Mechanical Systems and Signal Processing 111 (2018) 303–313

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Wideband holography based spherical equivalent source method with rigid spherical arrays

Guoli Ping [a,b], Zhigang Chu [a,b,*], Yang Yang [b,c], Zhongming Xu [a,b]

[a] The State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400044, PR China
[b] College of Automotive Engineering, Chongqing University, Chongqing 400044, PR China
[c] Faculty of Vehicle Engineering, Chongqing Industry Polytechnic College, Chongqing 401120, PR China

ARTICLE INFO

Article history:
Received 27 July 2017
Received in revised form 10 March 2018
Accepted 5 April 2018

Keywords:
Spherical equivalent source method
Near-field acoustical holography
Rigid spherical arrays
Three-dimensional acoustic source identification
Reconstruction performance

ABSTRACT

Spherical equivalent source method (S-ESM) with rigid spherical arrays is able to achieve good sound field reconstruction and acoustic source identification in three-dimensional free-field spaces. However, the S-ESM solved by the standard Tikhonov regularization is restricted to the low-frequency reconstruction and source identification at small measurement distances. To make S-ESM achieve good reconstruction and source identification at high frequencies and large hologram distances, this study proposes a sparsity-promoting approach denoted as wideband holography based S-ESM (WBH-based S-ESM), which applies a steepest descent method to iteratively solve S-ESM. Firstly, the framework of WBH-based S-ESM is established. Subsequently, to examine its validity, the performance of reconstruction and source identification is compared with Tikhonov regularization. Finally, a focus is concerned with the adaptability to large hologram distances. Several meaningful results have emerged from simulations and experiments: (1) WBH-based S-ESM can make good sound field reconstruction and acoustic source identification at medium-high frequencies. It extends the upper frequency limit of S-ESM. (2) The maximum hologram distance of WBH-based S-ESM at high frequencies is greater than that of Tikhonov regularization. It enlarges the measurement distance of S-ESM. This study will demonstrate the potential of WBH-based S-ESM as a useful tool for reconstruction and source identification.

1. Introduction

Near-field acoustical holography (NAH) technique [1–4] with microphone arrays has become widely popular in the fields of acoustic source identification and sound field reconstruction. Planar, cylindrical and spherical microphone arrays are all commonly employed in NAH [5–8]. Therein, rigid spherical arrays possess excellent features of three-dimensional (3D) symmetry and omnidirectional visualization [9,10]. They can not only simultaneously record sound fields from all directions, but also effectively realize the complete measurement and the omnibearing acoustic imaging [11]. Therefore, the spherical near-field acoustical holography (S-NAH) technique with spherical arrays [12–15] is especially suitable for sound field reconstruction in 3D spaces.

* Corresponding author at: The State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400044, PR China.
E-mail address: zgchu@cqu.edu.cn (Z. Chu).

https://doi.org/10.1016/j.ymssp.2018.04.006

The basic framework of S-NAH is to reconstruct the sound pressure [16], particle velocity [17] and sound intensity [18] via a spherical harmonics expansion. Based on the propagation of radial functions, the sound field measured by spherical arrays can be expanded into the reconstruction position in 3D spaces, so as to obtain the incident sound field [19] or the total sound field [18] containing the scattering. However, the valid domain of S-NAH is restricted to nearby spherical surfaces concentric to the array [20]. S-NAH fails to reconstruct the sound field very close to the source and the sound field of medium-high frequencies. To overcome the geometrical constraint of S-NAH and improve its reconstruction precision, Fernandez-Grande [21] proposed a spherical equivalent source method (S-ESM) based on rigid spherical arrays in 2016. The basic framework of S-ESM is that the radiated sound fields of arbitrary shape sources can be equivalent to the superposition of sound fields radiated by a series of monopole point sources near the radiation sources [22]. The strength of these equivalent sources can be estimated by the measured sound pressure on spherical arrays and a Neumann Green function. Further, the incident or total sound fields in discretionary 3D spaces can be reconstructed via a new free-field Green function or the Neumann Green function. The standard Tikhonov regularization method [23] is utilized to solve an ill-posed inverse problem in S-ESM. Compared with S-NAH, the reconstruction precision of the S-ESM solved by Tikhonov regularization is higher, and its reconstruction domain is no longer restricted to the spherical surfaces close to the array. As expected, S-ESM is also suitable for arbitrary shape sources. Nevertheless, the applicable frequency of S-ESM has not been improved. The S-ESM solved by Tikhonov regularization can merely achieve the acceptable reconstruction at low frequencies. It is obvious that the S-NAH and S-ESM algorithms with spherical arrays are limited by the Nyquist sampling theorem. To avoid the spatial aliasing, the microphone spacing must be somewhat less than half of the acoustic wavelength, which limits the upper frequency. Hence, for S-ESM, it is worthwhile achieving good reconstruction and source identification for high frequencies. This paper is motivated to address this issue.

