model the sound propagation through the shear layer and the flow. The back-propagated pressure field is then investigated, both in terms of energy and phase. Some preliminary simulations show that it is possible to localize a monopolar source located in a flow by using this method. The experimental results at Mach number 0.12 show that a monopolar source at 5 kHz can be satisfactorily located, with an error of the order of half-the acoustic wavelength. Some measurements concerning a dipolar source are also presented: the effects of the flow on the radiation appear clearly on the data, and the source position is estimated with an error of the order of the acoustic wavelength.

## INTRODUCTION

Array processing has been developed extensively over the last decades, and is now widely used in a wide range of engineering applications. Among the most popular techniques is the beamforming technique, which allows to estimate the direction of propagation of the sound waves emanating from monopolar sources and propagating onto the array. In particular this technique is currently applied in the context of aeroacoustics measurements (Mueller et al. (2002)). In this context, the effects of flow on propagation are usually taken into account using analytical models (Amiet (1978)) and a simplified flow profile (Koop et al. (2005)).

The goal of this study is then to present an inverse method, enabling the localization of a sound source with arbitrary directivity in a flow, by taking into account accurately the flow effects on propagation (i.e., convection and refraction). In this purpose, the Time-Reversal (TR) technique is applied to the experimental problem of source localization in a wind-tunnel flow. The TR technique has been developed extensively over the last years since its first applications (Fink (1992)). It lays on the following principle: the acoustic pressure radiated by a sound source is spatially sampled by a set of transducers. Then the acquired signals are time-reversed, and back-propagated from the transducer array, which allows finally to localize the initial sound source. This technique is specially adapted to the case of heterogeneous media, which is the case for aeroacoustic measurements, as the mean flow gradients induce some spatial variations of the speed of sound.

Very recently, the time-reversal method has been applied for the first time in aeroacoustics (Deneuve et al. (2010)). In this completely numerical study, the Euler equations are time-reversed

and a complex differentiation is used to tag acoustic disturbances. The method is applied to the localization of shear-layer noise sources. Most recently, an approach combining one experimental step and one numerical step was used by Padois et al. (Padois et al. (2010)). This study demonstrated the potentiality of using experimental pressure measurements to produce the input data for a numerical time-reversed calculation, based on the resolution of the Linearized Euler Equations (LEE).

The present paper investigates in more detail the way of applying the TR technique in the context of sound source localization in wind-tunnel measurements, and in particular investigates the case of both monopolar and dipolar sources, as these types of radiation are typical in the context of aeroacoustic measurements. After describing the experimental setup used in this study, the details of the numerical application of the TR technique is presented; some numerical results are then analysed. In a last section, the experimental results concerning the localization of the two kinds of sound sources (monopolar and dipolar) are presented.

## EXPERIMENTAL SETUP

The source localization method proposed in this paper is applied in the context of wind-tunnel measurements. The investigations are carried out in an anechoic Eiffel-type wind-tunnel (Figure 1). The nozzle exit has a square cross-section of  $(0.46 \times 0.46) \text{ m}^2$ , and the test section has a length of 2.13m. The maximum operating flow speed is 40m/s (Mach number  $\mathcal{M} = 0.12$ ), which was the flow speed used during the present study. Mean flow measurements have been undertaken by using a hot-wire, in order to model properly the mean flow for the numerical simulations. The flow is bounded on its lower side by a plywood plate; the boundary effects will be neglected in the simulation.

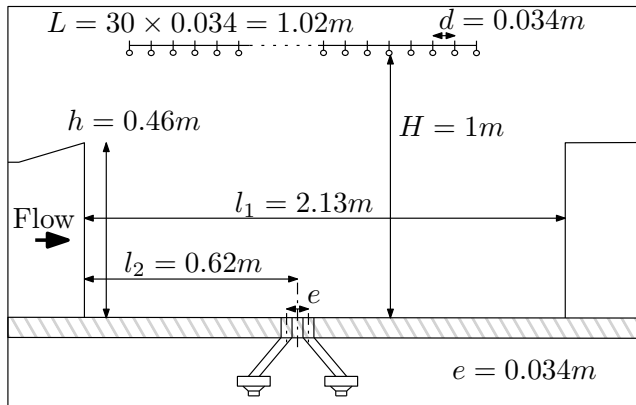


Figure 1: Scheme of the experimental setup.

