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Enhanced focal-resolution of dipole sources using aeroacoustic time-reversal in a wind tunnel

A. Mimani [a,*], D.J. Moreau [b], Z. Prime [b], C.J. Doolan [b]

[a] School of Mechanical Engineering, The University of Adelaide, South Australia 5005, Australia
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, New South Wales 2052, Australia

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ABSTRACT

This paper presents the first application of the Point-Time-Reversal-Sponge-Layer (PTRSL) damping technique to enhance the focal-resolution of *experimental flow-induced* dipole sources obtained using the Time-Reversal (TR) source localization method. Experiments were conducted in an Anechoic Wind Tunnel for the case of a full-span cylinder located in a low Mach number cross-flow. The far-field acoustic pressure sampled using two line arrays of microphones located above and below the cylinder exhibited a dominant Aeolian tone. The aeroacoustic TR simulations were implemented using the time-reversed signals whereby the source map revealed the lift-dipole nature at the Aeolian tone frequency. A PTRSL (centred at the predicted dipole location) was shown to reduce the size of dipole focal spots to 7/20th of a wavelength as compared to one wavelength without its use, thereby dramatically enhancing the focal-resolution of the TR technique.

1. Introduction

Acoustic Time-Reversal (TR) is a robust method used to accurately localize noise sources due to its ability to refocus waves exactly at the source location by back-propagating them along the same trajectory created during their emission [1]. Rosny and Fink [2] note that during TR, converging and diverging wave-fronts (formed due to energy-conservation [3,4]) interfere locally in the source vicinity. This interference leads to the breakdown of TR symmetry and, as a result, the size of the focal spot (the source location) is at least a half-wavelength (referred to as the diffraction limit), even if the source is point-like, thereby limiting the TR resolution [2]. Techniques to obtain a focal spot size significantly smaller than the half-wavelength limit [2] are subject matter of several investigations [2,5–14] and is often referred to as super-resolution of sources [6,12–14] or sub-wavelength TR focusing [5,9,11].

Rosny and Fink [2] reported the first experimental demonstration of super-resolution by implementing a time-reversed source (*acoustic sink*) during TR on a reverberant glass-plate cavity system using an ultrasonic pulse, i.e., a transient signal. The implementation of a sink at the predicted initial location of pulse (obtained from first-TR step) generated outgoing waves that are nearly equal in amplitude but opposite in sign to the diverging waves formed near the source; these wave fronts undergo destructive interference. Therefore, in effect, the sink absorbs the progressive wave-fronts converging at the source from all directions and produces a highly reduced focal spot due to the generation and reinforcement of near-field

* Corresponding author.
E-mail addresses: akhilesh.mimani@adelaide.edu.au (A. Mimani), d.moreau@unsw.edu.au (D.J. Moreau), z.prime@unsw.edu.au (Z. Prime), c.doolan@unsw.edu.au (C.J. Doolan).

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evanescent waves. The new 'super-resolved' focal spot is of considerably larger amplitude and diminished size; less than $\lambda/14$, λ being the source-wavelength, thereby demonstrating a dramatic improvement in focal-resolution.

The implementation of a sink has been shown to overcome the half-wavelength diffraction limit for an impulsive source [2,5,6]. However, its implementation for enhancing the focal-resolution of aeroacoustic sources of a *time-harmonic* nature [3,4,7,8], requires an accurate *a-priori* estimate of the source characteristics (monopole or multipole nature), its strength (volume-source strength Q_0 for an idealized monopole source or amplitude F_D of the fluctuating point force for an idealized dipole source, see Refs. [4,7,8]) and its phase. The direct determination of strength/phase is impossible because the TR simulation numerically solves the homogenous governing equations [3,4,7,8,15,16], rather, only the location/characteristics of source can be predicted from the first-TR step. In light of these challenges, the authors have developed a fundamentally new and alternate approach that does not rely on cancellation using a time-reversed source; rather, the technique employs a passive radial damping approach termed as the Point-Time-Reversal-Sponge-Layer (PTRSL) that mimics a sink to enhance the focal-resolution of *idealized monopole/dipole* sources, either of a *tonal or broadband* nature located in different mean flow fields using aeroacoustic TR [7,8]. It is noted that the PTRSL was centred at the predicted source location and also accounted for the monopole/dipole nature of the source (obtained from first-TR step); therefore, in effect, the PTRSL enhanced the TR source map in vicinity of the predicted location [2,5] of idealized aeroacoustic sources. In particular, it was shown that PTRSL reduces the size of focal spots of a dipole to 0.3λ as compared to 0.6λ without its implementation and almost completely suppresses the side-lobes. Their TR simulations [7,8], however, used *numerical or simulated data* recorded during forward simulation at two Line Arrays (LAs) of nodes located on opposite sides of idealized sources. Despite the promising improvements in the TR source map possible by using PTRSL, it has not yet been applied to *experimental* aeroacoustic problems of practical importance [17–24]. In fact, application of TR in experimental aeroacoustics has received only limited attention [3] and certainly, this method has not yet been applied to characterize the source nature of flow-induced noise using experimental data.

