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Reducing Number of Transfer Function Measurement in Local Sound Field Reproduction using Acoustic Modeling

Qiaoxi ZHU[1]; Xiaojun QIU[1]; Philip COLEMAN[2]; Ian BURNETT[1]

[1] Centre for Audio, Acoustics and Vibration, Faculty of Engineering and IT, University of Technology Sydney, Sydney, Australia

[2] Institute of Sound and Recording, University of Surrey, Guildford, UK

ABSTRACT

Broadband local sound field reproduction over an extended spatial region is a challenging problem when only limited transfer function measurements are available. An approach based on acoustics modeling is proposed in this paper to reduce the required number of transfer function measurements in local sound field reproduction. The proposed method only requires measuring the transfer functions from each source to a few samples over the boundary of the controlled region, and the transfer functions to the samples inside the controlled region are then estimated through efficient acoustic modelling. Simulations demonstrate that the proposed method requires fewer transfer function measurements than existing methods such as the least squares and the spatial harmonic decomposition methods.

Keywords: Sound field control, Spatial audio, Acoustic modelling

1. INTRODUCTION

Local sound field reproduction delivers a sound field within a given region of space (1-3). A simple approach uses multiple microphones as matching points and derives the loudspeaker weights based on the least square (LS) match (4, 5). It allows arbitrary loudspeaker placement but requires the knowledge of the transfer functions between the loudspeakers and the matching points. One remaining challenge is to design effective systems with a practical number of microphones in the transfer function acquisition.

According to the Kirchhoff-Helmholtz integral equation, an interior sound field can be expressed by the integral of the sound pressure and its gradient over the boundary of the region (6). Therefore, the transfer functions from each source to the region samples can be estimated from those to the samples over the boundary, as long as there are sufficient measurements on the boundary. Unfortunately, limited measurements with a small number of microphones are often used in practice due to the cost and efficiency.

The spatial harmonic decomposition (SHD) method (7, 8) provides a practical way to determine the transfer function between each loudspeaker and every point in the reproduction region. In this method, the transfer functions over a region are effectively parameterized by the superposition of spatial harmonics. For two dimensional sound field reproduction, the spatial harmonics are the cylindrical wave functions, and the required number of boundary samples is proportional to the square of the product of the frequency and the size of the region. However, this method becomes impractical when a large number of measurements are required to reproduce a sound field over a broad region or a broad frequency band.

In this paper, an approach based on acoustic modeling (AM) is proposed to facilitate broadband local sound field reproduction with fewer transfer function measurements. In the proposed method, an acoustic model is constructed based on the prior information of the loudspeaker location. Then, the

[1] Qiaoxi.Zhu@uts.edu.au; Xiaojun.Qiu@uts.edu.au; Ian.Burnett@uts.edu.au

[2] p.d.coleman@surrey.ac.uk

acoustic model is used to estimate the transfer functions over the reproduction region from measurement at a few samples over the boundary. Compared to the spatial harmonic method, the acoustic model can better match the actual transfer functions by using information on the control region and the loudspeaker location.

2. LOCAL SOUND FIELD REPRODUCTION

2.1 Least Squares Method

The least squares method minimizes the reproduction error over the desired region at each frequency,

$$\min_{\mathbf{w}} \left\| \mathbf{Hw} - \mathbf{p}_{\mathrm{des}} \right\|_2^2 , \tag{1}$$

where $\mathbf{p}_{\mathrm{des}}$ represents the desired sound pressure values at V sound field samples produced by a virtual source, and $\mathbf{H}$ represents the transfer function matrix between L loudspeakers and the sound field samples. The loudspeaker weights are derived as

$$\mathbf{w} = \mathbf{H}^{+}\mathbf{p}_{\mathrm{des}} , \tag{2}$$

where the upper script "+" denotes the Moore–Penrose inverse, that $\mathbf{H}^{+}=(\mathbf{H}^{\mathrm{H}}\mathbf{H}+\delta\mathbf{I})^{-1}\mathbf{H}^{\mathrm{H}}$ and $\delta > 0$ is the regularization parameter to avoid ill-conditioning. The spacing between the samples should be less than half a wavelength ($\lambda/2$), to ensure accurate reproduction over the region (4). Considering a circular region with a radius of r, the required number of samples is

$$V \geq \frac{\pi r^2}{\left(\lambda/2\right)^2} = \frac{\left(kr\right)^2}{\pi} , \tag{3}$$

where the wavenumber $k = 2\pi/\lambda$. The required number V can be very large for an enlarged reproduction region or a broad frequency band, resulting in impractical numbers of the transfer function measurement.

