Research on Directivity Pattern Control for Phased Rectangular Loudspeaker Array

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ABSTRACT

This paper studies the control technologies of directive property for a phased rectangular loudspeaker array. The sound field directivity pattern and sound pressure level(SPL) of the main beam was analyzed with numerical simulation and experiments. The results show that the suppression of grating lobe is most efficient when horizontal deflection angle(α_0) is 45°. The SPL of the main beam decreased less than 1dB when the beam deflected in the plane of $\alpha_0 = 0^\circ$. The directional accuracy deviation of the main beam occurs when the vertical deflection is over 50°, and the deviation level is about 5°. The reasons resulted in SPL reduction was that the array elements are not the pulsating sphere source and the mutual acoustic impedance effect existed between elements. The directional accuracy of main beam is due to the mutual acoustic impedance and the diffraction in the edge of baffle.

Keywords: Directivity Pattern; Beam Deflection; Loudspeaker Array; Sound Pressure Level.

1. INTRODUCTION

Usually, the sound wave from point source spreads around it, but in fact, sound field distribution that emitted by a single loudspeaker is not constant in all direction, and the transmission is of directivity. But the direction of propagation can be changed by phase-controlled technique. To obtain intense directivity sound field, the loudspeakers arraying technique is proposed, the beam deflection can be realized by delayed the interval of time between array elements.

Early In 1930, Wolfe I and Malter L[1] researched the directivity of point source, linear source, and curve source. A similar linear arrays method was studied by H F Olson in his famous acoustic monograph "Acoustical Engineering"[2]. In 1998, P Hong, from Georgia Institute of Technology, researched directional transmission of sound by arraying loudspeakers[3]。

Under the circumstance of phase-controlled, the beam deflection range of linear array is limited in two-dimensional plane, but the beam deflection range of a plane array is in tridimensional space and the sound beam is like a horn. Compared with linear arrays, plane arrays have a bigger beam deflection range and a better directivity.

2. Fundamental Principles

The directivity function is used to represent the directivity features of loudspeakers arrays, the former is chose in this paper.

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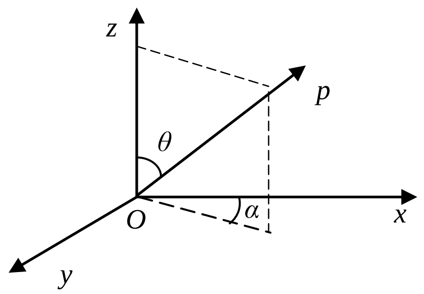


Figure 1-Left-handed coordinate system

It can be seen in Fig.1, $p(\alpha,\theta)$ is the top complex sound pressure in any direction (α,θ) that apart from the sound source, and the distance is *r*. $p(\alpha_0,\theta_0)$ is the top complex sound pressure at *r* from sound source in the direction of *Z* axis, thus the normalized sound pressure directivity function $D(\alpha,\theta)$ is given by

$$D(\alpha,\theta)=\frac{|p(\alpha,\theta)|}{|p(\alpha_0,\theta_0)|} \tag{1}$$

For a loudspeakers rectangular plane array in Fig.2, loudspeakers is arranged regularly in a plane. The number of array elements is *M*, the distance between each element is d_1 in *X* axis, and the number of array elements is *N* in the direction of *Y* axis, the distance between each element is d_2. The angle between the vector *OP* and *Z* axis is θ, and the angle α is between the vector *OP* and the plane *XY*. If the direction of *Z* axis is the main beam direction, and λ is the wavelength, then the un-phase-controlled normalized directivity function $D(\alpha,\theta)$ can be expressed as

$$D(\alpha,\theta)=\frac{\sin(\frac{\pi M d_1}{\lambda}\cos\alpha\sin\theta)}{M\sin(\frac{\pi d_1}{\lambda}\cos\alpha\sin\theta)}\cdot\frac{\sin(\frac{\pi N d_2}{\lambda}\sin\alpha\sin\theta)}{N\sin(\frac{\pi d_2}{\lambda}\sin\alpha\sin\theta)} \tag{2}$$

