Sound Field Control in Surround Screen Speaker Array by WFS and CBT Algorithms

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Abstract. This paper proposes a method to solve the problem that the sound reproduction system cannot work when the movie screen is made by a sound-proof material such as LED. It is demonstrated in an array of 192 speakers to surround a screen for sound reproduction, called surround screen speaker array. The speaker array is built in an actual cinema. The sound field control algorithms are implemented by mixers. In order to improve the uneven sound field distribution and sound field aliasing caused by the speaker array, two algorithms WFS and CBT are used in this paper. A new control algorithm is proposed and demonstrated to improve the uniformity of the sound field distribution and reduce the sound field interference.

1. Introduction
With the development of display technology, LED has satisfied the requirements of cinema screen and applied to many large screens for cinemas [1, 2]. As a movie screen, the display effect of LED is better than traditional screen. The material of screen used in the traditional cinemas is generally a kind of sound-permeable material. However, when the movie screen is a sound proof material such as LED screen, the traditional main channel of sound reproduction system cannot work. Array of speakers to surround the screen for sound reproduction, called surround screen speaker array, is proposed in this paper to solve this problem. The surround screen speaker array is mainly used to replace the main sound channel of a traditional cinema, so the traditional 5.1 sound system can be combined with this new system [3]. This new combination can solve the LED movie screen’s sound-proof problem, but there are two problems need to be solved. Firstly, the sound field distribution of the speaker array is non-uniform. Secondly, the interference of sound fields from the speaker array usually occurs [4].

Corresponding sound field control algorithms can solve these problems. There were many studies on the sound field control of speaker arrays in the past. The HOA algorithm proposed by Gerzon [5] used a spherical harmonic function to represent the reproduced sound field. The wave field synthesis algorithm proposed by Berkhout [6] could make the speaker array form a virtual sound source during playback and form a correct sound image in the entire sound field to control the sound field. Kirkeby and Nelson [7] proposed a plane wave reproduction method based on sound pressure matching, which used the least squares method to minimize the error between the sound field generated by the speaker array and the desired sound field. The CBT algorithm proposed by Keele [8] used each speaker unit in the speaker array to perform delay processing to make the delay of each speaker unit of the line array equal to the delay of the circular array itself, thereby changing the sound field distribution. Zhang W [9] utilized the mode domain method to control the sound field of multiple sound zones, and independently and simultaneously reproduce multiple sound fields in different spatial regions in the same space. Gauthier P A [10] used the frequency domain optimization algorithm for sound field control and performs sound field reconstruction in free field or closed space.
In this paper, new algorithms are proposed and demonstrated in an array of 192 speakers to surround the screen for sound reproduction, called surround screen speaker array. The speaker arrays of the center channel are arranged in horizontal rows. According to the sound wave superposition theorem, the sound field is more complicated, so this article mainly analyzes the sound field of the center channel. Two different control algorithms, WFS [11] and CBT [8], are used for the center channel. Finally, new control algorithms are proposed and demonstrated to solve the problem of uneven sound field distribution and sound field interference.

2. Experiment Setup

As shown in figure 1, 192 speakers are used to form a speaker array surrounding the screen to replace the main channel in the cinema sound reproduction system. 64 speaker units are arranged in the upper and lower rows, respectively. 32 speaker units are arranged in left and right columns, respectively. All speakers are the Soundking KM5B. Each speaker unit has a width of 0.21 m, which leads to the screen width of 13.44 m and the height of 6.72 m. The combination of the upper speaker array and the lower speaker array replace the center channel of the main speaker, the left speaker array on the left column replaces the left channel, and the right speaker array on the right column replaces the right channel.

The measurement is conducted in an actual cinema. The measurement area is in the audience seat area. There are 14 rows of audience seats, and each row has 32 seats. The spacing distance among seats in the same row is 0.6 meters. The interval distance between rows of seats is 1 meter. The measurements are conducted in every row. 17 points per row are carried out. So the measuring point interval is 1.2 m × 1 m. The sound level meter used for the measurement is NTI, and the sound level meter uses a type I measuring microphone. The speaker array play 10 seconds pink noise and record the octave equivalent sound pressure level Lzeq. The measurements are in compliance with the ISO 2696-2015 [12] standard for the measurement of sound field in cinemas.

