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A correction method for acoustic source localisation in convex shear layer geometries

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ABSTRACT

In this paper, a new method is presented to correct for the distortions in beamforming maps caused by wind-tunnel shear layers during aeroacoustic testing. The shear layer correction method can be used for any convex shear layer shape including circles, ellipses, triangles, rectangles, octagons and squares. After deriving the methodology and proving its equivalence to one-dimensional methods, the shear layer correction method is used to correct the beamforming maps obtained experimentally from an airfoil placed in the potential core of a circular jet. The results show that the method can successfully remove the distorting effects of the shear layer on the airfoil trailing edge source distribution. Thus a new method is available to researchers to correct for the effects of shear layers in three-dimensions, which may also be extended to three-dimensional beamforming.

1. Introduction

Acoustic measurements in open-jet anechoic wind tunnels are often performed with the microphones located outside of the flow and in a quiescent environment within the surrounding anechoic room [1]. This means that ray paths describing acoustic propagation exiting the potential core of the jet will cross a shear layer before reaching the microphone. The shear layer is defined as the layer of fluid between the potential core and the stagnant flow where a velocity gradient exists in the direction normal to the mean flow direction [2]. Consequently, the ray paths will be refracted during their path toward the microphone, changing the propagation time of the ray from what it would have been, had the entire domain consisted of stagnant air. This is an important effect to model when considering acoustic source localisation with a phased microphone array. Phased arrays utilise the expected differences in propagation time between array microphones to phase shift each signal the appropriate amount and accurately localise an acoustic source [3]. Therefore, in the presence of a shear layer, time delays based on a simple straight-line source-to-receiver model will cause erroneous source localisation results and must be corrected.

Currently, there are several practical methods to correct for shear layer refraction in aeroacoustic beamforming. The most straightforward, is a simple shift of the entire source map upstream by a distance $x_s = Mh$, where M is the Mach number of the potential core of the flow and h is the distance from the source to the shear layer, see [4]. This method is a simple approximation based on the convected wave equation. It is only valid for propagation perpendicular to the flow and does not take into account refraction due to flow speed gradients. The method has however, been shown to work sufficiently well in practice for planar microphone arrays with low Mach number shear layers [5] (up to a Mach number of 0.4).

Another well-established approach is the geometrical acoustics approximation [6], where sound propagation and refraction in an open jet wind tunnel are calculated geometrically. However, this method is restricted to short wavelengths, and certain diffraction phenomena are not accounted for. The most commonly employed method to correct for both the position as well as for amplitude of the source is the vortex sheet method of Amiet [7]. This method involves analytically solving for the change in propagation time due to the acoustic waves convecting and refracting through the shear layer. The shear layer is assumed to be an infinitely thin boundary (a line) that separates two media; one medium where there is a mean flow and one where there is no flow. The method is mathematically simple, but implicit for source-receiver locations, so iterative schemes must be employed to solve for the propagation time. As mentioned, the method is strictly only suitable for a two-dimensional case, where the microphone and the source lie in the same plane. Later, Amiet [8] extended the methodology for out-of-plane source/microphone combinations (although it still has the restriction of a planar shear layer shape), the explicit formulation for which is presented in Bahr et al. [9]. The amplitude correction used in

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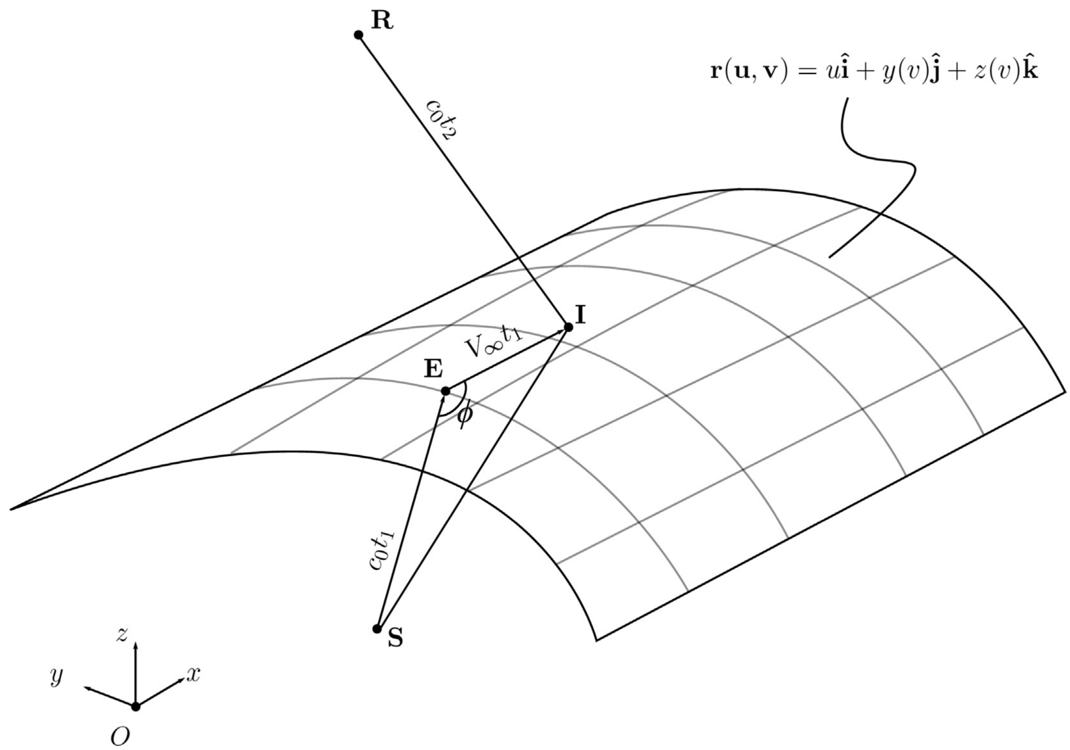

