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Effects of array scaling and advanced beamforming algorithms on the angular resolution of microphone array systems

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ABSTRACT

Several advanced beamforming methods have been developed in the past 20 years that have dramatically improved the angular resolution of microphone array systems. Meanwhile, the Rayleigh criterion has long been considered the standard criterion for angular resolution of such systems. In this investigation four microphone arrays were constructed as scaled models of a fifth microphone array. All of the arrays were subjected to a thorough regimen of testing with both broadband and narrowband sources. Using conventional beamforming, the angular resolution of each scaled array was determined as a function of frequency and compared to the Rayleigh criterion. The analysis was repeated with the advanced TIDY, DAMAS, DAMAS2, and CLEAN-SC beamforming algorithms so that the effects of array scaling and advanced beamforming can be determined as a function of frequency and compared to conventional beamforming.

1. Introduction

Microphone array systems have been in use for more than 40 years and have proven useful in a variety of applications [1]. The most traditional form of acoustic beamforming is the Delay-and-Sum (DAS) beamforming algorithm, wherein time delays are applied to the pressure signal from each sensor and the resulting signals are summed to form the beamform map [2]. However, the angular resolution of the DAS beamforming algorithm is poor. Frequency-domain beamforming (FDBF) methods were developed in the 1980s using the Fast Fourier Transform. Researchers have since developed improved frequency-domain beamforming algorithms such as CLEAN, RELAX, and SEM. Many such algorithms are based on the idea of manipulating the Cross Spectral Matrix and the concept of spatial source coherence [3–8]. More recently, beamforming algorithms have been developed based on methods of deconvolution [9,10], methods based on the spatial coherence of point sources and sidelobes in the frequency domain [11], and spatial coherence methods in the time domain [12]. These are the DAMAS, DAMAS2, CLEAN-SC, and TIDY algorithms, respectively. The current investigation will explore the concept of angular resolution utilizing two time-domain beamforming algorithms and three frequency-domain algorithms: the conventional DAS algorithm as well as the more advanced TIDY, DAMAS, DAMAS2, and CLEAN-SC beamforming algorithms.

The concept of angular resolution refers to the ability of a system to differentiate between two closely-spaced sources. A system with inadequate angular resolution will show two closely-spaced sources as a single source. The most widely-used criterion for the angular resolution of a microphone array system is the Rayleigh criterion, which indicates that angular resolution is proportional to array diameter and inversely proportional to the signal's wavelength. This criterion was originally utilized in the field of optical imaging, but is also applicable to acoustics. However, the Rayleigh criterion is a convenient reference point rather than a fixed physical limit. The Rayleigh resolution criterion defines the angular separation between two sources at the point where the maximum of the Airy disk (analogous to a diffraction pattern) of one source is located at the first minimum of the Airy disk of the second source. Using the small angle approximation, the Rayleigh criterion is given by:

$$W = \frac{rD}{\lambda z}, \tag{1}$$

where r is the separation distance between the two sources, D is the diameter of the array, λ is the wavelength of the sources and z is the separation distance between the source and the array [13]. The Rayleigh criterion W is given by the first zero of the first-order Bessel function of the first kind, divided by a factor of pi to convert into radians. This results in a value of W = 1.22 for a circular, continuous

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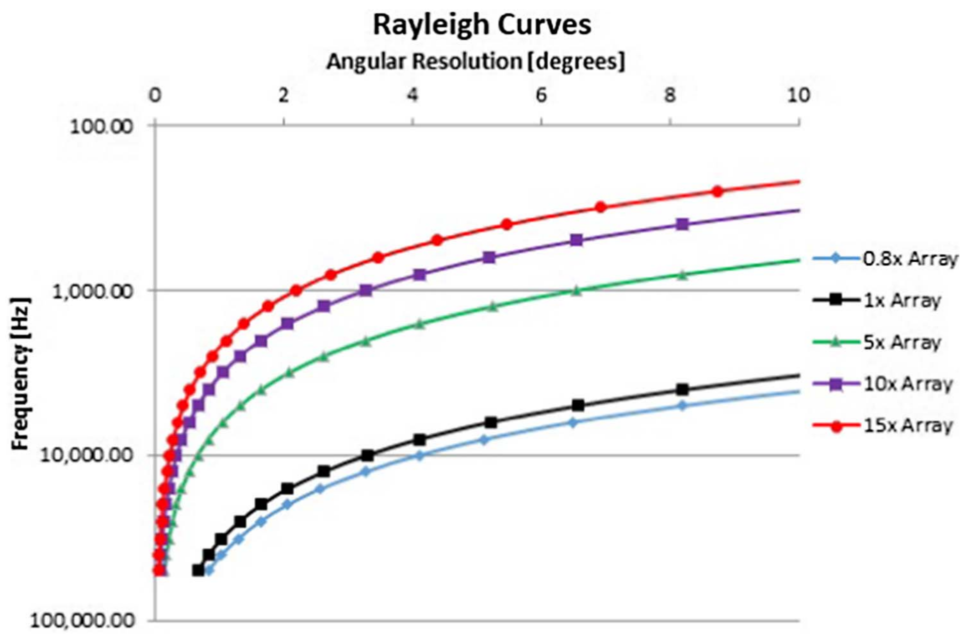

Fig. 1. Expected angular resolution based on Rayleigh criterion for each of the five microphone arrays.

Fig. 2. OptiNav compact microphone array and data acquisition chassis.

Fig. 3. Completed 0.8× Array.

aperture. Re-arranging Eq. (1) to show the minimum resolvable separation angle explicitly gives:

$$\theta = W\frac{\lambda}{D}. \tag{2}$$

Although a great deal of understanding can be gained from mathematical analysis, the effects of array scaling on angular resolution have not been clearly demonstrated in practice. A deeper understanding of the effects of array geometry and advanced beamforming algorithms can be gained by performing carefully controlled experiments. The purpose of this work is to experimentally determine the angular resolution of microphone arrays as the array size is scaled to larger and smaller dimensions, and to explore the effect of five beamforming algorithms on the angular resolution of the array. To accomplish this, four microphone arrays were constructed as scaled models of a fifth commercially-available baseline array. A battery of tests was then performed on each of the five arrays using the DAS, TIDY, DAMAS, DAMAS2, and CLEAN-SC algorithms, and the results were analyzed and compared. In this way the effect of array scaling and the effect of the advanced beamforming algorithms can be determined as a function of frequency and compared to conventional DAS beamforming.

For the experiments carried out in the following sections, the baseline microphone array has a diameter of 0.73 m and is hereafter referred to as the "1 × " array. An 80% scale model of this array, called the "0.8 × " array was constructed with a diameter of 0.59 m. Scaled-up versions of the baseline array were constructed with diameters that are