3. Sound Field Control Algorithms For Surround Screen Speaker Array

3.1. WFS Algorithm
The upper speaker array and the lower speaker array are controlled by the same algorithm. The acoustic energy ratio of the upper and the lower speaker arrays is 1:1. The WFS algorithm uses the 2.5D [9] algorithm and the driver function formula is

\[
D(x_0, t) = w \delta(t - \frac{|x_0 - x_s|}{v}) \ast (f(t) \ast s(t))
\]
Where $x_0$ denotes the position of each speaker unit, $x_s$ denotes the virtual sound source position, $w$ denotes the weighting value, $s(t)$ denotes the pre-filter function, and $f(t)$ is the original signal. The virtual sound source is set at a position 5 meters behind the speaker array.

3.2. **CBT Algorithm**
The arc shape is set to 10 degrees in the CBT algorithm.

4. **Experimental Results and Analyses**
The simulated sound field map and the actual sound field map measured of different algorithms at different frequency bands are given below. The simulated map is marked with S mark in the figure.

4.1. **WFS Algorithm**
As shown in figure 2, below 1000Hz, the measured sound field processed by the WFS algorithm is closer to the sound field of the theoretical simulation, and the energy distribution is relatively average. However, at 500Hz, there is a horizontal energy band in the middle of the audience area, which is similar to the original sound field map without the algorithm. Above 2000Hz, the measured sound field map processed by the WFS algorithm is more similar to the original sound field map processed without the algorithm. It is indicated that in the frequency range below 1000 Hz, the WFS algorithm can control the sound field of the speaker array, while in the frequency range above 2000 Hz, the WFS algorithm has no effect on the sound field control of the actual speaker array.

4.2. CBT Algorithm
As shown in the figure 3, below 1000Hz, the energy of the original sound field is concentrated and the simulated sound field processed by the CBT algorithm has vertical light and dark stripes, while the energy distribution of the measured sound field processed by the CBT algorithm is relatively uniform, which is not similar to the two cases mentioned above. It is indicated that the CBT algorithm changes the original sound field distribution below 1000 Hz, but it doesn’t achieve the effect of algorithm control. Above 2000 Hz, the measured sound field processed by the CBT algorithm is similar to the original sound field, there is no obvious interference fringe and the energy distribution is more dispersed than the original sound field.

5. Conclusions
In order to solve the soundproof problem of LED screen in the cinema, this paper uses 192 speaker units to form a surround screen speaker array to reproduce the main sound channel. The combination of the
upper and lower side speaker array replaces the center channel, the left side speaker array replaces the left channel and the right side speaker array replaces the right channel. The sound field of the center channel is controlled by two different algorithms and the actual cinema sound field is measured. After comparative analysis, it is found that the WFS algorithm has better control effect on the sound field in the low frequency range, and CBT algorithm has better control effect on the sound field in the high frequency range. So an overall control algorithm is proposed.

The low frequency adopts the WFS algorithm, the high frequency adopts the CBT algorithm, and the high frequency and low frequency crossover points are 2000 Hz. The formula is as follows:

\[
Y(w) = AS(w)F(w)e^{-j\frac{|x_0-x_s|}{\nu}} \quad \frac{w}{2\pi} < 2000
\]

\[
Y(w) = F(w)e^{-jw(1-\cos\theta)r} \quad \frac{w}{2\pi} \geq 2000
\]

X0 denotes the position of each speaker unit, Xs denotes the virtual sound source position, A denotes the weight value, and r and Θ are the parameter related to x0. S (w) is a pre-filter function, F (w) is the original signal, and Y (w) is the signal processed by the algorithm.

This algorithm can distribute the sound field as a whole evenly. The WFS algorithm can obtain the correct sound image at low frequency, and the CBT algorithm makes the sound field distribution more uniform at high frequency.

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