RESEARCH ON AXIAL SOUND FOCUSING OF 16-ELEMENT CIRCULAR PISTON ARRAY

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The axial sound field of 16-element circular piston array was investigated when the sound was focused at the axial location. Firstly, the sound focusing formulas of 16-element circular piston array were derived from circular piston sound field radiation and phased array delay-time theories. Secondly, the axial sound focusing field was simulated at 8 kHz. The relations of far-field maximum, crossing points and focal points were analyzed, and the sound fields were compared at focal distances 0.5 m, 1.5 m, 2.5 m and 3.8 m. The results showed that the near-field sound pressure was improved obviously and lower down fast in the far field when the focal distance was 1.5 m. Finally, the experiment system was set up to testify the simulation results, and the axial sound pressures of locations 1 m, 1.5 m, 2.5 m and 3.8 m were measured at focal distances 0.5 m, 1.5 m, 2.5 m and 3.8 m. The experiments showed that the axial sound pressure was improved obviously and the maximum was 9.2 dB at focal distance 1.5 m. The sound pressure was reduced quickly when the axial distance was more than 3 m. The results show that the theoretical predictions agree well with the experimental results. The sound focusing can be used to improve the sound pressure level of 16-element array.

Keywords: circular piston, phased focusing, delayed time, focal distance

1. Introduction

Sound focusing can be applied to directional propagation of sound in air, improving the sound power and propagation distance along specific direction. The focusing techniques include phased focusing, reflector, Time Reversal Mirror, self-focusing (curved surface array, annular array, concave spherical transducer, etc.). Compared with the other methods, phased focusing is featured as flexible operation, high focusing ability and high anti-jamming capability. Furthermore, the beam angle, focusing range, and focusing dimension can be controlled by programmed software which is substituted for the traditional mechanical turntable in sound scanning and focusing system. Phased focusing has wild application in medical ultrasonic machines[1], industrial nondestructive test[1-3], bird-scaring equipment[4], underwater defense[5].

Based on theoretical derivation, Azar[6] analyzed the delayed time and sound pressure of rectangular-element linear array in two-dimensional sound field, and further investigated the radiated sound field of sound focusing and phase steering. However, only the two-dimensional sound field of linear array was discussed with the two-dimensional delayed time and sound pressure. And then, Li[7], Huang[8] and Du[9] investigated three-dimensional sound field of rectangular-element linear array, and further discussed element width, length, interval spacing, and element numbers’ effects on focused sound field. However, the focal point was confined to the axial plane of linear array. Hao[10] realized the phased focusing of 61-element shell transducer in engineering, applying FPGA chip design to 61-channel phase-controlled system with the phase shift accuracy of 1.42°. Assuming the element number as odd or even, Li[11] derived the computational formulae of steering, focusing
and steering-focusing in two-dimensional sound field of linear array. And then, the experiments were carried out to test the steering and focusing of CMUT.

The aerial sound focusing of one-dimension linear array is researched sufficiently, but the aerial phased focusing of two-dimension plane array needs to be investigated further. This paper presents the axial phased-focusing sound field of 16-element piston array. The axial sound pressure at 8 kHz was simulated and analyzed, and then experiments were carried out.

2. Theory

2.1 Critical distance of far and near field

In the near field, sound pressure oscillates and has many maximum values as propagation distance changes. After the critical distance, sound pressure declines as distance increases. The critical distance of far and near field is the key to distinguishing focusing and steering. When the focal point is in far field, the sound field of phased focusing is consistent with that of phased steering. When the focal point is in the near field or close to the critical distance, the sound fields of focusing and steering are of obvious difference.

The critical distance of array\(^{[6,12]}\)

\[
Z_{c} = \frac{D^2}{4\lambda}
\]

where \(D\) is array dimension, \(\lambda\) is wavelength. Distance less than critical distance, the sound field is the near field and otherwise, the sound field is the far field.

The critical distance of a circular piston\(^{[13]}\)

\[
Z_{0} = \frac{r^2}{\lambda}
\]

where \(r\) is piston radius. Distance less than critical distance, the sound field is the near field and otherwise, the sound field is the far field.

2.2 Delayed-time phased focusing

Based on the sound wave superposition theory, the array element’s initial phase is controlled to radiate sound waves at specific point where the sound wave phases are of no difference. The specific point is defined as the focal point where the sound pressure reaches to maximum. Because the element phase is the only factor changed, the focal point can be directed to any position without the array structure changed.

Figure 1 is a sketch of array sound focusing, where the original point locates in the array center, the focal point is \((x_f, y_f, z_f)\), the element center coordinate is \((x_i, y_i, z_i)\) and the propagation distances from element center to focal point are

\[
r_{fi} = \sqrt{(x_f - x_i)^2 + (y_f - y_i)^2 + (z_f - z_i)^2}
\]

\[
r_{f0} = \sqrt{x_f^2 + y_f^2 + z_f^2}
\]

Figure 1: sound field focusing of the sound array\(^{[14]}\).
Figure 2 is a sketch of 16-element circular piston array, whose delayed time of phased focusing for elements is

\[ \Delta t_i = \frac{r_{ij} - r_{i0}}{c}, \quad i = 1, 2, \ldots, 16 \]

\[ t_i = \Delta t_i + t_0 \]

where \( t_0 \) is a constant for avoiding negative delayed time. The distance from the element center to the focal point \((x_i, y_i, z_i)\) is

\[ r_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + (z_i - z_f)^2} \]

\[ r_0 = \sqrt{x_0^2 + y_0^2 + z_0^2} \]