A linear array of 31 microphones, parallel to the flow direction, is located outside the flow, with a regular spacing of  $d=3.4$  cm between the microphones. The array length  $L$  is then 1.02 m, and the distance  $H$  to the source is equal to 1 m. The microphone signals are sampled by using a 32-channels ETEP acquisition system; the sampling frequency is 50 kHz.

The sound waves are generated by one or two horn-drivers (type B&C Speakers DE10); these devices have a small diaphragm (diameter 25 mm) and an important output acoustic power in the frequency range [1;18]kHz. Two source configurations are used in this study. The first one uses one compression chamber: a tube of diameter 20 mm and length 50 cm is plugged to the speaker, and comes out through the plywood plate. This generates a monopolar sound source. The second configuration uses two compression chambers (a photograph of this configuration is presented in Figure 2). Each one is connected to a tube (similar to the above-mentioned tube) that comes out through the plate. This creates two monopolar sources; the distance between these two sources is equal to  $e=3.4$  cm in this study. By a proper adjustment of the relative phase of the input signals of the two compression chambers, it is then possible to create a dipolar source.



Figure 2: Photograph of the dipolar source configuration.

## TIME-REVERSAL OF LINEARIZED EULER EQUATIONS (LEE)

### Principle

In this paper, the numerical simulation of the propagation through the flow is carried out by using a numerical solver based on the two-dimensional LEE. This set of equations has been shown to be able to model satisfactorily the acoustic propagation through a mean shear flow (Bailly and Juvé (2000)). Starting from the Euler equations, a linear system of first order differential equations is obtained by decomposing the density, the streamwise and vertical velocity components and pressure (respectively,  $\rho(x,y,t)$ ,  $u(x,y,t)$ ,  $v(x,y,t)$  and  $p(x,y,t)$ ) into mean and fluctuating quantities. After solving this linear system, the fluctuating parts of density, pressure and velocity are recovered as a function of time over the simulation domain. In the numerical application proposed in this paper, the spatial discretization is carried out by using a 4<sup>th</sup> Dispersion Relation Preserving Scheme (Tam and Webb (1993)), and a 4<sup>th</sup> order Runge-Kutta scheme is used for time discretization.

The simulated configuration represents a typical wind-tunnel experiment, such as the one presented in the last section (Figure 1). An acoustic source radiating a monopolar sine-wave sound field is located in the flow. The wavefronts propagate through the flow, undergo some convection and refraction effects when they cross mean flow and the shear-layer. The aim of the proposed method is then to use the fluctuating pressure data as recorded by the array as the input data for the simulated time-reversal procedure.

Indeed, Padois et al. (Padois et al. (2010)) have shown that it is possible to time-reverse the LEE in order to refocus virtually the sound field into the flow, and then back to the emitting acoustic source, enabling its localization. The original set of LEE equations must then be modified in order to ensure the invariance of LEE by TR. The following change of variables is then carried out:

- $t \rightarrow -t$ ,
- $\rho(x,y,t) \rightarrow \rho(x,y,-t)$ ,
- $u(x,y,t) \rightarrow -u(x,y,-t)$ ,
- $v(x,y,t) \rightarrow -v(x,y,-t)$ ,
- $p(x,y,t) \rightarrow p(x,y,-t)$ .

