SOUND REINFORCEMENT TECHNOLOGY BASED ON SOUND FIELD RECONSTRUCTION WITH ENERGY CONTRAST CONTROL

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Sound field reconstruction using the least-square method is employed in sound reinforcement applications to achieve uniform sound pressure level (SPL) over audience area in this study. A practical problem that the radiated sound energy decline in audience area appears at low frequencies with conventional least-square method. An approach based on energy contrast control is devised to solve this problem. The new solution is verified both by simulations and experiments. Results show that the proposed method can improve acoustic energy at low frequencies without much impact on the uniform distribution of SPL at high frequencies.

1. Introduction

Loudspeaker arrays have been developed for decades,[1] and they are now widely used in all kinds of sound reinforcement applications to achieve uniform sound pressure level distribution and high signal to noise ratio (SNR) over the audience area. Conventional loudspeaker arrays are geometrically steered, like curved or arc arrays, J-shape arrays, and progressive arrays.[2] These arrays are used to eliminate the disadvantage of straight line sources which produce a polar response that changes substantially against arrays' length and frequencies.

Solutions to optimize the sound fields produced by loudspeaker arrays progress rapidly in recent years. Constant beamwidth transducer (CBT) theory is originally used in underwater projectors and receivers, but it is now applied in loudspeaker arrays to achieve a beam pattern that is independent of frequencies.[3] Wavefront sculpture technology which based on the Fresnel approach in optics reduces the effects of the units' discontinuities in arrays.[4] There is another similar technology called digital and geometric radiation control (DGRC) achieved with the Fresnel method which applies the advantages of the J-shape arrays in the vertical loudspeaker arrays using DSP technologies.[5] However, these methods mainly focus on the improvement of loudspeaker arrays' polar responses rather than the effect of total environment in sound reinforcement applications. The traditional least squares (LS) method [6, 7, 8] which is originally used in sound field reproduction applications, is investigated in this study. This method generates spatial sound field over the audience area with approximate to the desired SPL distribution using multiple-input multiple-output (MIMO) channel inversion. Effect of the loudspeaker arrays is optimized by minimization of the reproduction error on control points in the desired sound field.

Loudspeaker weights obtained by the least squares method are calculated in the frequency domain. A practical problem appeared in our previous study that the radiated acoustic energy intensity

over the audience area decline in low frequencies. A new solution based on energy contrast control is devised to solve this problem in this paper. Contrast between the acoustic energy over the audience area and the input energy of loudspeaker arrays is controlled to improve the SPL at low frequencies. This paper is organized as follows. Theory of the classic LS method and proposed method is described in Section 2. The simulation and experimental results are shown in Section 3, and the conclusions are provided in Section 4.

2. The least squares method with energy contrast control

2.1 Sound reinforcement with classic least squares method

In sound field reproduction using the least squares method[8], a loudspeaker array of L units is employed to generate a sound field which is composed by a grid of M control points. Sound pressure in each control points can be expressed as the sum of responses from the L units in the array with vector p. In the m-th control point, the vector is

$$p_m = \sum_{k=1}^{L} H_{m,k} \cdot q_k ,$$ (1)

where $H_{m,k}$ stands for the acoustic transfer function from k-th loudspeaker to this control point and q_k is the input signal. In this way the entire sound field can be written as

$$\boldsymbol{p} = \boldsymbol{H}\boldsymbol{q} ,$$ (2)

where $\boldsymbol{p} = [p_1 \ p_2 \cdots p_m \cdots p_M]^{\mathrm{T}}$ is the vector of sound pressure, $\boldsymbol{q} = [q_1 \ q_2 \cdots q_m \cdots q_M]^{\mathrm{T}}$ stands for the driving signals of this loudspeaker array and $\boldsymbol{H}$ is the matrix of acoustic transfer functions. A specific sound field can be obtained by adjusting the vector of driving signals $\boldsymbol{q}$ as described in Eq. (2). The desired sound field $\boldsymbol{p}_d$ is required to calculate such input signals with the minimization of least squares errors between the reproduced sound field and the desired sound field over the control points:

$$\min_{\boldsymbol{q}} \left\| \boldsymbol{H} \cdot \boldsymbol{q} - \boldsymbol{p}_d \right\|_2^2$$ (3)

where $\| \ \|_2$ represents the l_2 norm. Solution of this problem is given by

$$\boldsymbol{q} = (\boldsymbol{H}^{\mathrm{T}}\boldsymbol{H})^{-1}\boldsymbol{H}^{\mathrm{T}}\boldsymbol{p}_d .$$ (4)

