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Resolution and quantification accuracy enhancement of functional delay and sum beamforming for three-dimensional acoustic source identification with solid spherical arrays

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ABSTRACT

Functional delay and sum (FDAS) is a novel beamforming algorithm introduced for the three-dimensional (3D) acoustic source identification with solid spherical microphone arrays. Being capable of offering significantly attenuated sidelobes with a fast speed, the algorithm promises to play an important role in interior acoustic source identification. However, it presents some intrinsic imperfections, specifically poor spatial resolution and low quantification accuracy. This paper focuses on conquering these imperfections by ridge detection (RD) and deconvolution approach for the mapping of acoustic sources (DAMAS). The suggested methods are referred to as FDAS+RD and FDAS+RD+DAMAS. Both computer simulations and experiments are utilized to validate their effects. Several interesting conclusions have emerged: (1) FDAS+RD and FDAS+RD+DAMAS both can dramatically ameliorate FDAS's spatial resolution and at the same time inherit its advantages. (2) Compared to the conventional DAMAS, FDAS+RD+DAMAS enjoys the same super spatial resolution, stronger sidelobe attenuation capability and more than two hundred times faster speed. (3) FDAS+RD+DAMAS can effectively conquer FDAS's low quantification accuracy. Whether the focus distance is equal to the distance from the source to the array center or not, it can quantify the source average pressure contribution accurately. This study will be of great significance to the accurate and quick localization and quantification of acoustic sources in cabin environments.

1. Introduction

By virtue of the ability to record panoramic sound scenes, solid spherical microphone arrays have become widely prevalent in the 3D acoustic source identification field [1–3]. Spherical harmonics beamforming (SHB) [4–8] is the commonly utilized array data processing algorithm. Regrettably, it presents some intrinsic limitations, specifically poor spatial resolution and severe sidelobe contaminations. These two factors make it difficult to interpret the resulting map and therefore to visualize the actual sound field accurately. To alleviate these limitations, Filter-And-Sum [9] and deconvolution [10] have been particularly developed in recent years. The former can attenuate sidelobes effectively and is fast, but is incapable of ameliorating the spatial resolution. The latter performs excellently in both sidelobe attenuation and spatial resolution amelioration, but suffers from heavy computational cost. In a nutshell, these solutions are not sufficient to quickly result in a clear and unambiguous map for acoustic sources.

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Nomenclature

c	speed of sound
f	frequency
G	total number of focus points
$h_n^{(2)}$, $h_n^{(2)\prime}$	spherical Hankel function of second kind, derivative of
$\mathbf{H}$	Hessian matrix of L
j_n, $j_n^{'}$	spherical Bessel function of first kind, derivative of
k	wave number
L	object of RD
m,n	spherical harmonics degrees
N	truncated upper limit of spherical harmonics degree
p, $\mathbf{p}$, $\mathbf{C}$	sound pressure signal of microphone, vector of, matrix of cross-spectra of
psf, $\mathbf{A}$	point spread function, matrix of
P_{AC}, $\mathbf{P_{AC}}$	source average pressure contribution, vector of
ΔP_{AC}	absolute difference between the true and the reconstructed source average pressure contributions
$\Delta P_{AC}^{'}$	absolute difference between the measured and the reconstructed source average pressure contributions
q, Q	serial number of microphones, number of microphones
r_e	residual
R_n	radial functions with degree n
s, S	source strength, source strength with power sense
t_q, $\mathbf{t}$	sound field transfer function, vector of
$\mathbf{U}$	unitary matrix
v_q, $\mathbf{v}$	focusing component, vector of
W, $\mathbf{W}$	output of DAS, vector of
W_F	output of FDAS
Y_n^m	spherical harmonics with degree $n$and$m$
σ_q, $\mathbf{\Sigma}$	eigenvalues of $\mathbf{C}$, diagonal matrix of
ξ	exponent parameter
λ, $\mathbf{u}_\lambda$	largest absolute eigenvalue of $\mathbf{H}$, eigenvector corresponding to λ
ρ	a scale field used for RD
χ	a constant defining spatial precision for RD
π	circumference-to-diameter ratio
∞	positive infinity

Sets

B	including all source positions
B'	including all focus points with same directions as real sources
D	including all focus points that have completed $(l+1)$th iteration
E	including all focus points that are not in D

Coordinates

a	radius of array
r	distance to origin
$\Omega = (\theta, \phi)$	direction with θ and ϕ being elevation and azimuth angles respectively
(r, Ω)	spherical coordinate
(a, Ω_q)	coordinate of qth microphone
(r_0, Ω_0)	coordinate of source
(r_0', Ω_0')	same as (r_0, Ω_0), but independently varied
(r_f, Ω_f)	coordinate of focus point

Operators

i	square root of −1
$(\cdot)^*$	conjugation
$(\cdot)^{\mathrm{T}}$	transposition
$(\cdot)^{\mathbf{H}}$	Hermitian transpose
$(\cdot)^{(l)}$	lth iteration
$\overline{(\cdot)}$	average
$\lvert\cdot\rvert$	modulo
$\lceil\cdot\rceil$	rounding of a floating point number to the nearest integer towards infinity
$\lVert\cdot\rVert_2$	2 norm
sgn	sign function
∇	gradient
$\cdot$	inner product
$\max(\cdot)$	maximizing

Abbreviations

CSM	cross-spectral matrix
DAS	delay and sum
DAMAS	deconvolution approach for the mapping of acoustic sources
FDAS	functional delay and sum
MSL	maximum sidelobe level
RD	ridge detection
SHB	spherical harmonics beamforming

Motivated to conquer the above problem, authors of this paper have lately suggested a novel FDAS algorithm for solid spherical arrays [11] under the inspiration of the functional beamforming proposed by Dougherty for two-dimensional planar arrays [12–14]. The algorithm is well suitable for incoherent sources and promises to play an important role in interior aeroacoustics. It can offer much lower sidelobes than any other existing beamforming algorithm to the authors' knowledge with speed essentially identical to SHB or Filter-And-Sum and much faster than any deconvolution technique. Nevertheless, the algorithm is still imperfect. Its spatial resolution is not good enough to definitely resolve closely spaced sources, and its quantification deviation to the source contribution is relatively large in practical applications. If these imperfections could be overcome without sacrificing the existing advantages, it is expected that a clear and unambiguous map will be quickly achieved for acoustic sources in 3D cabin environments, which will be of great significance to the accurate and quick identification of sources. This paper focuses on addressing the issue by RD and DAMAS. RD is a widely used image analysis method in computer vision, whose primary motivation is to capture the interior of elongated objects in the image domain, like roads in aerial images and blood vessels in retinal images [15–19]. In this paper, taking FDAS's