It may be noticed that the reversing of the velocity quantities involve that the flow is simulated in the direction opposite to the one of the physical flow, which allows that the convection and refraction are properly accounted for when the wavefronts back-propagate to the acoustic source. It is also important to point out that although all the physical variables are time-reversed in the calculation domain, only the acoustic pressure and density fluctuation (deduced from the acoustic pressure by the isentropic assumption) are provided as an input data for the TR simulation: indeed, in the context of experimental data, only this quantity can be actually measured.

### Numerical example

A numerical example is now provided in order to illustrate the method, and comment the type of output data that makes the source localization possible. A sine-wave monopolar acoustic source (frequency 5 kHz) is located in a flow with a Mach number equal to 0.5. The results for the no-flow configuration will also be provided for comparison. The  $X$  and  $Y$  coordinates denote the streamwise and vertical directions, the flow goes from the left to the right. The shear layer is located along a line at  $X=0.46$  m, and its profile is modeled to be as close as possible to the measured profile of the experimental shear layer (Padois et al. (2010)). The acoustic source is located at position

(0,0).

The propagation is simulated in a numerical domain of  $(213 \times 213)$  points representing a physical domain of  $(1.4 \times 1.4) \text{ m}^2$ . The number of iteration time-steps is 1000, and the acoustic pressure fluctuations are recorded over 31 points located along a line parallel to the flow, with a regular spacing  $d$  of 3.4 cm: this models the linear microphone array. The extremities of the array are located at points  $(1, -0.51)$  and  $(1, 0.51)$  in the  $(X, Y)$  coordinate system. The geometrical settings of the calculation (source-array distance, array length, shear layer thickness...) are equal to the experimental values (as given in the last section): array length  $L=1.02 \text{ m}$ , source-array distance  $H=1 \text{ m}$ . Indeed, some preliminary simulations have shown that, in the context of this application, the TR procedure performs best when the array length  $L$  and source-array distance  $H$  are of the same order of magnitude. Besides this, the microphone inter-distance  $d$  must be equal, at most, to a half of the sound wavelength. Note that in the further experimental results, this step is not simulated but the data are provided by real measurements.

The recorded pressure data are then time-reversed and used as input data for the TR simulation. The back-propagated wavefronts are then simulated over a number **1000** of iteration time-steps. Two snapshots of the pressure field over the simulation domain, at an arbitrary time step of the time-reversed simulation, are presented in Figure 3, in which the Mach number  $\mathcal{M}$  is respectively equal to 0 (top) and 0.5 (bottom). At this stage, the presence of a hard wall is not taken into account to avoid the reflections of the TR beam, which could make difficult the interpretation of the TR waves in the numerical domain.

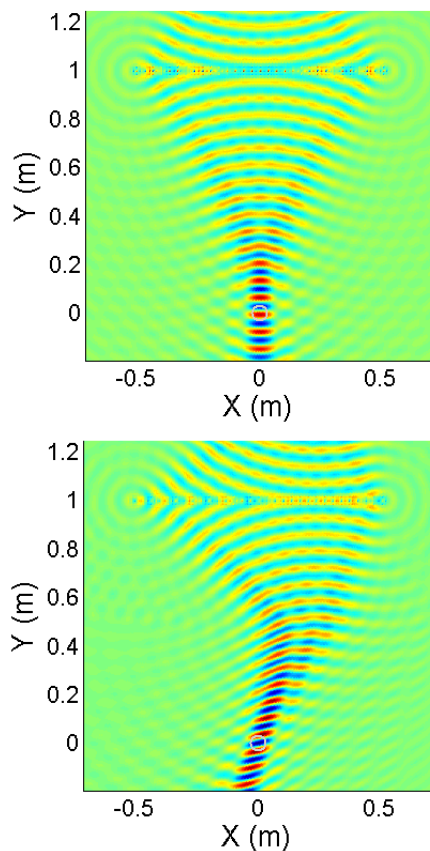


Figure 3: Time-reversed simulation: two snapshots of the pressure field. Top:  $\mathcal{M} = 0$ ; bottom:  $\mathcal{M} = 0.5$ . The shear layer is at  $X=0.46 \text{ m}$ . The circle indicates the real position of the source.

