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Array processing for the localisation of noise sources in hot flows

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ABSTRACT

This paper investigates the problem of localizing a sound source in a heated flow using a microphone array. Applications are found in studies dealing with the identification of sound sources in hot turbulent jets, or with the sound radiation from installed turbofans. Two configurations have been investigated: a shear layer flow (wind-tunnel type) and a jet flow. In the present study acoustic data are generated using a simulation based on the Linearized Euler Equations. For heated flows, refraction by temperature gradients is superimposed with refraction by velocity gradients, and the objective of this study is to assess whether this effect is important and how it can be accounted for in different source localisation methods. For this purpose, a time-reversal-based imaging method has been compared with a beamforming-based method in which the time-delays are computed based on ray tracing. For the shear flow, the results show that for high subsonic Mach numbers and steep thermal gradients, the thermal stratification must be taken into account to ensure a satisfactory precision of localisation for both methods. However, including the gradients of velocity and temperature is less crucial for imaging sound sources in the jet flow. The results indicate also that the localisation error is lower with the beamforming and ray-tracing technique than with the time-reversal technique, the latter being more sensitive to the limited array aperture.

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1. Introduction

In the context of aeroacoustic measurements in laboratories, two configurations are often encountered: (i) the case of a uniform flow separated from the medium at rest by a shear layer, which is a situation typical of open wind-tunnel flows, that will be called shear layer flow in the rest of the paper; (ii) the case of a free turbulent jet. In both cases, one classical issue is to describe the aeroacoustic sources, particularly in terms of spatial distribution and level, by using an array of microphones. The specificity of this problem is that the array of microphones used to record the noise is installed outside the flow. Consequently, before reaching each transducer, the acoustic waves undergo some convection and refraction effects induced by the flow profile. That is why ideally, for warranting reliable results, any phased-array method must include a propagation model that takes into account the spatial variations of the medium characteristics, such as the mean flow velocity [1], but also, if the flow is anisothermal, its temperature and density.

For the case of shear flows, Amiet [2] suggests a simplified analytical model to geometrically assess the refraction effects when the acoustic waves cross the the shear layer. In aeroacoustic studies, such a model is generally integrated to

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the beamforming technique [1], for calculating the propagation times in the propagation model. It has been validated both numerically [3] and experimentally [4] in the cases of bi-dimensional (aerofoil) and tri-dimensional (landing gear) shear flows. The Amiet model is limited to the simple case of an infinitely thin shear layer, and not applicable to turbulent jet flows. A more sophisticated (but more expensive computationally) approach consists in calculating the time delays required for beamforming by using a ray-tracing model [1]; the advantage of such an approach is that the ray-tracing estimation is much more flexible as it can deal with any arbitrary flow profile, although it is limited by a high-frequency approximation, *ie.*, the acoustic wavelength is smaller than the inhomogeneities variation scales in the flows.

Acoustic sources in flows can also be located by using an imaging technique based on the time-reversal (TR) principle. Such a technique has been extensively developed since the late eighties for a medium at rest [5,6], and the applicability of the technique to flows was further discussed by Roux et al. [7]. A first implementation of the TR technique to aeroacoustic applications was proposed by Deneuve et al. [8,9], based on numerical aeroacoustic data. The application of the TR principle to experimental data followed in 2012 [10]. Further developments and aeroacoustic applications were then proposed following those works [11–17]. In this paper, a localisation method based on the TR principle is used, based on the initial works of Padois et al. [10]. The radiated field is first measured with an array of microphones, either experimentally or by using simulated data. In a second step, a numerical code is used to simulate a TR process. For this purpose, the stored signals are played backward by each element of the array; the produced waves create a beam that focuses on the position of the initial source, which is commonly called *back-propagation* or *sound focusing*. Using this process, it is possible to reconstruct the acoustic field of the source and to use it for the localisation. One of the most important benefits of a numerical TR-based method for localizing sources in flows is the exact implementation of the refraction effects due to the gradients of velocity, and possibly those of temperature induced by the flow. A TR-based method is then applicable to any kind of shear flow, including jet flows.

This paper investigates how a classical source imaging technique, the beamforming technique, and one relatively more recent technique, based on the TR principle, can be used for localizing sources in heated flows. Relevant applications are found in studies dealing with the identification of sound sources in hot turbulent jets, or with the sound radiation from installed turbofans; this last case correspond to a heated shear flow. To our knowledge, no report is available on studying the possible implication of temperature effect on phased array results. Indeed, for example, sound sources in jets are typically carried out with no specific models for waves propagation through the jet flow (*eg.*, [18]), and studies dealing with phased-array measurements in the case of hot jets do not report any attempt of taking into account temperature effects in the used propagation model [19].

Following those observations, two objectives justify the fully numerical study presented in this paper. The first one is to assess the ability of two array-processing methods: (i) the beamforming technique associated to a ray-tracing code, and (ii) the TR-based numerical method, to locate a harmonic point source in a non–homogeneous medium including gradients of velocity and temperature. The other objective is to discuss the usefulness of including the temperature gradients into the model of the medium; two distinct types of flows are considered, the shear layer flow and the jet flow. In Section 2, the numerical method used to generate the acoustic data and both array processing methods are described. In Section 3, the generated acoustic fields are investigated in terms of flow and temperature effects, in order to allow a better understanding of the array processing results, which are presented in Section 4. The cases of the shear layer flow and jet flow are analysed separately, and some conclusions are drawn about the benefits of the inclusion of temperature and velocity effects in the sound propagation model for each inverse method. Finally, some concluding remarks are provided at the end of this paper.

2. Methodology

2.1. Numerical data generation

The inverse problem considered in the following is the localisation of a harmonic point source in a flow based on the time histories of the acoustic pressure at several points, which are recorded by a linear array of sensors. In the present study these input data are generated numerically. The two-dimensional simulation of acoustic waves propagation is performed through the resolution of the Linearized Euler Equations (LEE) in the space–time domain [20,21,10].

A harmonic point-like source emitting at $f_0 = 5$kHz, whose time evolution is proportional to $\sin(2\pi f_0 t)$, is placed at the origin of a bi-dimensional computational domain of dimensions $L_x \times L_y = 1.29$ m $\times$ 2.18 m. The linear array where the acoustic pressure is recorded has a fixed length of $L = 15\lambda_\infty$ and is placed at a fixed distance of R from the point source (Fig. 1(a)), where λ_∞ is the acoustic wavelength in the medium at rest in standard conditions of temperature and pressure. Subsequently, $R = 15\lambda_\infty$ for the shear layer and $R = 14\lambda_\infty$ for the jet. The propagation medium is animated by a parallel and stationary mean flow. In this study, we consider two different models of parallel flows: a shear layer flow (wind-tunnel-type) and a Gaussian-profile flow (jet-type). In both cases, the maximum velocity is denoted by u_f ("f" stands for "flow"). The shear layer flow is defined by a transverse profile of the velocity $u_0(y)$ [3]:

$$u_0(y) = \frac{u_f}{2}\left(1 - \tanh\left[\frac{2(y - y_s)}{b_s}\right]\right), \tag{1}$$

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