Fig. 1. Possible path of a ray travelling from source location **S** to receiver **R**. The rays will be propagated by the mean flow so that the ray intersects the shear layer at **I**.

Amiet's model, which is based on the work of Ribner [10], consists of the calculation of the sound intensity loss when the incident sound waves are transmitted through the shear layer. Amiet's method was verified by a detailed experimental investigation performed by Schlinker and Amiet [11] in an open jet wind tunnel. Besides the effect of refraction at the shear layer, the experiments also focused on the effect of shear layer turbulence scattering on a discrete tone. The observed attenuation of the amplitude and a broadening of the tone were found to be especially strong at angles close to the axis of the open jet. More recently, Bahr et al. [12] described a modification to Amiet's method to allow for a quasi 3D shear layer (a rectangle). A method that gives similar results to Amiet's method regarding the localisation effects is the approach proposed by Tester and Morfey [13] (also referred to in [14,15]), which was later confirmed experimentally by Ahuja et al. [16].

A third method is to numerically integrate the ray path through the assumed (or measured) velocity field to calculate the propagation time. The differential equations that are integrated are known as the 'ray tracing equations' [17] and come as a direct consequence of an Euler-Lagrange minimisation of the emission time (Fermat's Principle). While this method can theoretically account for any shear layer shape and is more accurate than the aforementioned methods, it is extremely computationally expensive and not practical when a large scanning grid is used. A current correction method utilizes ray tracing combined with an interpolation technique, which makes it considerably faster than traditional methods [18]. However, the method requires an explicit expression of the velocity and the velocity gradients in the jet, which may not always be available in practical situations.

Recently, several articles [19,20] have been published on extending source localisation into the third-dimension and it now appears practical to do so using non-planar arrays arranged around an open-jet. However, with the exception of ray tracing (and possibly the modified Amiet method of Bahr et al. [12]), the shear layer correction methods described above are exclusively for 2D (planar) shear layers, and are therefore not suitable for beamforming over a three-dimensional scanning grid.

Additionally, there are several instances where shear layer refraction effects cannot be accounted for accurately using Amiet's method, even when using a planar array to beamform a 2D scanning grid. This situation would occur when the shape of the open jet is not planar but curved such as a circular jet nozzle (as in the work of Geyer et al. [21]) or an octagonal jet. Morfey and Joseph [22] have developed an analytical method to calculate the ray propagation times for the specific case of off-axis sources inside a circular jet. The method, however, does not provide an explicit solution and is not suitable for other jet exit profiles, such as rectangles or ellipses.

Having provided an overview of the most popular shear layer correction schemes, it is apparent that the current methods available are either restricted to only 2D planar shear layers (Amiet's solution), are too specific (Morfey and Joseph's solution), or too computationally expensive (ray tracing, computational aeroacoustics methods). There is thus a requirement for the development of a computationally inexpensive method to solve the shear layer refraction problem for a variety of shear layer shapes for use in beamforming. In this paper, a new shear layer correction scheme is proposed as a potential solution. The scheme can be applied to any convex shear layer profile (where the cross-section of the shear layer is a convex shape) including circles, ellipses, triangles, rectangles, octagons and squares, thus making it suitable for beamforming over a three-dimensional scanning grid.

2. The shear layer correction scheme

The Shear Layer Correction Scheme (here in denoted SLCS) is inspired by the emission time calculation method presented by Koop et al. [23]. In this paper, the emission time of a ray from a source to a receiver through a planar shear layer is calculated as a one-dimensional time minimisation problem. Here, we extended the analysis to three-dimensions.

Consider a point source located at position $\mathbf{S} = (x_s, y_s, z_s)$ that lies in a uniform flow travelling in the x-direction (Fig. 1). The flow is bounded by a surface $\mathbf{r}$ that is convex in the y–z plane. The shear flow is parallel to this boundary. Outside of surface $\mathbf{r}$, the flow is quiescent ($V_\infty = 0$).