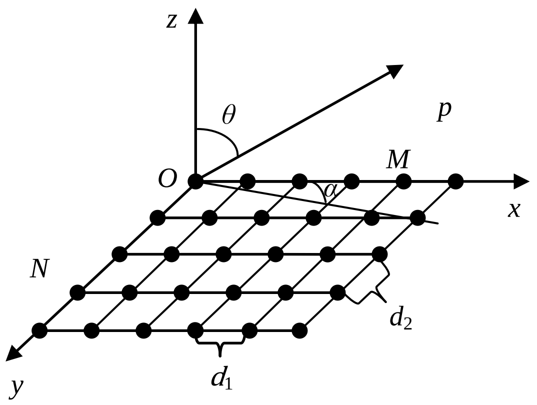


Figure 2-Structure diagram of rectangular planar array

If the beam deflection is considered, and the vertical deflection angle is θ_0, the horizontal deflection angle is α_0, then the phase-controlled normalized directivity function can be calculated by

$$D(\alpha,\theta,\alpha_0,\theta_0)=D_1(\alpha,\theta,\alpha_0,\theta_0)\cdot D_2(\alpha,\theta,\alpha_0,\theta_0) \tag{3}$$

when

$$D_1(\alpha,\theta,\alpha_0,\theta_0)=\frac{\sin(\frac{\pi M d_1}{\lambda}(\cos\alpha\sin\theta-\cos\alpha_0\sin\theta_0))}{M\sin(\frac{\pi d_1}{\lambda}(\cos\alpha\sin\theta-\cos\alpha_0\sin\theta_0))} \tag{4}$$

and

$$D_2(\alpha,\theta,\alpha_0,\theta_0)=\frac{\sin(\frac{\pi N d_2}{\lambda}(\sin\alpha\sin\theta-\sin\alpha_0\sin\theta_0))}{M\sin(\frac{\pi d_2}{\lambda}(\sin\alpha\sin\theta-\sin\alpha_0\sin\theta_0))} \quad (5)$$

Form Eq.(2) ,(3), it is obvious that the directivity of array bear on the number of array elements, the distance between each element, the wavelength and the deflection angle.

