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A plasma-based non-intrusive point source for acoustic beamforming applications

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ABSTRACT

A laser-generated plasma acoustic point source is used to directly measure the point spread function (PSF) of a microphone phased array. In beamforming analysis of microphone phased array data, the true acoustic field is convolved with the array's PSF. By directly measuring the PSF, corrections to the array analysis can be computed and applied. The acoustic source is measured in an open-jet aeroacoustic facility to evaluate the effects of sampling rate, microphone installation, source shift, reflections, shear layer refraction and model presence. Results show that measurements exhibit behavior consistent with theory with regard to source shift and shear layer refraction. Application of a measured PSF in beamforming analysis shows that the process provides an effective in situ method for array calibration both with and without flow and allows for corrections to incorporate reflections and scattering. The technique improves the agreement of beamforming results with the true spectrum of a known source, especially in the presence of reflections.

1. Introduction

In aeroacoustic wind tunnel testing, phased microphone arrays have become common instrumentation. Phased array techniques apply an acoustic field model to data measured with multiple microphones and generate a map of estimates of source locations and strengths [1]. Unfortunately, the conventional beamformer output, using the delay-and-sum technique in the time domain or an equivalent in the frequency domain, is convolved with the array's point spread function [2]. This point spread function (PSF) arises due to the array's finite aperture and finite sample locations [2], and is a representation of the array's output response to an ideal point source at a given location in space. The PSF is a function of frequency and, except for the special case of a plane wave source model, varies for every potential combination of source location and array position even for a simple free-space measurement [3].

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Multiple methods have been formulated to remove the effects of the PSF from a beamformer output, or beam map. A non-exhaustive list of frequency-domain methods includes DAMAS [4], DAMAS2 [3], FFT-NNLS [5], CLEAN-SC [6], CMF [7], LORE [8] and MACS [9]. DAMAS, CMF, LORE and MACS formulate the deconvolution problem as the non-negative constrained solution to a large linear system of equations. These methods allow for a variable PSF, but may be computationally intensive depending on the problem of interest. DAMAS2 and a component of FFT-NNLS treat the deconvolution problem as an image processing technique and attempt to iteratively remove the effects of the PSF in the spatial Fourier domain, similar to the Wiener Filter [3]. Strictly speaking, these two methods require that the PSF be a function of only the separation of the source position and scan position, or shift-invariant, rather than a function of both positions independently. However, the methods can be modified to allow for some flexibility in this restriction [5,10]. CLEAN-SC is the only method of those listed above which does not use a priori knowledge of the PSF, instead iteratively modifying the beam map to remove estimates of the PSF based on potential source locations (and having alternate limitations in application) [11]. This differs from the original CLEAN algorithm, which requires the PSF prior to processing.

For all of these methods except CLEAN-SC, an ideal PSF based on the array design is generally used. Array calibration techniques can be used to account for real installation effects such as microphone position errors [2]. These techniques can correct the steering vectors used in conventional beamforming. Corrections for shear layers when conducting experiments in open-jet wind tunnels [12] are also applied using the conventional steering vectors. As originally formulated, these methods do not directly account for real installation effects such as reflections and scattering, which alter the appropriate Helmholtz equation solution and thus the acoustic model which should be used when beamforming.

The PSF is generally treated as the array's response function to a point source input, often observed in the frequency domain [3]. It can also be considered as the array's observation of the response function of a test setup [13] for a particular source location, similar to a single observation of the installation's Green's function. In this sense, the theoretical free-field PSF may fall short of truly characterizing the observed array response for a point source. Due to the computational complexity of determining the point source response of a real test setup for all frequencies of interest, experiments currently provide the most promising route for evaluating the installation PSF, especially for high frequencies.

Some previous research has been conducted regarding experimental analysis of PSFs. PSF analysis and deconvolution have a long history in the fields of optics and radio astronomy [3]. Dougherty's work on group calibration can be considered an approximate measurement of a free-space Green's function [2]. Dougherty also discussed the effects of acoustically reflective walls on phased array output for a given facility. Oerlemans and Sijtsma experimentally studied the effect of sidewalls in an open-jet wind tunnel on phased array output [14]. Fenech and Takeda measured the appropriate Green's function for a facility to compare with an image source correction to the free-space Green's function [13]. Brooks et al. used an in-flow speaker source to calibrate measured array data prior to deconvolution [15]. All of these studies used intrusive acoustic sources. More recent work has incorporated acoustic sources flush-mounted into a novel aircraft model for non-intrusive point source measurements with and without flow [16].

The present study extends such a capability by utilizing a non-intrusive source that can be located anywhere within a measurement volume. Such a source can be used in circumstances where embedded speakers of desired performance characteristics cannot be installed at locations of interest in a given model or facility, or in situations where having a non-intrusive off-body source is important. The study first reviews the development of the theoretical PSF for a spherical-wave beamformer based on the assumption of an acoustic source region comprised of uncorrelated monopole sources in free space. It then describes how an experimental PSF measurement can be used in the formulation of experimental steering vectors or as a calibration correction to theoretical steering vectors. The experimental setup for measuring the response to a point source generated by a pulsed laser system is described. Source behavior is analyzed for varying experimental conditions, including sampling rate and microphone installation effects, different physical facility and model configurations as well as shear layer refraction. Finally, the output of the correction methodology is analyzed for a variety of point source configurations with and without flow, before being applied to a NACA 0012 trailing edge noise measurement.

2. Theoretical development and implementation

In phased array analysis, a microphone array like the one shown in Fig. 1a is used to sample an acoustic field in space and time. These arrays are often designed for broadband use and with non-uniform sensor spacing to mitigate spatial aliasing effects. For example, the array illustrated in Fig. 1b has a multi-arm logarithmic spiral design for all but the innermost ring. Aside from that ring, this array follows the design procedure described by Underbrink [17]. The data from the array measurement are acquired and, for conventional frequency-domain beamforming and related methods, averaged to obtain auto- and cross-spectral power estimates in the form of a cross-spectral matrix (CSM). For the entirety of this discussion, such time-harmonic analysis is assumed and frequency dependence is suppressed in most equations.

To review, for a monopole source in free space at location ℓ' the acoustic pressure field is expressed as [18]

$$y(r_{\ell'}) = A_{\ell'} \frac{1}{r_{\ell'}} e^{-\mathrm{j}kr_{\ell'}}, \tag{1}$$

where $r_{\ell'}$ is the distance from the monopole location to the observer location and $A_{\ell'}$ incorporates all non-geometric terms which determine the monopole magnitude. The imaginary unit is given as $\mathrm{j} = \sqrt{-1}$. The acoustic wavenumber is $k = 2\pi f / c_0$, where f is the narrowband frequency of interest and c_0 the isentropic speed of sound. Consider an array with S