Design Analysis and Experimental Research of Multi-Segment Linear Reflector

Houlin Fang¹, Liangyong Zhang¹,², Pengyi Li¹, Fang Zhang¹, Yunzhe Liu¹, Shiying Tang¹ and Dezhi Zhang¹*

¹ Northwest Institute of Nuclear Technology, Xi’an, Shaanxi, 710024, China
² College of Meteorology and Oceanology, National University of Defense Technology, Changsha, Hunan, 410073, China
*Corresponding author’s e-mail: zhangdezhi@nint.ac.cn

Abstract: The parabolic reflector provides one of the common sound wave convergence methods in acoustic engineering. To reduce the difficulty of fabricating large-size reflectors and improve the convergence effect, this paper proposes a multi-segment linear reflector design method. Through the normal vibration radiation analysis of the flextensional transducer shell, the reflector interface reflection was optimized, the reflection effect was improved and the reflector size was reduced. The transmission theory was used to analyze the impact of different material parameters and sound wave frequency on the reflector transmission coefficient, and the gain effect of the multi-segment linear reflector was further tested. The research results show that the reflector has a significant gain effect in the test frequency band of 20~100Hz, and the gain at 70Hz I reaches the maximum of 11.2dB.

1. Introduction
Using the curved baffle reflection and focusing principle, the reflector converges sound waves according to a certain geometric law, which offers one of the effective methods for concentrating sound wave energy and enlarging propagation distance in acoustic engineering. It is often used for focusing of shock waves or sound waves in water [1-3]. As early as 1947, conical reflector was used to improve the directivity of the line source [4]; in 1968, the cylindrical parabolic reflector was used to focus the sound of the cylindrical transducer, and the transducer placed on different axis positions of the focal point produced different radiated sound fields [5]. Later, parabolic and ellipsoidal reflectors were developed. In recent years, Lei Kaizhuo, Ma et al. [6-8] studied elliptical reflectors, finding that machining errors and installation errors could cause errors in the first focus of the reflector and deviations between the sound wave convergence point and the second focus of the reflector, thereby affecting focusing performance of the sound field. According to the ray theory, He Xudong et al. [9] analyzed and proposed the calculation formulas for the ellipsoidal reflector, parabolic reflector and spherical reflector. The analysis showed that ellipsoid has the best convergence effect against point sound source, the paraboloid is able to converge the diffused sound, while sphere has diffraction in convergence of the point sound source and is thus inappropriate for reflector. Moosad et al. [10] studied the use of parabolic reflector to enhance the directivity of the flextensional transducer, using numerical simulation and experiments to study the effect of the specific placement position and specific direction of the flextensional transducer on the directivity.

In summary, the parabolic reflector can converge the diffused sound of the flextensional transducer,
but the processing error of the reflector will impair the convergence effect. Moreover, large-size parabolic reflector is costly and difficult to manufacture. Therefore, this paper proposes parabolic reflector design method via multi-segment linear approximation, and uses the transmission theory to analyze the impact of different material parameters and sound wave frequencies on the reflector's transmission coefficient, using this as a guide to produce multi-segment linear reflector and then carry out experiments to verify the convergence gain effect of multi-segment linear reflector.

2. Design and analysis of multi-segment linear reflector

2.1 The principle of parabolic reflection

Commonly used in acoustic focusing design, parabolic reflectors are also suitable for the focusing of flextensional transducers. Parabolic reflectors radiate the sound waves radiated by the pulsed sound source located at the focal point along the axis of the parabola to generate cylindrical waves and reduce expansion loss. The parabolic reflector of the flextensional transducer adopts the MajR scheme as shown in the figure. As shown in Fig. 1, the parabolic equation can be expressed as

\[ y^2 = 2px \]  

(1)

The distance from the shell center to the vertex of the parabola is set to \( x_0 \), and the tangent equation of the parabola corresponding to the shell center is

\[ y = \frac{p}{y_0} (x + x_0) \]  

(2)

To simplify the analysis, it is assumed that the sound wave radiation is relative to the shell center, which propagates to the reflector and reflects the sound wave in straight forward direction. Therefore, the slope of the tangent at this point on the corresponding parabola is 1, with \( y_0 = p \) according to the above formula. Thus, the parabolic equation at this time is

\[ y^2 = 4x_0x \]  

(3)

For flextensional transducer with elliptical shell (major axis 824mm, minor axis 243mm), take the distance from the transducer center to the vertex of the parabola \( x_0 = 550 \)mm, then the parabolic equation is obtained as follows

\[ y^2 = 2200x \]

The curve of the parabolic reflector obtained at this time is shown in Fig. 1. Since the elliptical shell vibrates in the outer normal direction and excites the sound wave, the sound wave propagates in the normal direction and is reflected when it encounters a parabola. The propagation direction after reflection is shown in the figure. Only the sound wave radiated at the shell center is reflected by the parabolic reflector and propagated along the \( x \)-axis direction, while the remaining reflection lines move closer to the propagation direction.