2.2 Spatial Harmonic Decomposition Method

In the spatial harmonic decomposition method (7), the transfer function matrix $\mathbf{H}$ is estimated from $\mathbf{H}_{\mathrm{M}}$. $\mathbf{H}_{\mathrm{M}}$ denotes the transfer functions measured at M samples over the boundary of the reproduction region. The parameterization of the acoustic transfer functions over the circular region is obtained through spatial Fourier transformation f_{SHD} over the measured samples,

$$\mathbf{a}_{\mathrm{SHD}} = f_{\mathrm{SHD}}\left(\mathbf{H}_{\mathrm{M}}\right). \tag{4}$$

Then, the transfer function matrix $\mathbf{H}$ is estimated with the inverse transformation for sound field samples, that

$$\tilde{\mathbf{H}}_{\mathrm{SHD}} = f_{\mathrm{SHD}}^{-1}\left(\mathbf{a}_{\mathrm{SHD}}\right). \tag{5}$$

Based on the transfer function estimation, the loudspeaker weights are derived as

$$\mathbf{w}_{\mathrm{SHD}} = \tilde{\mathbf{H}}_{\mathrm{SHD}}^{+}\mathbf{p}_{\mathrm{des}} . \tag{6}$$

In this method, the required number of measured boundary samples is

$$M \geq 2kr\mathrm{e}+1 . \tag{7}$$

Compared to (3), the spatial harmonic decomposition method requires much smaller number of samples when $kr >> 1$.

2.3 Acoustic Modelling Based Method

In the proposed method, an acoustic model is constructed to calculate the transfer function between the ith loudspeaker (i=1, 2, …, L) and the reproduction region from the measured transfer functions at M boundary samples. The acoustic model includes a set of randomly distributed monopole point sources around the known location of the ith loudspeaker. The 'cloud' of point sources around the loudspeaker location is applied because the exact loudspeaker location and radiation feature are not always available in practice. It is used to model the unknown spatial sound radiation features of the loudspeaker to the reproduction region. The relationship between the transfer functions to the M measured boundary samples and those to the V sound field samples is

$$\mathbf{T}_i = \mathbf{h}_{\text{A},i}\left[\left(\mathbf{h}^{\text{H}}_{\text{A-M},i}\mathbf{h}_{\text{A-M},i} + \lambda\mathbf{I}\right)^{-1}\mathbf{h}^{\text{H}}_{\text{A-M},i}\right], \tag{8}$$

where $\mathbf{h}_{\text{A},i}$ and $\mathbf{h}_{\text{A-M},i}$ are respectively the transfer function matrix between the acoustic model of the ith loudspeaker and the sound field samples or the boundary samples, and λ>0 is the regularization parameter to avoid ill-conditioning. The transfer functions $\mathbf{h}_{\text{A},i}$ and $\mathbf{h}_{\text{A-M},i}$ are theoretically calculated by the acoustic model, rather than obtained from measurements. Based on this relationship, the estimation of $\mathbf{H}$ is

$$\tilde{\mathbf{H}}_{\text{AM}} = \left[\tilde{\mathbf{h}}_{\text{AM},1} \quad \tilde{\mathbf{h}}_{\text{AM},2} \quad \cdots \quad \tilde{\mathbf{h}}_{\text{AM},L}\right] \tag{9}$$

where

$$\tilde{\mathbf{h}}_{\text{AM},1} = \mathbf{T}_i\mathbf{h}_{\text{M},i} \tag{10}$$

and $\mathbf{h}_{\text{M},i}$ is the ith column of the measured transfer function matrix $\mathbf{H}_\text{M}$ over the boundary samples. Then, the loudspeaker weights are derived as

$$\mathbf{w}_{\text{AM}} = \tilde{\mathbf{H}}^{+}_{\text{AM}}\mathbf{p}_{\text{des}}. \tag{11}$$

Compared to modelling each loudspeaker as a monopole point source in the authors' previous work (9), the new model can be adaptive to the unknown loudspeaker's radiation feature and robust to the loudspeaker's location mismatch.

3. SIMULATIONS

3.1 Comparison among Different Methods

The proposed acoustic modelling based method is compared with the least squares method and the spatial harmonic decomposition method. As shown in Fig. 1(a), the desired sound field is produced by a point monopole source located at (–2.0, 0.0) m, and is labeled as virtual source in the figure. The reproduction region is centered at (0.0, 0.0) m, with a radius of 0.2 m. A uniform line array of 5 loudspeakers is used to reproduce the local sound field. The loudspeakers are located at x = –0.4 m and y = –0.4 m ~ 0.4 m. Each loudspeaker is set as a point monopole source. Since the spacing between the loudspeakers is 0.2 m, the aliasing frequency of the array is 850 Hz.