To apply this method in the sound reinforcement applications, the application scenario should be set as illustrated below in Fig. 1. The vertical loudspeaker array is placed in y axis with a height of H_1 while audience area lies in the x axis from point B_1 to B_2.
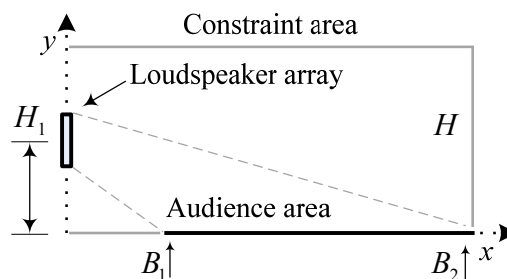

Figure 1. Application scenario of the sound reinforcement system.

The desired sound filed is separated into two parts, the audience area and the constraint area. The audience area is expressed with solid black line while the constraint area is express with solid gray lines in Fig. 1. Control points distribute with relatively equal spaces in these two areas. Re-

sponse in the constraint control points is set to zero to restrict the acoustic energy in the sound field, while the desired response in the m-th control point on the audience area can be written as

$$p_d(\vec{r}_m) = e^{-jk\vec{r}_m} .$$ (5)

In above equation, the magnitude response here is set to one to achieve uniformly distribution of SPL while the phase response changes with the distance from array to the control points.
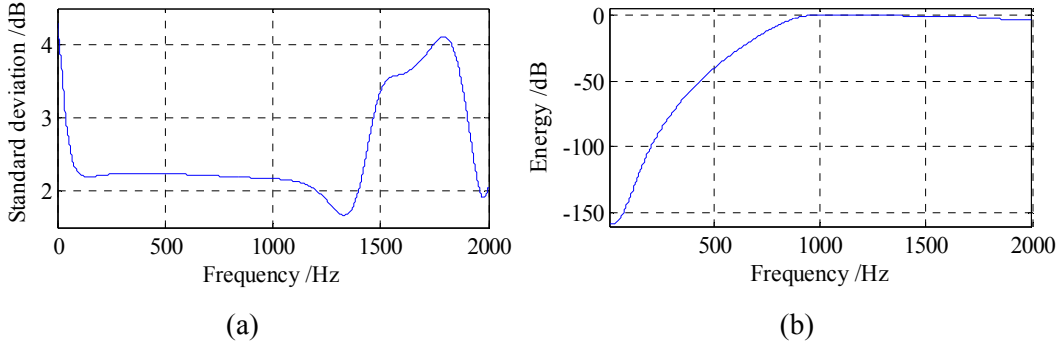

(a)	(b)

Figure 2. Acoustic point-source simulation results against frequency in the audience area. (a) Standard deviation; (b) acoustic energy.

Simulation results where units in the array act as acoustic point-sources is illustrated in Fig. 2. The vertical array consists of eight loudspeakers that are equally spaced with intervals of 0.13 m. Height of the array is 3 m while audience area locates from 1.5 m to 12 m in x axis. Height of constraint control points is 6 m and all control points distribute uniformly with an interval of 0.1 m around the sound field. Frequency range in this simulation is limited to $1 \sim 2000$ Hz considering the bad effects by side lobes. Standard deviation of SPL in the audience area is used to show the degree of uniformity of SPL distribution. Although a smaller standard deviation can be achieved in frequencies below 700 Hz, acoustic energy decline accordingly rapidly as described in Fig. 2(b). Consequently, the classic least squares method is impractical.