In the no-flow calculation case, it is observed that the beam is back-propagated from the array to the position of the source.

When the flow is present, the back-propagated beam is clearly bended, which is due to the strong refraction and convection effects during the back-propagation through the shear layer. This effect seems to be modeled correctly as the beam is back-propagated through the source position. However, from those data, it is difficult to estimate the source position.

In this purpose, the spatial distribution of the energy received at each node of the computational domain is computed: for each node the squared pressure is summed over the simulation time, and the energy is then obtained. The results of such a process lead to the energy distribution graphs of Figure 4, and will be called «TR energy distribution» in the following. It is observed that a region with an important energy is enhanced by this representation: it can be interpreted as the focalisation zone of the re-emitted waves. This zone is deviated to the right for  $\mathcal{M} = 0.5$ , due again to the convection effect. From those graphs, it is now possible to estimate the source position: it is defined as the point at which the TR energy distribution is maximum. From the results of Figure 4, it appears clearly that the source is localized very satisfactorily, with a maximum error of 3.5 cm, i.e. a half of the sound wavelength at 5 kHz.

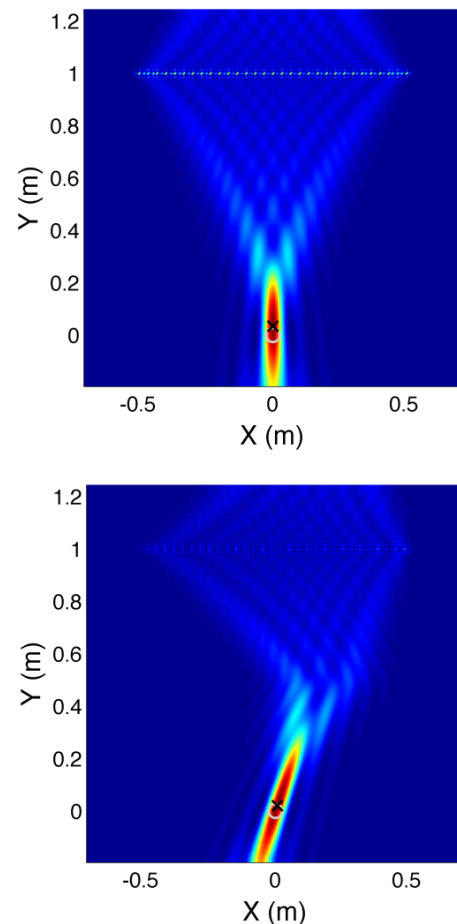


Figure 4: TR energy distribution at frequency 5 kHz. Top:  $\mathcal{M} = 0$ ; bottom:  $\mathcal{M} = 0.5$ . The shear layer is at  $X=0.46 \text{ m}$ . The cross and the circle indicate, respectively, the estimated and the real position of the source.

Another important type of output data is the distribution of the phase of the TR pressure field. In the same manner than the energy distribution is calculated, the local phase of the waves can be estimated at the frequency of interest (here, 5 kHz), by calculating the argument of the Fourier transform of the local pressure fluctuations. An example of results is presented in Figure 5 for the same simulated case; this kind of output



graph is termed as «TR phase distribution» in the following. For the no-flow case, the phase isolines between the array and the source correspond to the re-emitted wavefronts. The source position corresponds to a point where the phase isolines seem to converge. Moreover, a characteristic feature of TR results is also observed: the waves pass through the source and diverges from it, as there is no dissipation at the point source. When the flow is present, the same observations can be made, but there is a clear deformation of the phase isolines. It is likely that a specific treatment could be applied to the phase distributions graphs in order to localize the source, but it is not critical here as the TR energy distribution graphs make possible this localization. However, the interest of the phase distributions will be more obvious for a dipolar radiation (next section).