The least squares, spatial harmonic decomposition and the proposed acoustic modelling based methods are compared, when the transfer functions are measured at 16 boundary samples. The reproduction error is present in Fig. 1(b), which is defined as

$$\text{MSE}(f) = 10\log_{10}\frac{\sum_{v=1}^{V}\left|\tilde{p}_v(f) - p_v(f)\right|^2}{\sum_{v=1}^{V}\left|p_v(f)\right|^2}. \tag{12}$$

where p_v is the desired sound pressure and $\tilde{p}_v$ is the reproduced sound pressure at the vth sound field sample. The metric is evaluated by V = 5025 grid samples, with 0.005 m spacing over the reproduction region.

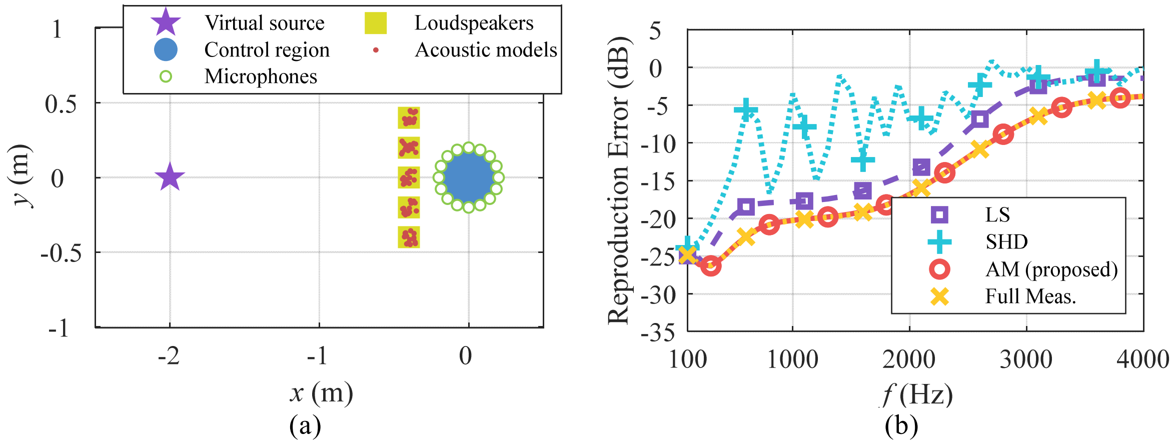

Figure 1 – (a) The system geometry of the local sound field reproduction employing transfer function measurement at 16 boundary samples. (b) The reproduction error of the least squares, spatial harmonic decomposition and the proposed acoustic modelling based methods, employing transfer function measurement at 16 boundary samples, and the least squares method employing full transfer function measurement over the reproduction region as reference.

As shown in Fig. 1(b), the SHD method performs the worst and suffers the inaccuracy caused by the zeros of the Bessel functions impacting the measurement. The proposed method employing 16 samples has better accuracy than the least squares method with the same samples and achieves the same performance with the least squares method employing 5025 samples (Full Meas.) over the region. The 'Full Meas.' indicates the 'ideal' reproduction error achieved by the same loudspeakers with sufficient microphones, which is free of the degradation caused by reduced sound field sampling.

3.2 Reproduction Error with Reduced Number of Samples

Figure 2 presents the performance of different methods employing fewer transfer function measurements. With decreasing number of transfer function measurements, all the three methods have performance degradation. However, the proposed acoustic modelling based method performs better than the least squares and spatial harmonic methods with the same transfer function measurements employed. Furthermore, the proposed acoustic modelling based method achieves reproduction error less than −10 dB over 100 Hz to 2500 Hz, even with 2 boundary samples. Table 1 presents the performance averaged over 40 uniform samples between 100 Hz and 4000 Hz. It shows the proposed method using 4 microphones achieves the same performance with the least squares method using 5025 microphones throughout the region. Besides, the proposed method using 2 microphones has only 1.4 dB broadband degradation compared to the least squares method using 5025 microphones throughout the region.

Table 1 – The mean square error (dB) of the local sound field reproduction averaged over 100 ~ 4000 Hz, using the LS, SHD and AM methods, employing different number of sound field samples in the transfer function measurement, respectively.