2.2 Energy contrast control method

Control methods can be applied to improve the acoustic energy in low frequency range, such as the widely used methods like the acoustic contrast control (ACC) [9, 10] or the constraint on loudspeaker weight energy [11, 12]. Since the input energy of loudspeaker array is not constant, contrast control between acoustic energy on the control points in the audience area and the loudspeaker weight energy is necessary. Acoustic energy in the audience area is defined as

$$e_l = \sum_{k=1}^{N} p_k^H p_k = (H_l q)^H (H_l q) ,$$ (6)

where H_l stands for the transfer function matrix from array to control points in the audience area, and N is the number of these control points. Similarly, the loudspeaker weight energy can be written as

$$e_i = q^H q ,$$ (7)

and therefore the energy contrast can be defined as

$$J = \frac{e_l}{e_i} = \frac{(H_l q)^H (H_l q)}{q^H q} ,$$ (8)

The proposed energy contrast control approach can then be described as the following equation

$$\min_q \| Hq - p_d \|_2^2, \text{ s.t. } J \geq J_c ,$$ (9)

where $\| \ \|_2$ represents the l_2 norm, J stands for the contrast of these two kinds of energy and J_c is the limit to control this ratio. Value of J_c can be chosen referring to the contrast ratio J_u in the uncontrolled LS method. Effect of the proposed constraint control method changes with different J_c compares with J_u, there are two conditions:

1. $J_c \leq J_u$, in this condition, requirement of the energy contrast control is always satisfied. Acoustic energy achieved in the audience area with the new method is equivalent to that with the uncontrolled LS method, and the same SPL distribution will be obtained with these two methods.

2. $J_c > J_u$, here the energy contrast control method will improve the acoustic energy intensity in the audience area. However, since the uniformity of the SPL distribution has been maximized by the uncontrolled method, it will be affected by adding constraints.

Acoustic energy intensity in the audience area reduces only in low frequencies as illustrated in Fig. 2, and value of J_c can be chosen no larger than the energy contrast ratio in high frequencies. In this condition, the uniformity of the SPL distribution in these frequencies will not be impacted with the new method.
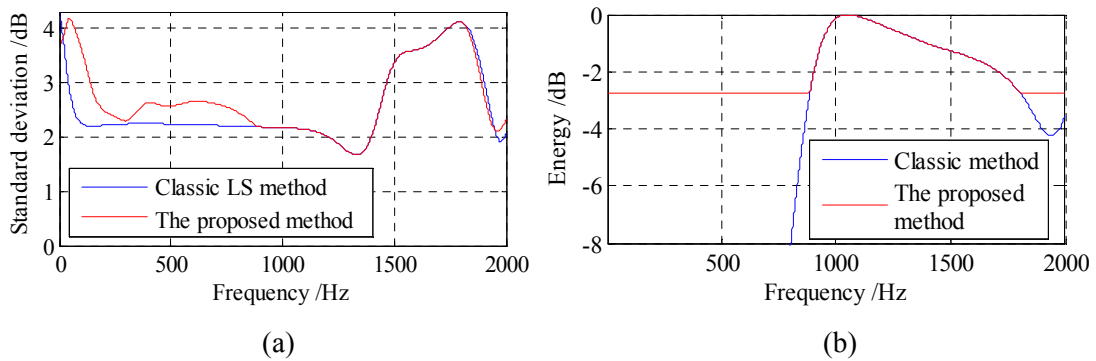

Figure 3. Simulation results against frequency with two methods. (a) Length of uniform region; (b) acoustic energy in audience area.

Simulation results with classic LS method and the improved approach are illustrated in Fig. 3, in which values of the simulation parameters are defined as that in Section 2.1. J_c in the energy contrast control method is selected about -3 dB lower than the maximum value in the uncontrolled method. Although the standard deviation of the SPL increases in frequencies below 900 Hz, acoustic energy is also improved over the audience area while the uniformity of the SPL distribution is not affected in other frequencies. This shows the effectiveness of the proposed approach.

3. Performance of the energy contrast control approach

3.1 Experimental setup

Experiments were carried out in the semi-anechoic chamber at the Institute of Acoustics, Chinese Academy of Sciences shown in Fig. 4. The vertical loudspeaker array is composed of eight loudspeaker units with intervals of 0.13 m and is fixed in a holder of 4 m high. Middle of the array is about 3.3 m high to the ground and the microphone array is about 0.3 m high, thus their relative distance is 3 m. The microphone array consists of 16 microphones spaced 4 cm apart, which is less than the half wavelength at the frequency of 3600 Hz. The audience area is 1.5 to 12 m on the ground, same as that in the simulations above. Reflection of sound waves from the ground is impaired using sound-absorbing material. The frequency range of interest in this experiment is 200 to 2000 Hz to avert the effect of side lobes, while the spatial aliasing frequency is 1310 Hz due to the array unit's gaps.