3. Directivity Simulation

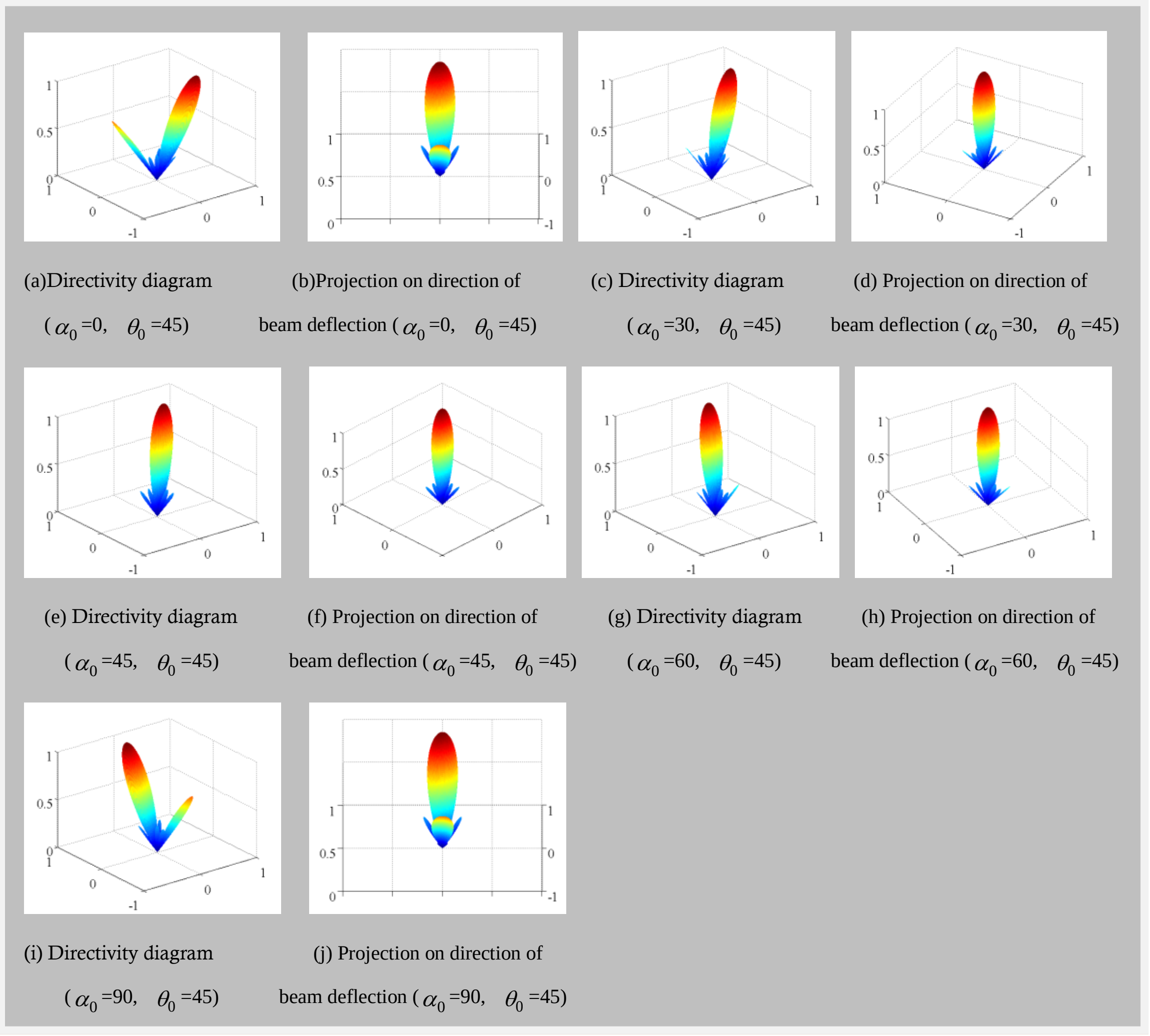
3.1 Programming Ideas

When the array parameters M, N, d_1, d_2, λ, α_0, θ_0 are fixed, the directivity function is only related to α, θ, the 3D grid can be divided through α, θ, and the value of each grid point can be figured out to project onto X Y Z axis, the 3D directivity figure can be achieved. Through the figure, it is more clearly to research the features of directivity function.

3.2 Simulation Results

In the 3D figure, the details of sound field directivity can be observed from any angle, and the projection on any direction can be obtained so as to analyze features of directivity.

Considering the 4×4 rectangular plane array as the sample, in the condition of phase-controlled, the sharpness angle of main beam get larger when beam deflects[4], and the range of beam deflection is limited. Taking this reference into account, when the frequency is 1000Hz and the distance is 0.18m, the simulation result of beam deflection is shown in Fig.3.



(a)Directivity diagram (α_0=0, θ_0=45)
(b)Projection on direction of beam deflection (α_0=0, θ_0=45)
(c) Directivity diagram (α_0=30, θ_0=45)
(d) Projection on direction of beam deflection (α_0=30, θ_0=45)
(e) Directivity diagram (α_0=45, θ_0=45)
(f) Projection on direction of beam deflection (α_0=45, θ_0=45)
(g) Directivity diagram (α_0=60, θ_0=45)
(h) Projection on direction of beam deflection (α_0=60, θ_0=45)
(i) Directivity diagram (α_0=90, θ_0=45)
(j) Projection on direction of beam deflection (α_0=90, θ_0=45)

Figure 3-Directivity diagram of phase-controlled rectangular planar array

Form Fig.5(b), Fig.5(d), Fig.5(f), Fig.5(h) and Fig.5(j), it is clearly shown that the directivity varies with the change of vertical deflection, and the suppression of grating lobe is the most efficient when $\theta_0 = 45^{\circ}$ and $\alpha_0 = 45^{\circ}$.

4. Realization of Beam Deflection

4.1 Analysis of Phase-controlled Delay

When the sound beam of acoustic emission array deflects, the change of wave front is shown in Fig.4.

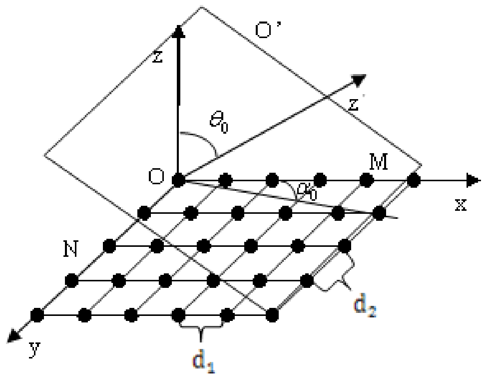


Figure 4-Diagrammatic sketch of beam deflection of rectangular array

The distance between each array element and deflected wave front O' are different, thus the time toke by sound wave transmission form each array element to wave front O' are not same. Through time delay compensation between each neighboring element of the array, beam deflection can be realized.

