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A comparison of time-reversal and cross-spectral beamforming for localizing experimental rod-airfoil interaction noise sources

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ABSTRACT

This paper compares the results of different implementation methods of Time-Reversal (TR) and Conventional Beamforming (CB) array processing techniques for localizing experimental flow-induced rod-airfoil interaction noise sources. Experiments were conducted in an anechoic wind tunnel for low Mach number cross-flow whereby the far-field acoustic pressure was recorded using two line arrays (LAs) of microphones located above and below the rod-airfoil test-model for a range of flow speeds. TR simulations were carried out for the highest flow speed considered, without and with the rigid-wall modeling of the scattering surfaces which include the experimental facility and the airfoil. The predicted location, resolution and strength of the flow-induced dipole source was noted across different frequency bands wherein it was observed that modeling the airfoil during TR simulation helps to identify location of the scattered field source and simultaneously improves resolution. A Dipole phase-correction method for TR is presented (wherein the scattering surfaces are not modeled) which yields a single focal spot, thereby unambiguously localizing the dipole source. However, the predicted source location and focal-resolution in the Dipole phase-correction TR maps were found to be nearly the same as that obtained by TR without phase-correction and without scatterer modeling. It was shown that the CB maps based on monopole/dipole steering vector formulations were highly comparable to their counterpart TR maps in terms of source characteristics, predicted location, strength and focal-resolution. This demonstrates the equivalence of the TR and CB methods for aeroacoustic source localization when the experimental facility and airfoil were not modeled during TR simulations. Additionally, the Point-Time-Reversal-Sponge-Layer (PTRSL) damping and the deconvolution CLEAN-SC techniques used for enhancing the resolution of TR and dipole CB source maps, respectively, were compared. It was shown that while both methods were equally effective in suppressing side-lobes, the former produced a commensurate reduction in focal spot size whilst the latter yields a nearly constant focal spot size across the frequency bands. Moreover, the simultaneous use of the PTRSL damping and scatterer (in particular, the airfoil) modeling during TR not only yields a further enhanced resolution but also improves the accuracy of the scattered field source location in the low-frequency range.

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1. Introduction

In aeroacoustics testing, it is important to localize sources and quantify their strength [1,2]. Microphone phased-array processing techniques such as beamforming are popular as they are ideally suited for use inside wind tunnels and can yield important information on aeroacoustic source location [3]. Such knowledge provides an understanding of the underlying flow-induced noise generation mechanisms essential for reducing noise emissions. In delay-and-sum beamforming (DSB) operating in the time-domain [2,4,5], the acoustic pressure data recorded at the microphones are delayed and summed coherently to enhance the signal from a desired focal position while minimizing the signal from out-of-focus locations. The array response is a maximum when the focal position coincides with the source location. Therefore, the source location can be determined by scanning over a grid of focal points referred to as the scanning grid. A computationally efficient variant of the DSB is the cross-spectral conventional beamforming (CB) that operates in the frequency-domain [2,6–8]. It often assumes monopole source propagation characteristics to compute the response from the array to the focusing point. The CB method has been very widely used in experimental aeroacoustic source localization problems including airfoil self-noise [3], aircraft fly-over tests [9], field measurements of wind turbine noise [10]. Recently, the CB method has been used to localize a loudspeaker source in a reverberant test-section (hard-wall wind-tunnel) [11].

The classical acoustic Time-Reversal (TR) method, originally proposed by Fink et al. [12], is an equally promising array processing technique. The underlying principle of TR is: if the acoustic field is known as a function of time on a set of boundary nodes surrounding a region (containing the source), then it can also be computed at every point inside the region at previous times by enforcing the time-reversed boundary data during a numerical retro-solution of the wave equation. TR has been used in diverse engineering fields, some of them being ultrasonic medical imaging [12], long-range communication in deep underwater acoustics [13] and structural health monitoring [12,14]. Givoli [15] presented an excellent review of the use of TR as a computational tool for different engineering applications involving acoustic and elastodynamic wave propagation.

The application of TR for localizing sources in experimental aeroacoustics [4,16–20] and computational aeroacoustics [21–23] is gaining popularity. In particular, there has been a considerable interest towards comparing the performance of the TR and CB methods [4,17–19,24]. Rakotoarisoa et al. [4] and Wei et al. [19] present an analytical implementation of TR method which is based on reconstructing the response signal at a focusing point as the sum of the convolution product of the assumed 3-D free-space impulse response function with the time-reversed array signal. In both papers, it was shown that the analytical TR implementation is mathematically equivalent to the time-domain DSB and thus, analytical TR and time-domain DSB would yield identical source maps. In Ref. [4], it is noted that the analytical TR method is computationally efficient and is inherently stable. However, it relies on prior knowledge of an appropriate Green's function (impulse response) that can accurately model wave propagation from a focusing point to the microphone in the array. In situations such as the presence of non-uniform mean flow profile and density gradient causing refraction, presence of rigid wall sections inducing wave reflections and scattering objects such as the test-model and experimental facility, a Green's function which can model the complex wave paths may not exist. For this reason, most previous studies have used the straightforward 3-D free-space Green's function to compute the steering vectors required during CB for localizing aeroacoustic sources [7,8,25,26].

A more rigorous and exact TR implementation for localizing aeroacoustic sources is to numerically solve the Linearized Euler Equations (LEE) wherein the time-reversed acoustic pressure data is enforced at boundary nodes that initiate back-propagation and convergence of waves at the source location [4,16–18,21,23,27–30]. This method is termed as numerical TR by Rakotoarisoa et al. [4] wherein it was shown that both numerical and analytical TR implementations yield comparable results for detecting intermittent aeroacoustic sources around a 3-D bluff body in flow. It is important to note here that in previous studies by Mimani et al. [16,17,27–30], a numerical TR implementation was carried out by solving LEE over a 2-D domain and the same approach is considered in the present work which is henceforth, referred simply as TR. The numerical TR computes the spatio-temporal evolution of the acoustic fields without presuming the source-type because it does not rely on assumption of Green's function for back-propagation unlike the cross-spectral CB or time-domain DSB methods. Furthermore, the TR method can readily model the experimental non-uniform flow profile and rigid-wall conditions [29]. This signifies that the TR method can analyze the impact of modeling the experiment facility [17] and in principle, the test-geometry itself on source localization and focal-resolution. Through the use of a radial flux damping technique, TR can also yield super-resolution of sources [16,31]. Previous simulation-based analysis have demonstrated the equivalence of TR and cross-spectral CB methods for localizing idealized sources in a non-uniform flow field in a free-space [18,27] and in the presence of a rigid boundary [29]. Padois et al. [18], however, further demonstrated that using acoustic pressure data measured over a linear array of microphones, TR can accurately localize loudspeaker source(s) in a non-uniform flow in a wind-tunnel. It is however, important to note that a loudspeaker in flow is essentially a simulated-experimental aeroacoustics test-case because noise is generated even in the absence of flow.

Mimani et al. [17] presented the first comparison of the TR and CB methods for an actual flow-induced noise problem of a cylinder (rod) in low Mach number cross-flow. A cylinder in flow sheds periodic counter-rotating vortices (von Karman street) from either side into its wake [32–34]. The vortex shedding occurs at a particular frequency referred to as the Aeolian tone and generates unsteady forces on the cylinder surface that support dipole source known as the lift-dipole [33,34]. Using two line arrays (LAs) of microphones, the TR source maps at the Aeolian tone produced two focal spots, one located above