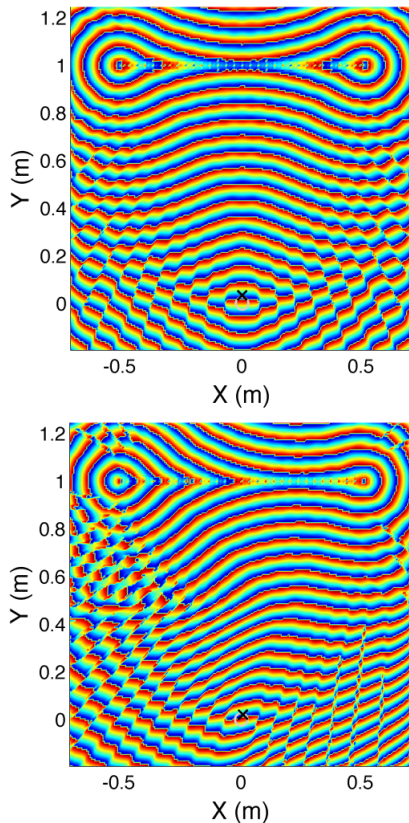


Figure 5: TR phase distribution at frequency 5 kHz. Top:  $\mathcal{M} = 0$ ; bottom:  $\mathcal{M} = 0.5$ . The shear layer is at  $X=0.46$  m. The cross and the circle indicate, respectively, the estimated and the real position of the source.

## EXPERIMENTAL RESULTS

### Monopolar sound source

In this section, the case of an experimental sine-wave monopolar sound source is presented. The flow velocity is 40 m/s ( $\mathcal{M} = 0.12$ ). The emission frequency is 5 kHz. The radiated sound field is measured by the microphone array, and 1000 points of signals are stored. This set of data ( $31 \times 1000$  points) is used as an input dataset for the TR simulation.

As explained in the preceding section, the EEL simulation tool is then used in its time-reversed version, and the wavefronts are back-propagated in order to obtain the TR energy distribution graph, as displayed in Figure 6. A region of high energy (the focalisation spot) is located around the source position, which demonstrates that the proposed method is applicable to real data. The focalisation spot appears to be slightly inclined, which is again, the result of convection and refraction effects. However

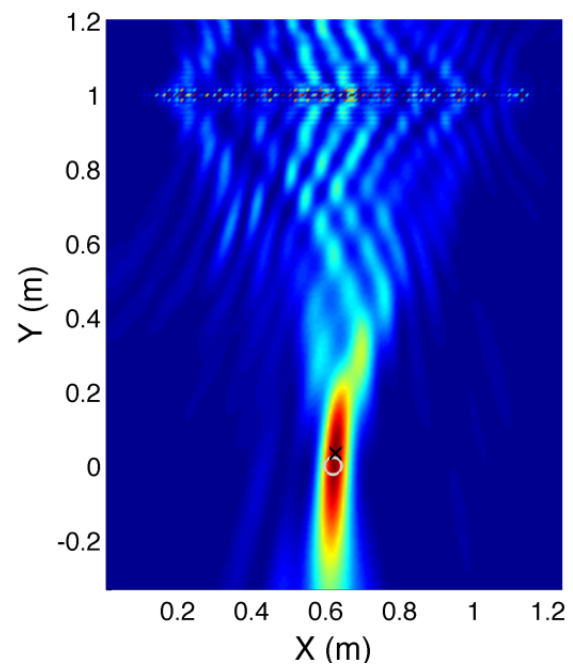


Figure 6: TR energy distribution for a monopolar source at frequency 5 kHz. The input data of the simulation are experimental,  $\mathcal{M} = 0.12$ . The shear layer is at  $X=0.46$  m. The cross and the circle indicate, respectively, the estimated and the real position of the source.

this effect is less obvious than for the case of Figure 4 (higher Mach number). By searching the point where the energy is maximum, the source position is estimated; this estimation is very satisfactory, as the error is of the order of 3.5 cm; this amounts to a half of the acoustic wavelength.