According to the circular piston radiated sound field theory in the infinite baffled plate, the sound pressure distribution with the focal point \((x_f, y_f, z_f)\) is

\[ p_f = \sum_{i=1}^{16} p_i \]

\[ p_i = j\omega u_i p_0 a^2 \frac{2J_1(k a \sin \theta_i)}{2r} \left[ \frac{2J_1(k a \sin \theta_i)}{k a \sin \theta_i} \right] e^{i(k a \sin \theta_i - \omega t)} \]

![Figure 2: 16-element array.](image-url)

### 3. Simulation

#### 3.1 Simulation conditions

For 16-element circular piston array, piston radius \(a\) is 0.025 m, interval distance \(d\) between elements is 0.16 m, velocity amplitude \(u_i\) of piston vibrating uniformly is 3 m/s, air density \(\rho_0\) is 1.225 kg/m\(^3\), sound velocity \(c_0\) is 340 m/s.

#### 3.2 Simulation results

For 16-element circular piston array whose interval distance is 0.16 m and frequency is 8 kHz, the theoretical critical distance is 3.3 m. Figure 3 is the axial sound pressure changing with axial distance. The far-field sound pressure maximum is 198.5 Pa, and the corresponding axial distance is 2.9 m, beyond which the sound pressure declines as axial distance increases. Within 2.9 m, the sound pressure oscillates as the axial distance changes.

Sound waves are focused along the axial direction. As shown in Figure 4, X-axis represents the axial distance from array center to wave-reached position and Y-axis represents the corresponding sound pressure. In the legend, array represents elements without delayed time control and the other numbers represent the focal distance controlled by delayed time.
Figure 3: relationship of axial sound pressure and axial distance at 8 kHz.

Figure 4 shows that the sound pressure in the near field is obviously improved by sound focusing and decreases monotonically after the far-field maximum. Compared with the sound pressure of array, the sound pressure controlled by phased focusing will be smaller after some specific distance which is defined as crossing distance. Table 1 describes the far-field sound pressure maximums and corresponding distances. The focal distance reaching to 1.5 m, the SPL difference value between phased focusing and array attains the maximum 10.2 dB.

Figure 4: axial sound field.

<table>
<thead>
<tr>
<th>focal distance/m</th>
<th>corresponding distance of far-field maximum/m</th>
<th>far-field sound pressure maximum/Pa</th>
<th>SPL difference value between phased focusing and array /dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2.4</td>
<td>275.7</td>
<td>2.9</td>
</tr>
<tr>
<td>1.5</td>
<td>1.2</td>
<td>640.7</td>
<td>10.2</td>
</tr>
<tr>
<td>2.5</td>
<td>1.7</td>
<td>458.8</td>
<td>7.3</td>
</tr>
<tr>
<td>3.8</td>
<td>2.0</td>
<td>364.7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Figure 5 presents the far-field sound pressure maximum and corresponding distance changing with focal distance. The results show that far-field sound pressure maximum and corresponding distance of phased focusing change monotonically with focal distance and reach to the far-field
sound pressure maximum 198.5 Pa and the corresponding axial distance 2.9 m of array as the focal distance tends to be infinite.

![Graph](image1)

**Figure 5:** relationship of focal distances and far-field maximums.

Crossing distance (CD) is the axial distance beyond which the axial sound pressure of array is larger than that of phased focusing. Figure 6 shows that focal distance larger than 2 m, the corresponding sound pressure amplitude of crossing distance decreases monotonically with focal distance. Focal distance larger 1 m, the crossing distance increases monotonically with focal distance. However, sound pressure amplitude and crossing distance change ups and downs, respectively focal distance smaller than 2 m and focal distance smaller than 1 m.

![Graph](image2)

**Figure 6:** relationship of crossing distances and focal distances.

### 4. Experiments

A signal generator, an amplifier, a delayed-time device, array and sound measurements are included in the experiment system as shown in Figure 7.

![Image](image3)

**Figure 7:** experiment scene.
The single-frequency signals produced by the signal generator are input to the delayed-time unit and then the unit generates 16-channel delayed signal amplified subsequently by 16 amplifiers. The signals from amplifiers will be input to the array launching the phase-controlled sound waves which will be collected by transducers and a signal acquisition device.

As shown in Figure 8, the SPLs within 2 m are obviously improved at the focal distance 1.5 m where the maximum improvement is 9.2 dB. The axial distance larger than 2 m, the SPLs are reduced rapidly and the reduction from 2 m to 5 m is 15.6 dB. In sum, the experiment results showed that the sound field could be obviously enhanced at the focal distance of 1.5 m, which agrees well with the simulation results. The maximum improvement difference between experiment results and simulation results is less than 1 dB.

![Figure 8: measured results of sound focusing.](image)

### 5. Conclusion

This paper described the axial sound field of 16-element circular piston array when the sound was focused at the axial location. Firstly, the sound focusing formulas of 16-element circular piston array were derived from circular piston sound field radiation and delayed-time phase-controlled array theories. Secondly, the axial sound focusing field was simulated at 8 kHz and the results showed that the near-field sound pressure was improved obviously and lower down fast in the far field at the focal distance 1.5 m. Finally, the experiment system was set up to testify the simulation results. The experiment results showed that the axial sound pressure was improved obviously and the maximum was 9.2 dB at focal distance 1.5 m. The sound pressure was reduced quickly at the axial distance more than 3 m. The theoretical predictions agree well with the experimental results. The sound focusing can be used to improve the sound pressure level of 16-element array.

## REFERENCES


