Research on the directivity of transducer array based on typical array elements

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Abstract. In order to analyze the directivity of the array composed of different shape array elements, a line array is made up of the point source, circular, annular and rectangular piston sound source, and the directivity of the array is analyzed by simulation software. The results show that the directivity of line array is influenced by many factors, such as array element spacing, geometric dimensions, array shape, number of array elements, wave number or frequency, etc. When the condition is equivalent, the directivity of the transducer array composed of annular array element is relatively optimal.

1. Introduction

Transducers are important components of acoustic-electrical conversion and are widely used in industrial, agricultural, medical, transportation, military and life. With the increase in the requirements of the transducer, a single transducer cannot fully achieve high power, high directivity and wide frequency band performance indicators, and considering the combination of a single transducer in a certain way to form a special transducer array is a good choice for solving the problem. Line arrays have been widely studied due to their simple structure, excellent performance and wide application. YAO Xu et al. studied the influence of line array element spacing and width on wave number directivity; HUANG Jing et al. improved the directivity of the line array by adjusting the parameters of the line ultrasonic transducer array; PAN Min et al. studied the suppression of line array grating lobes. Some studies only consider the case of one or two shape elements, and some ignore the influence of the geometric dimensions or shapes of the elements. This paper analyzes the directivity of arrays of different shape array elements, and forms a line array with point source, circular, annular and rectangular array elements, and studies its directivity influenced by the spacing, geometric dimensions, shape, number of array elements, wave number or frequency, and finally analyzes and compares these results.

2. Line array directivity function model

Based on the theory of non-directional point source line array, the directivity of circular, annular and rectangular array element transducer arrays is calculated by Bridge product theorem.

2.1. Point source line array directivity function

The point source line array is shown in Figure 1. M non-directional point sources are evenly arranged in the $xoy$ plane, the adjacent elements are spaced by $d$, and the point source line array directivity function is $[3]$. 
2. Among them, \( k \) is the wave number.

\[
D(\alpha, \theta) = \frac{\sin\left(\frac{kdM}{2}\cos\alpha\sin\theta\right)}{M\sin\left(\frac{kd}{2}\cos\alpha\sin\theta\right)}
\]  

(1)

Figure 1. Schematic diagram of dot matrix array.

2.2. Circular line array directivity function

The single circular array element directivity function is \(^6\)

\[
D_2(\alpha, \theta) = \frac{2J_1(kb\sin\theta)}{kb\sin\theta}
\]  

(2)

According to the Bridge theorem, the composite system directivity function is

\[
D(\alpha, \theta) = D_2(\alpha, \theta) \cdot D_2(\alpha, \theta) = \frac{\sin\left(\frac{kM}{2}\cos\alpha\sin\theta\right)}{M\sin\left(\frac{k}{2}\cos\alpha\sin\theta\right)} \cdot \frac{2J_1(kb\sin\theta)}{kb\sin\theta}
\]  

(3)

Among them, \( b \) is the radius of the circular array element and \( J_1 \) is a first-order column Bessel function.

2.3. Annular line array directivity function

The single annular array element directivity function is \(^7\)

\[
D_3(\alpha, \theta) = \frac{2}{k\sin\theta(f^2-c^2)} \left( fJ_1(kf\sin\theta) - cJ_1(ke\sin\theta) \right)
\]  

(4)

According to the Bridge theorem, the composite system directivity function is

\[
D(\alpha, \theta) = D_3(\alpha, \theta) \cdot D_3(\alpha, \theta) = \frac{\sin\left(\frac{kM}{2}\cos\alpha\sin\theta\right)}{M\sin\left(\frac{k}{2}\cos\alpha\sin\theta\right)} \cdot \frac{2}{k\sin\theta(f^2-c^2)} \left( fJ_1(kf\sin\theta) - cJ_1(ke\sin\theta) \right)
\]  

(5)

Among them, \( c \) and \( f \) are respectively the inner and outer radius of the ring.
2.4. Rectangular Line Array Directivity Function

The single rectangular array element directivity function is [8]

\[
D_i = \frac{\sin\left(\frac{k d_i}{2} \cos \alpha \sin \theta\right)}{k d_i \cos \alpha \sin \theta} \cdot \frac{\sin\left(\frac{k d_i}{2} \cos \alpha \sin \theta\right)}{k d_i \cos \alpha \sin \theta} \cdot \left(\frac{k d_i}{2} \cos \alpha \sin \theta\right)
\]

(6)

According to the Bridge theorem, the composite system directivity function is

\[
D(\alpha, \theta) = D(\alpha, \theta) \cdot D(\alpha, \theta) = \frac{\sin\left(\frac{kM d}{2} \cos \alpha \sin \theta\right)}{M \sin\left(\frac{k d_i}{2} \cos \alpha \sin \theta\right)} \cdot \frac{\sin\left(\frac{k d_i}{2} \cos \alpha \sin \theta\right)}{k d_i \cos \alpha \sin \theta} \cdot \left(\frac{k d_i}{2} \cos \alpha \sin \theta\right)
\]

(7)

3. Comparative analysis of directivity of line array

3.1. The influence of array shape on directivity

The directivity of the line array consisting of point source, circular, annular and rectangular array elements is simulated by simulation software. The number of wave (which is related to wavelength and frequency) is selected as 500, the number of array elements is 4, the spacing of array elements is 6mm, the inner and outer radius of the ring are 4mm and 5mm respectively, the radius of circular array elements is 3mm, and the length and width of rectangular array elements are respectively 10mm and 3mm. For the convenience of observation, take the \(xOy\) plane as the orientation surface and take \(\alpha\) as 0. The simulation results are shown in Figure 2.