Some further experiments have shown that, in this experimental configuration, the method can be applied to frequencies ranging down to about 3 kHz, with a maximum error of source position still ranging about a half of the acoustic wavelength. The method could be applied to higher frequencies, at the condition that the microphone spacing is reduced to respect a minimum of half-a-wavelength. The method has also been applied to wideband sound sources. After band-filtering the signal in the frequency range [3;5] kHz, the source position can be estimated in the same way.

### Dipolar source

The experimental results for the dipolar source at frequency 5 kHz are now considered. The distance between the two monopolar sources that create the dipolar radiation is equal to a half-wavelength. The cases with no flow and  $\mathcal{M}=0.12$  are considered. The center of the dipole (located half-way between the two monopoles) is located at point (0.62,0).

Figure 7 depicts the TR energy distribution graphs. In the no-flow configuration, it is observed that two energy spots are localized, corresponding to the two monopolar sources. The estimated distance between the positions of the source is equal to 9.6 cm, i.e., about 1.5 times the sound wavelength; the error is then of the order of one wavelength. More generally, in a dipole case, some simulation results (not presented in this study) show that if the distance between the two monopoles is smaller than the wavelength, the estimated distance is equal to about the wavelength. This error is apparently slightly higher for experimental results. However, the estimated position of the dipole (half-way between the positions of the two monopoles) is located with an error of about 1.5 cm, which is much smaller

than the wavelength. When the flow is present, the error of the estimated positions of the monopoles increases. The error of the estimated position of the dipole is then 5.5 cm, i.e. of the order of the sound wavelength; it is then concluded that the error increases when a flow is present.

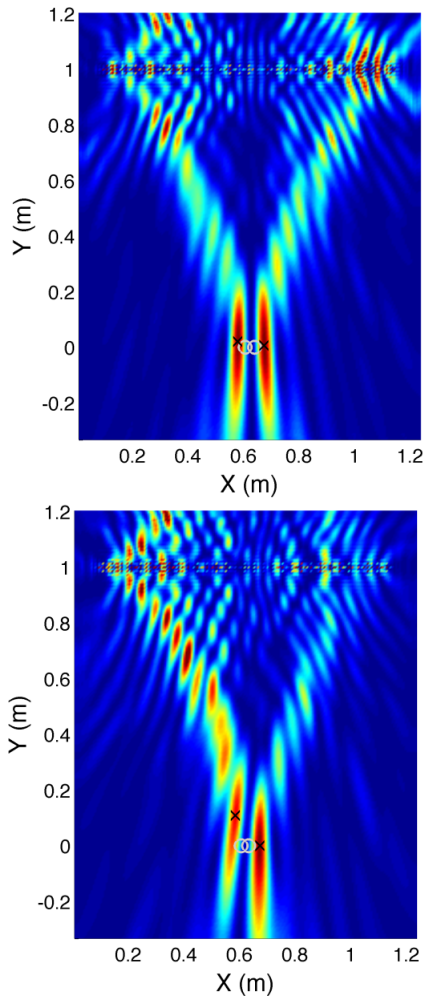


Figure 7: TR energy distribution for a dipolar source at frequency 5 kHz. The input data of the simulation are experimental. Top:  $\mathcal{M} = 0$ ; bottom:  $\mathcal{M} = 0.5$ . The shear layer is at  $X=0.46$  m. The crosses and circles indicate, respectively, the estimated and the real positions of the two sources generating the dipolar radiation.