Method	Number of measured sound field samples				
	1	2	4	16	5025
LS	−1.5	−2.1	−7.1	−11.5	**−14.6**
SHD	6.4	4.3	3.7	−6.6	
AM	−6.4	**−13.2**	**−14.6**	**−14.6**	

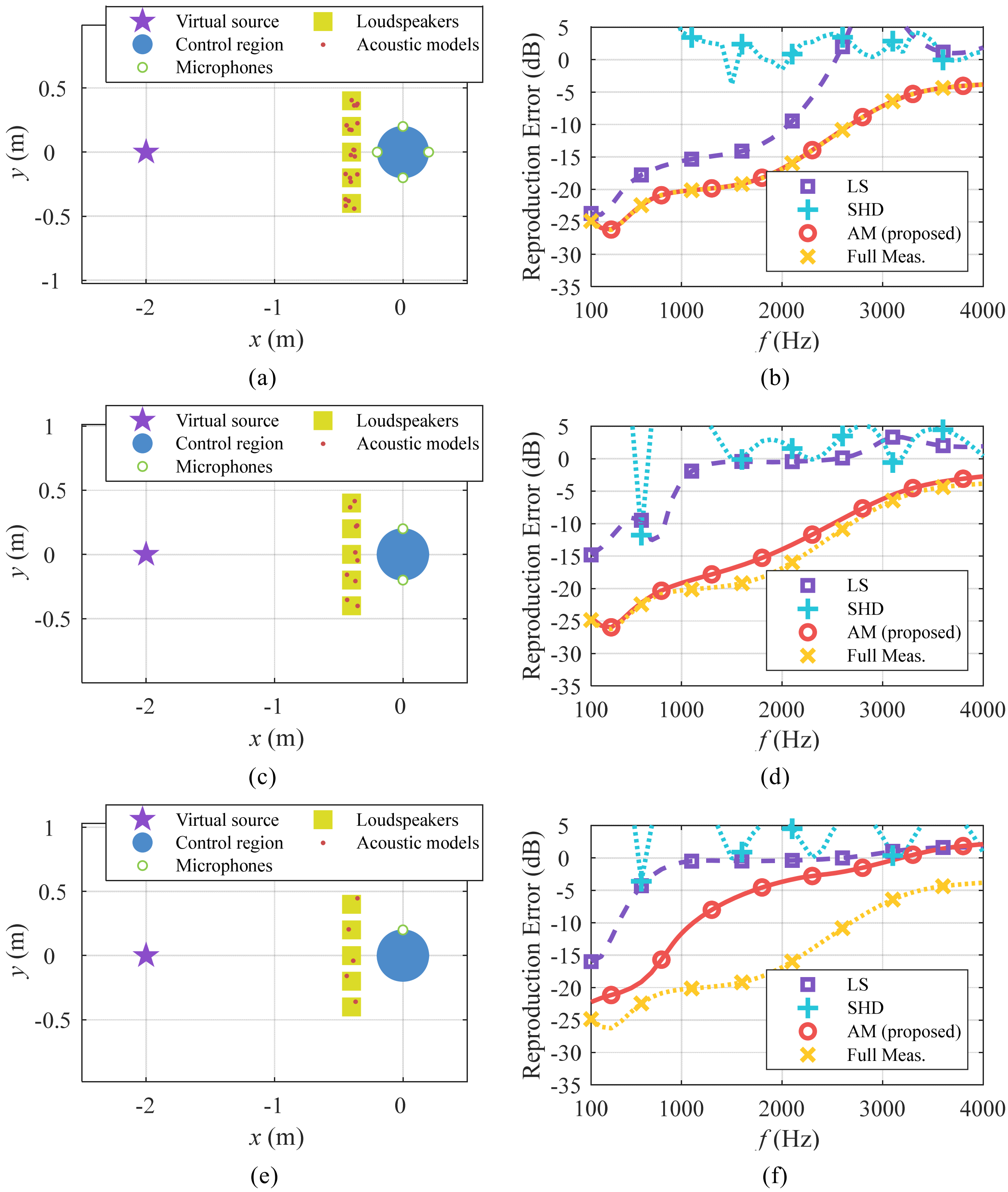

Figure 2 – The system geometry and the reproduction error of the least squares, spatial harmonic decomposition and the proposed acoustic modelling based methods, employing transfer function measurement at 4 boundary samples in (a) and (b), 2 boundary samples in (c) and (d), 1 boundary sample in (e) and (f), and the least squares method employing full transfer function measurement over the reproduction region as reference.

4. CONCLUSION

An approach based on acoustic modeling is proposed to reduce the number of the transfer function measurement for implementing local sound field reproduction. In the proposed method, the acoustic model is constructed for each loudspeaker by the information of its location. The acoustic model is applied to estimate the transfer function between each loudspeaker and each sample of the reproduction region. Simulation shows that the proposed method performs better than the spatial harmonic decomposition method and the least squares method when employing the same number of transfer function measurements. Furthermore, the proposed method requires much fewer transfer function measurements to achieve the same the broadband local sound field reproduction with the conventional least squares method. However, the simulation only considers sound sources with simple radiation features. Future work includes experimental validation on a real-world local sound field reproduction system.

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