The core of S-ESM is to solve the strength of equivalent sources from an ill-posed inverse problem. The existing S-ESM utilizes the standard Tikhonov regularization method to estimate the source strength. Although the reconstruction performance of Tikhonov regularization is good at low frequencies, the precision of high frequencies needs to be improved, due to the limitations of the Nyquist frequency and the regularization parameters [24]. To solve the ill-posed inverse problems in spherical arrays, some scholars presented sparse solution methods by the use of compressive sensing model [25–28]. Sparse recovery algorithms can improve the quality of the reconstruction. Meanwhile, Hald [29] proposed a wideband holography (WBH) algorithm based on two-dimensional (2D) planar arrays in 2016, which satisfies the reconstruction and source identification of medium–high frequencies. WBH employs a steepest descent iteration method to solve the ill-posed equation in the 2D ESM model and to promote the sparsity of source strength. More accurate source strength can be estimated, as the source distribution is sparse or close to sparse in the general case. Inspired by that, we manage to extend the WBH solution (steepest descent iteration) into the 3D S-ESM model. Main contributions include: (1) WBH-based S-ESM is proposed by a combination of the S-ESM model and the WBH solution. It is actually a kind of sparsity-promoting spherical acoustic holography algorithm. It utilizes a steepest descent method to minimize the quadratic residual function, and removes the ghost sources (sidelobes) associated with the real sources in an iterative solution process. (2) The performance of reconstruction and source identification is presented to examine its validity.

The paper is organized as follows. In Section 2, the framework of WBH-based S-ESM is established on the basis of the S-ESM model and the WBH solution. In Section 3, the performance of reconstruction and source identification for WBH-based S-ESM is discussed in detail: firstly, the reconstruction results of two/five sources of different strength are addressed; then, the adaptability to large hologram distances is examined; lastly, its limitations are explored. In Section 4, WBH-based S-ESM is examined with the experimental data measured by a 36-channel rigid spherical array in practical applications. Finally, conclusions and perspectives are drawn in Section 5.

2. Theory of WBH-based S-ESM

The basic principles of S-ESM are as follows: the radiation source in 3D free-field spaces can be equivalent to the superposition of a series of extended point sources near the radiation source, and the strength of these equivalent sources can be estimated by the measured sound pressure on spherical arrays and a Neumann Green function, then the discretionary sound field will be reconstructed via the estimated source strength. S-ESM can be viewed as an extension algorithm of the ESM model to spherical arrays. WBH-based S-ESM employs a steepest descent method to iteratively solve source strength in S-ESM. Its fundamentals are comprised of theories of the S-ESM model and the WBH solution.

2.1. S-ESM

Fig. 1(a) depicts the coordinate system of S-ESM and configurations of the source, the rigid spherical array, the equivalent sources spherical surface and the reconstruction spherical surface. The origin is located at the center of the spherical array with a radius of a. An arbitrary observation position in 3D spaces can be described by $\mathbf{r} = (r, \theta, \phi)$, where r is the distance between the origin and the observation position. θ and ϕ are the elevation angle and the azimuth angle, which represent the directions of observation positions, and are marked by $\Omega \equiv (\theta, \phi)$. The positions of the source, the equivalent sources and the reconstruction surface are at $\mathbf{r}_0 = (r_0, \Omega_0)$, $\mathbf{r}_e = (r_e, \Omega_e)$ and $\mathbf{r}_r = (r_r, \Omega_r)$, respectively.