4.2 Realization of Sound Signal Delay

The acoustic emission system is composed by signal source, delay unit, amplification unit and loudspeakers unit. The audio signal is divided into 16 channels through delay unit, and signal of each channel is delayed accordingly, then exported to loudspeakers unit.

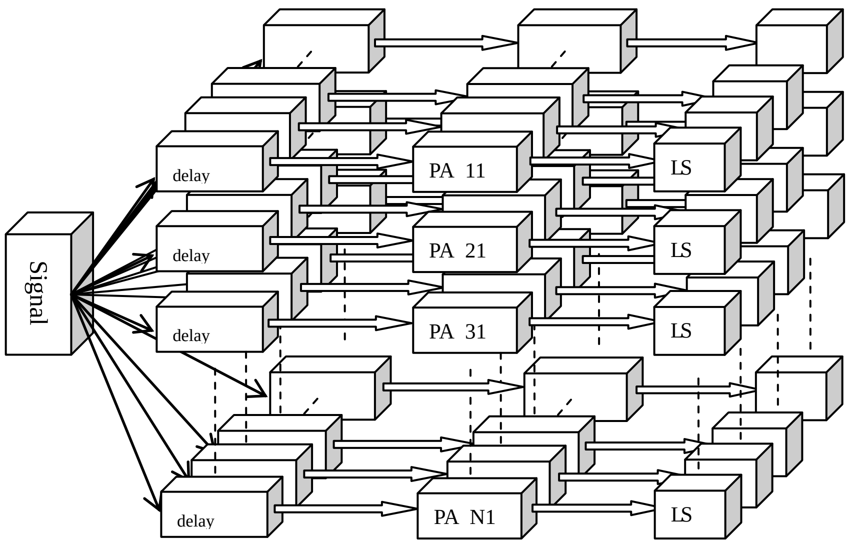


Figure 5-Structure diagram of acoustic emission rectangular array

The delay unit is key part of the system and is make up of control software and signal delay device. The software are programs that generate delay orders' and control serial debugging procedure. By inputting the desired parameters the delay orders can be achieved, then they are sent to signal delay device. According to the delay orders, the signal of each channel is delayed and then transmitted to amplification unit.

4.3 Experiment Scheme

The definition of directivity is the ratio of top sound pressure of any direction and of main beam direction in the same distance away from the sound source. Therefore, the distance between sound source and each sensor should be the same. In order to make the measurement more convenient, the array is placed on a swivel table and it can be swiveled in experiment. Therefore, sensors can only be arranged in arc and placed in the front of the array. Fig6 is the experiment image of acoustic emission array.

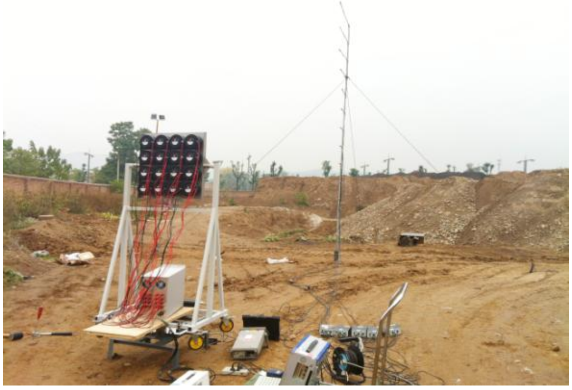


Figure 6-Experiment image of acoustic emission array

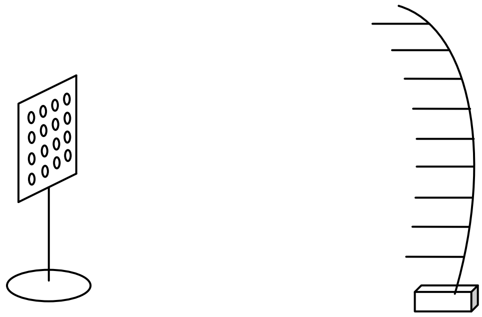


Figure 7-Experiment sketch

The experiment site is on a big open soil ground, and there are few obstacles around. Owing to the distance between acoustic array and sensors array is 7m and the maximum frequency of sound in this experiment is 2000Hz, the far field condition is satisfied.