This paper therefore presents, for the first time, an application of aeroacoustic TR source localization method to investigate its suitability for characterizing the source nature of experimental flow-induced noise generated by a 2-D cylinder located in a wind tunnel providing a uniform cross-flow and subsequently, demonstrate the effectiveness of the numerical PTRSL damping technique to enhance the focal-resolution of experimental flow-induced noise sources.

2. Experimental set-up and test-model

Experiments were conducted in the Anechoic Wind Tunnel (AWT) at the University of Adelaide. The AWT is nearly cubic having internal dimensions 1.4 m × 1.4 m × 1.6 m and its walls are acoustically treated with foam wedges providing a near reflection-free environment above 250 Hz. It contains a contraction-outlet of rectangular cross-section of height $h = 75$ mm and width $w = 275$ mm that produces a quiet, uniform test-flow. The maximum free-stream velocity of the jet and turbulence intensity at the contraction-outlet is $U_\infty \approx 40\ \mathrm{m\ s^{-1}}$ and 0.33%, respectively [21–24].

The test-model, a full-span circular cylinder (of diameter $D_0 = 4$ mm) is secured between two side-plates attached to the contraction-outlet flange as indicated in Fig. 1(a) and (b), which shows the photograph and a schematic of the front-view, respectively, of the experimental set-up. It is noted that end-effects are reduced because the cylinder-span $l = 450$ mm along the z (span-wise) direction is sufficiently beyond the width of contraction-outlet [22]. A schematic of the side-view of the experimental set-up and the co-ordinate system convention is shown in Fig. 1(c) where x is the *stream-wise* direction and y is the *vertical* direction. The origin ($x = y = 0$) is taken on the axis of the contraction-outlet at its opening and the cylinder is located downstream at $x = 50$mm, $y = 0$.

In this work, a set of experiments were carried out at $U_\infty = \{32,\ 24,\ 16\}\ \mathrm{m\,s^{-1}}$ with the flow issuing out from the contraction-outlet towards the positive x direction as indicated in Fig. 1(c).

3. Measuring and analyzing the far-field acoustic spectra

Acoustic measurements were taken with two LAs of microphones aligned parallel to the flow and located 700 mm apart, on opposite sides and equidistant from the cylinder, i.e., at $y = \pm L_y = \pm 350$ mm and are co-planar (located in the $z = 0$ plane) as shown in Fig. 1(a) and (c). Each LA consists of 32 GRAS 40 PH 1/4″ phase-matched microphones (mounted in a timber-frame) positioned such that the spacing between two consecutive microphones is 30 mm, therefore, the total array length equals 930 mm. The length of each LA measured upstream from the contraction-outlet (with four microphones located upstream) is given by $L_{x1} = 96$ mm whilst that measured downstream denoted by $L_{x2} = 834$ mm. Each of the 64 microphones were connected to a National Instruments PXI-8106 data acquisition system containing 4 PXI-4496 simultaneous sample and hold Analogue-to-Digital Converter cards. The data (acoustic pressure time-history) at the microphones are recorded at sampling frequency $f_s = 65536$ Hz for a sample time of 10 s.

When a cylinder is immersed in uniform flow, vortices of alternate rotation are shed from either side of the cylinder into its wake [18]. This periodic shedding, known as a von Karman vortex street, occurs at a particular frequency, f_a, represented in a non-dimensional form by the Strouhal number $St_{D_0} = f_a D_0 / U_\infty$, based on D_0. The von Karman vortex street generates unsteady forces on the surface of the cylinder that support dipole sound sources known as the Aeolian tone [17,25]. Fig. 2