Whereas the two monopoles can be clearly detected from the graphs of Figure 7, it is not possible to assess if the two monopoles are radiating sound in phase, or with a  $\pi$  difference (thus generating a dipolar radiation). The answer to this question can be found by investigating the TR phase distributions presented in Figure 8. For a dipolar radiation, the phase distribution exhibits a trend that is clearly different of what it would be for a monopolar source, as presented earlier in Figure 5. While for the monopolar case the phase isolines depict some arc portions emanating from the source, the phase isolines show a clear  $\pi$  phase jump following the axis of the dipole. By investigating the TR phase distributions, it is then possible to identify the monopolar or dipolar nature of the source. In Figure 8, the effect of the flow can also be investigated: the line indicating the  $\pi$  jump of the phase undergoes a deviation to the right. This deviation is due to the effect of the flow convection: the directivity of the dipole is deviated to the right by the flow. However, the dipolar nature of the source can still be assessed by investigating this graph.

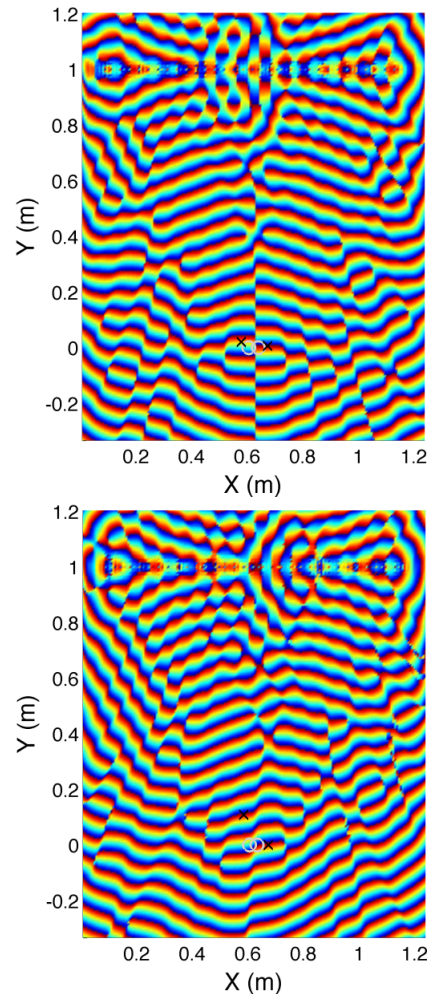


Figure 8: TR phase distribution for a dipolar source at frequency 5 kHz. The input data of the simulation are experimental. Top:  $\mathcal{M} = 0$ ; bottom:  $\mathcal{M} = 0.5$ . The shear layer is at  $X=0.46$  m. The crosses and circles indicate, respectively, the estimated and the real positions of the two sources generating the dipolar radiation.

## CONCLUSIONS

In this study, an application of the Time-Reversal method is applied to an aeroacoustic inverse problem: the localization of a sine-wave sound source in a wind-tunnel flow. Some experiments have been conducted, where monopolar and dipolar sound sources are generated in the flow. The radiated acoustic pressure waves are measured by using a linear array of microphones located outside the flow. The obtained data are used as input data for a numerical tool, solving the time-reversed Linear Euler Equations.

Some simulations results show that from the numerical data, some time-reversal energy and phase distribution can be produced, that allow a total localization of the source (i.e. not only the direction of the waves can be obtained but also the distance of the source to the array). Even at substantial Mach numbers, the effects of the flow on propagation (refraction, convection) are well taken into account.

Some experimental measurements at Mach number 0.12 show that a monopolar source at 5 kHz can be satisfactorily located, with an error of the order of half-the acoustic wavelength. The characterization of a dipole in a flow is more problematic, because both phase and energy distributions must be considered to assess the dipolar nature of the source and its position. How-

ever, the dipolar nature of the source, and the effect of flow on radiation appear clearly on the data. The error in the estimation of the position of the dipole has been found to be of the order of the sound wavelength (about 7 cm). Some further investigations are required to allow a systematical assessment of a sound source directivity in a flow. The method can also be applied to wideband acoustic sources, provided that they are filtered in the operating frequency range of the array (in the present application, [3;5] kHz), and could be used as a complementary approach to beamforming analysis.

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