The sampling frequency f_s is set to 8 kHz and the length of the filter is 800. Loudspeaker weights of LS method are calculated every 10 Hz and loudspeakers units act as acoustic point-sources. The time domain filter is calculated using the inverse Fourier transfer with the filter response acquired in the frequency domain to achieve real-time measurement results.
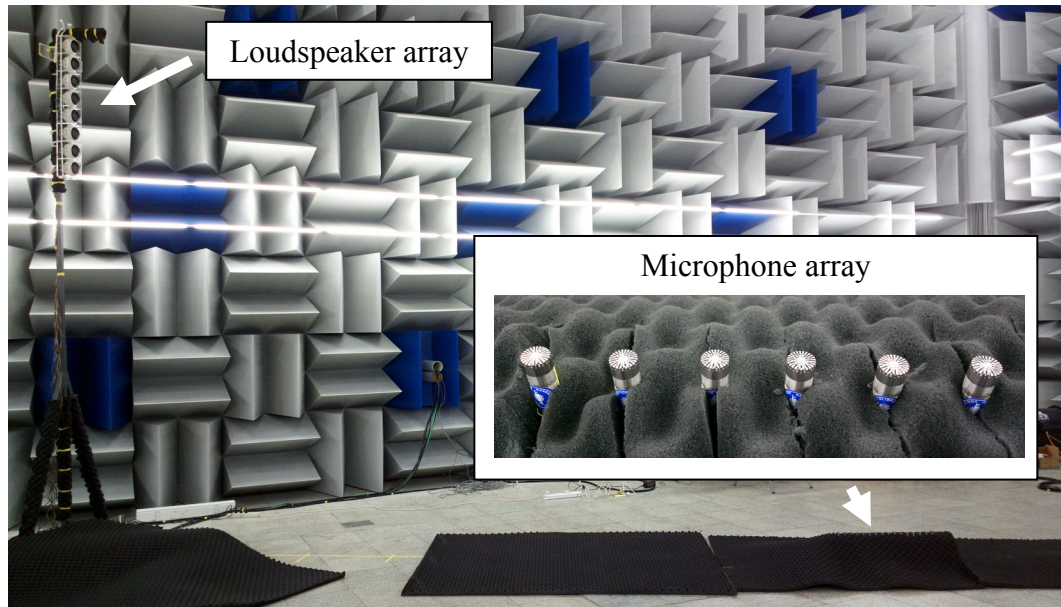

Figure 4. Setup of the measurements in the semi-anechoic chamber, microphone array is covered by the black sound-absorbing material and it is shown in the little figure above.

3.2 Experimental results

In the experimental tests, we observed that the results were affected seriously by the frequency response of the loudspeaker units. This effect was not considered in the simulations mentioned above. So we measured the frequency response of array units in the anechoic chamber and the result is given in Fig. 5.
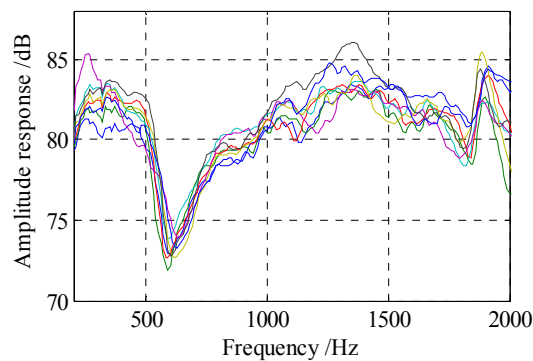

Figure 5. Frequency response of the eight loudspeaker array units.

The standard deviations versus frequency which stand for the uniformity of SPL distribution in the audience area are shown in Fig. 6. The offline simulation results with the loudspeaker units' frequency response are given in Fig. 6(a) while the corresponding real-time experiment results are shown in Fig. 6(b).