4.4 Experiment Content

The experiment content is as follows:

(1) distance 0.16m, frequency 1500Hz, $\theta_0 = 30^\circ$, $\alpha_0 = 0^\circ$, directivity diagram。

(2) distance 0.16m, frequency 1500Hz, $\theta_0 = 30^\circ$, $\alpha_0 = 30^\circ$, directivity diagram。

(3) distance 0.16m, frequency 1500Hz, $\theta_0 = 30^\circ$, $\alpha_0 = 45^\circ$, directivity diagram。

(4) distance 0.16m, frequency 1500Hz, $\theta_0 = 30^\circ$, $\alpha_0 = 60^\circ$, directivity diagram。

(5) distance 0.16m, frequency 1500Hz, $\theta_0 = 30^\circ$, $\alpha_0 = 90^\circ$, directivity diagram。

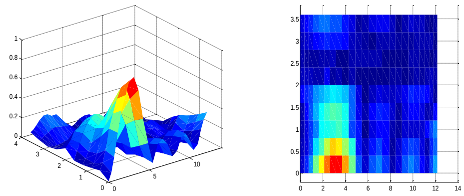
(6) distance 0.14m, frequency 1000Hz, $\alpha_0 = 0^\circ$, $\theta_0 = 20^\circ, 25^\circ, 30^\circ, 35^\circ, 40^\circ, 45^\circ, 50^\circ, 55^\circ, 60^\circ$, directivity diagram。

5. Experiment Results

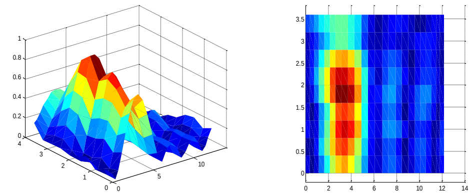
5.1 Experiment Results

In this section, the experiment results of α_0 from 0^o to 90^o, and θ_0=30^o Directivity diagram in cartesian grid, and $\alpha_0 = 0^\circ$, θ_0 from 0^o to 60^o, directivity diagram are described.

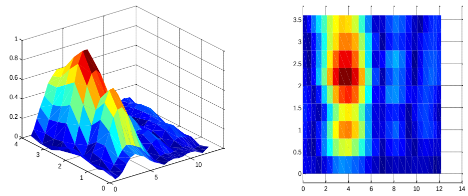
(1) In Fig.8 f=1500Hz, d=0.16m, α_0 from 0^o to 90^o, and θ_0=30^o, directivity diagram in 3D space.



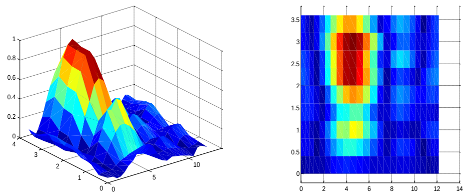
α_0=0°,θ_0=30° Directivity diagram in cartesian grid



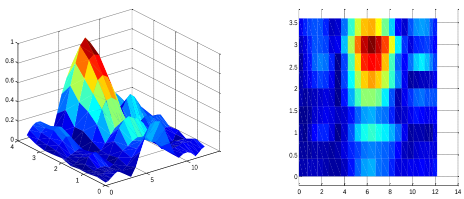
α_0=30°,θ_0=30° Directivity diagram in cartesian grid



α_0=45°,θ_0=30° Directivity diagram in cartesian grid



α_0=60°,θ_0=30° Directivity diagram in cartesian grid



α_0=90°,θ_0=30° Directivity diagram in cartesian grid

Figure 8-α_0=90°,θ_0=30° Directivity diagram in cartesian grid

(2) In Fig.9 $\alpha_0 = 0^\circ$,*f*=1000Hz,*d*=0.14m, directivity diagram

Table 1-The SPL of Main Beam

vertical deflection angle $\theta_0/^\circ$	0	20	25	30
SPL of main beam dB	115.0	114.9	114.8	114.5
vertical deflection angle $\theta_0/^\circ$	35	40	45	50
SPL of main beam dB	114.9	114.5	114.7	114.5
vertical deflection angle $\theta_0/^\circ$	55	60		
SPL of main beam dB	114.3	114.0		