![Figure 2. Relationship between directivity and array shape.](image)

It can be seen from Figure 2 that the directivity of the line array is affected by the shape of the element. When the area of the array is equivalent, the array directivity main lobe composed of different shape elements is basically equivalent and the side lobe is obviously different. The amplitude of the directional side lobes of the array consisting of point source, circular, rectangular and annular array elements decreases in turn, and the directivity increases sequentially. Different shape elements have a significant influence on the directivity of the array, and the geometric dimensions of the elements cannot be ignored.
3.2. The influence of array spacing on directivity

The wave number is 500, the number of array elements is 4, the inner and outer radius of the ring are 4mm and 5mm, the radius of the circular element is 3mm, and the length and width of the rectangular element are 10mm and 3mm respectively. The spacing of the array elements is 6mm, 8mm and 10mm in sequence. The $xoy$ surface is oriented surface, and the simulation results are shown in Figure 3.

![Figure 3](image1)

**Figure 3.** Relationship between directivity and array element spacing.

It can be seen from Figure 3 that the width of the main lobe of the array of different shape elements is equivalent, but the width of the main lobe is narrowed, the side lobes increase, and the directivity increases as the spacing of the elements increases. The amplitude of the directional side lobes of the array consisting of point source, circular, rectangular and annular array elements is sequentially reduced, and the directivity is sequentially increased.

3.3. The influence of array geometric dimensions on directivity

The wave number is 500, the number of array elements is 4, and the spacing of array elements is 6 mm. Adjust the geometry of each array element while ensuring that the area of different shape elements is equivalent. The inner and outer radius of the ring are 2mm, 3mm; 4mm, 5mm and 9mm, 15mm. The radius of circular array elements is 2.24mm, 3mm and 12mm respectively. The length and width of rectangular array elements are 10mm, 1.57mm; 10mm, 2.83mm; 22.62mm, 20mm respectively. With $xoy$ surface as orientation surface, the simulation results of the array elements from small to large are shown in Figure 4.

![Figure 4](image2)

**Figure 4.** Relationship between directivity and array element geometric dimensions.

It can be seen from Figure 4 that when the size of the array element is small, the width of the main lobe of the array of different shape elements is basically the same, but the side lobe amplitudes are different. The amplitudes of the side lobes of circular, rectangular and annular array elements are sequentially reduced, and the suppression of side lobes is not obvious. As the size of the array element increases, the main lobe width does not change significantly, but the side lobe amplitude decreases relatively.
3.4. The influence of the number of array elements on directivity

The wave number is 500, the inner and outer radius of the ring are 4mm and 5mm respectively, the radius of the circular element is 3mm, the length and width of the rectangular element are 10mm and 3mm respectively, and the number of array elements is 3, 7 and 10 respectively, the $xoy$ surface is oriented, and the simulation results are shown in Figure 5.

It can be seen from Figure 5 that the width of the main lobe of the array of different shape elements is narrowed as the number of elements increases, and the amplitude of the side lobes is correspondingly suppressed, and the directivity is improved. Among them, the array consisting of annular array elements has the best directivity.

![Figure 5. Relationship between directivity and the number of elements.](image)

3.5. The influence of wave number or frequency on directivity

The inner and outer radius of the ring are 4mm and 5mm respectively, the radius of the circular element is 3mm, the length and width of the rectangular element are 10mm and 3mm respectively, the number of elements is 4, and the number of waves is 300, 500 and 700 respectively, the $xoy$ surface is oriented, and the simulation results are shown in Figure 6.

It can be seen from Figure 12~14 that the width of the main lobe of the array of different shape elements is narrowed with the increase of the wave number, the amplitude of the side lobes is correspondingly suppressed, and the directivity is improved. Among them, the array consisting of annular array elements has the best directivity. Therefore, increasing the wave number or increasing the frequency can enhance the array directivity.

![Figure 6. Relationship between directivity and wave number or frequency.](image)

4. Conclusions

With the geometric dimensions of the array elements are considered, the directivity of the line array consisting of point source, circular, annular and rectangular array elements is compared and analyzed. The conclusions are as follows:

(1) The line array directivity composed of different shape elements is similarly affected by element spacing, geometric dimensions, number of array elements and wave number. As the dimension of the
array element increases, the main lobe changes less, while the side lobe amplitude decreases. As the spacing of the elements increases, the main lobe becomes narrower, the side lobes increase, and the directivity is enhanced. As the number of array elements increases, the main lobe becomes narrower, the side lobe amplitude is suppressed, and the directivity is enhanced.

(2) The shape of the array element has a certain influence on the directivity of the line array. Under the premise that other parameters are basically the same, the amplitude of the side lobes of the array directivity consisting of point source, circular, rectangular and annular array elements is sequentially reduced, while the directivity is sequentially enhanced. In all cases, the annular array element has the best directivity.

(3) This paper only studies and analyzes the two-dimensional directivity, which can only reflect the spatial distribution of sound pressure of a particular orientation surface. The three-dimensional map can fully describe the orientation of the array, which needs to simply convert $\alpha=0$ to any angle to achieve. And this is for further study.

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