The measurement results are interfered by measurement error and background noise, which make the standard deviations in the experiment results become larger than that in the simulation results. In higher frequencies from 900 to 2000 Hz, standard deviations acquired with classic LS method matches that acquired from the energy contrast control method in both simulation and ex-

periment results. Uniformity of the SPL distribution is not degraded by the energy contrast control. The classic LS method has a larger standard deviations in frequency range during 500 to 900 Hz in both results, which is different from the simulation results in Fig. 3(a). Frequency responses of array units bring about this distinction.
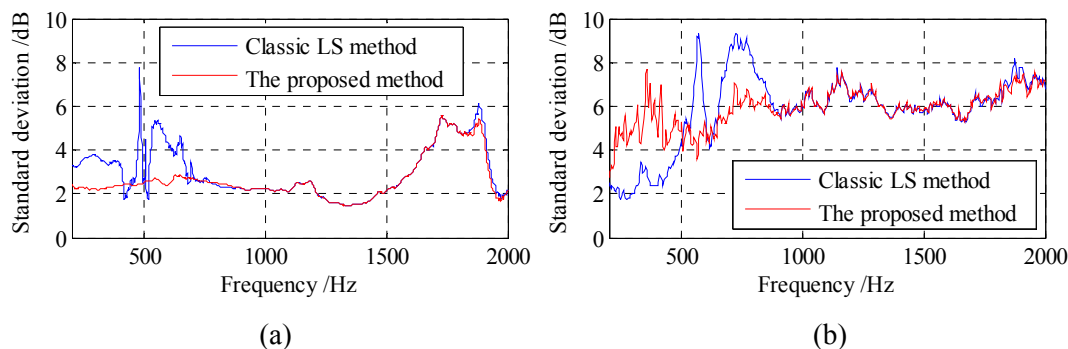

(a)

(b)

Figure 6. The standard deviations versus frequency in the audience area. (a) Offline simulation results with frequency responses of the loudspeaker units considered; (b) real-time experiment results.

Fig. 7 shows the average SPLs versus frequency in the audience area, which is used to show the intensity of acoustic energy. In both simulation and experiment results, SPLs become lower in about 600 Hz than that in other frequencies. This effect is caused by array units' responses. Average SPLs obtained by both methods have similar trends from 900 to 2000 Hz while the amplitudes have minor differences. The simulation results match the experiment results here. This means that the energy contrast control method have no degradation on the acoustic energy intensity in this frequency range. The average SPL differences are caused by the adjustment in amplitude of time domain filters when we convert the filter obtained in the frequency domain. The proposed energy contrast control approach improved acoustic energy in lower frequencies in both results. The improvement of this new method is obvious here.
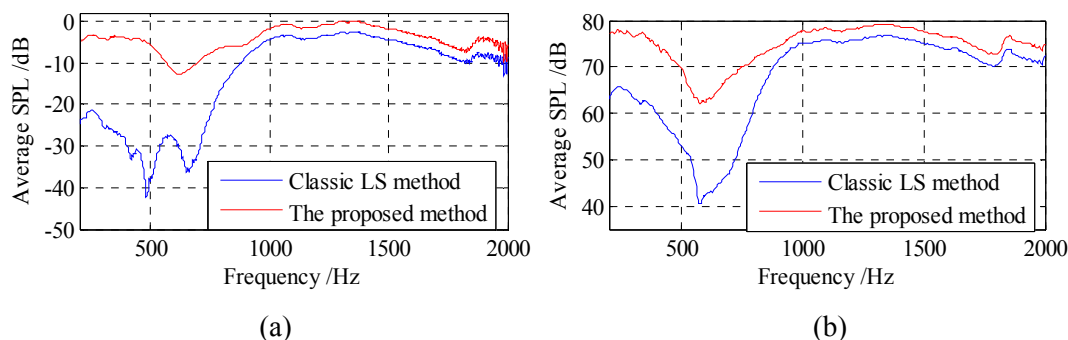

(a)

(b)

Figure 7. Average SPLs versus frequency in the audience area. (a) Offline simulation results with frequency response of the loudspeaker units; (b) Real-time experiment results.

4. Conclusion

An improved LS method with energy contrast control applied in sound reinforcement systems is investigated in this study. To achieve uniform SPL distribution in the audience area, this approach is proposed to solve the disadvantage of the classic LS method that acoustic energy intensity depresses in low frequencies. Uniformity of the SPL distribution as well as acoustic energy intensity in audience area achieved by both methods are compared. Offline simulations and real-time experiment results demonstrate that the new approach performs well. The acoustic energy in low fre-

quencies can be enhanced with appropriate contrast ratio while the uniformity of SPL distribution is not degraded in higher frequencies.

5.   Acknowledgements

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