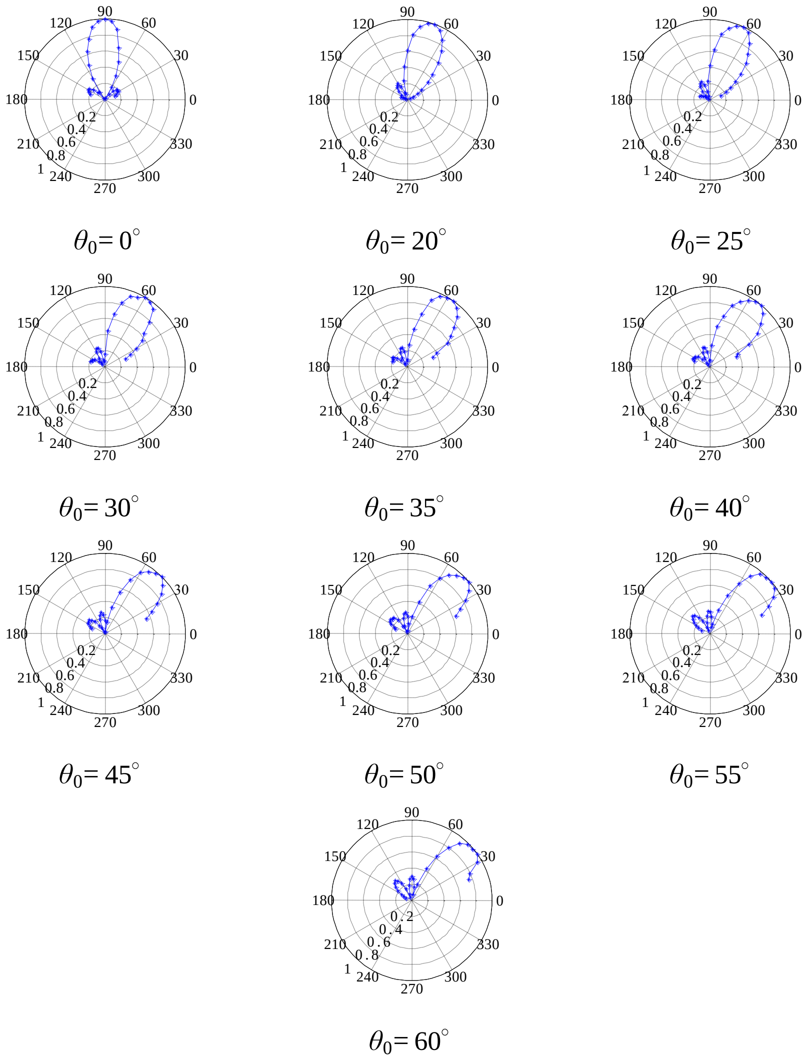


Figure 9-α_0=0°, directivity diagram

In Fig8, it is obvious that the main beam deflects in the condition of phase-controlled. Through Fig9 and Table1, the variation regulation of the SPL of main beam can be figured out.

5.2 Analysis of Results

The experiment results show that the suppression of grating lobe is most efficient with the vertical deflection angle θ_0 fixed when $\alpha_0 = 45^\circ$. The SPL of main beam decreases less than 1dB, when the beam deflects in the plane of $\alpha_0 = 0^\circ$. The directional accuracy deviation of main beam occurs when the vertical deflection is over 50°, and the deviation level is approximately 5°.

6 CONCLUSIONS

The directivity features of phase-controlled and unphase-controlled rectangular arrays are researched in this paper. Some regular pattern and conclusion which have certain reference significance are obtained by simulation and experiment.

By measuring sound pressure of sound field from phase-controlled and unphase-controlled rectangular loudspeaker arrays, the authors showed that when the frequency, the distance between each array element and the horizontal deflection angle are certain, the SPL of main beam decreases when beam deflects. For 1000Hz audio signal, the SPL of main beam decreases less than 1dB if the vertical deflection angle is smaller than 60°. The directional accuracy deviation of main beam occurs when the vertical deflection is over 50°, and the deviation level is approximately 5°. The reasons resulted in SPL reduction was that the array elements are not the pulsating sphere source and the mutual acoustic impedance effect existed between elements. The directional accuracy of main beam is due to the mutual acoustic impedance and the diffraction in the edge of baffle.

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