![Fig. 1 Schematic diagram of parabolic reflector and reflection direction](image-url)
2.2 Multi-segment linear reflection curve design

In view of the above-mentioned problems present in the reflection of the elliptical shell structure, we consider multi-segment design of the reflection curve. First, determine the multi-point parameters on the reflection curve, and then obtain the reflection section curve through the spline curve. In this method, the tangent slope of multiple points is known, while the specific position of the point is unknown, which incurs great trouble to curve fitting. Further, we consider the use of multiple straight lines in place of curves. For the specific operations: (1) Starting from the center position (symmetrical on both sides) along the major axis of the elliptical shell, select a number of points with a certain distance interval in the negative direction of the $x$-axis, plot auxiliary line based on these points (plus the center point) along the positive direction of the $y$-axis, intersect it with the ellipse; take the elliptic normal at the intersection of the ellipse (the normal bisects the angle between the two focal points and the point); (2) The normal is extended to the parabola, and at the intersection of the parabola, draw a straight line parallel to the $x$-axis (that is, the direction after the sound wave reflection), take the angular bisection between the elliptic normal and the reflection line. The vertical line of the bisector is a straight line that makes the sound waves parallel to the $x$-axis. Connect multiple straight lines to obtain the reflector curve; (3) Draw the multi-segment straight line from the straight line close to the origin. The key now is how to determine the boundary of the multi-segment straight line. After analysis and comparison, we consider using the intersection point of the straight line and elliptic normal angular bisection as the boundary of the multi-segment straight line.

Fig. 2 Schematic drawing of multi-segment linear reflection curve

To further reduce the reflector size, change the starting points of multiple straight lines to obtain multiple sets of reflector curves. In Fig. 3, $y$-axis size (single side) of the minimum reflector can be reduced to about 1000mm, and the relative parabolic size is reduced by nearly 50%. For the minimal reflector, the reflection of the entire curve can be obtained. Where, the short arrow shows the deviation of the reflection direction on each straight line. It can be seen that the reflection direction on each straight line basically follows the $x$ direction.
Fig. 3 Multiple sets of reflector curve and minimal reflector reflection

2.3 Transmission analysis of multi-segment linear reflector

For the determined multi-segment linear reflection curve, analyze the transmission conditions when different material parameters are adopted to guide the manufacture of the reflector. The reflector is applied in the air medium and sound waves pass through the intermediate layer. Place an intermediate layer medium (i.e. reflector material) with a thickness of \( D \) and a characteristic impedance of \( R_2 = \rho_2 c_2 \) in an infinite medium with characteristic impedance \( R_1 = \rho_1 c_1 \). Then, it is easy to obtain the ratio of the transmitted sound pressure to the incident sound pressure, as well as the ratio of the transmitted wave sound intensity to the incident wave sound intensity. That is, the sound intensity transmission coefficient can be expressed as

\[
\frac{t_p}{p_{ia}} = \frac{2}{4 \cos^2 \theta_i' D + \left( \frac{Z_{z2}}{Z_{z1}} + \frac{Z_{z1}}{Z_{z2}} \right)^2 \sin^2 k_i' D} \left( 4 \cos \theta_i' \right)
\]

In the formula, \( Z_{z1} = \frac{\rho_1 c_1}{\cos \theta_i'} \), \( Z_{z2} = \frac{\rho_2 c_2}{\cos \theta_i'} \), \( \theta_i' \) is the refraction angle in the intermediate layer.

The size of the transmitted wave when the sound wave passes through the intermediate layer concerns not only the characteristic impedance of the two media, but also the ratio of the intermediate layer thickness to the propagating wavelength. According to the available reflector material, we select the working frequency 20–100Hz. From the total reflection conditions \( D = \frac{(2n-1) \lambda_z}{4} \) and \( \lambda_z = \frac{c_2}{f} \), there is,

\[
D = \frac{(2n-1) \frac{c_2}{f}}{4}
\]

It can be seen from the formula that the lower the sound velocity and the higher the frequency of the reflector material is, the smaller the required material thickness is. Choose polyethylene with a low sound speed: sound speed \( c = 920\text{m/s} \), frequency \( f = 100\text{Hz} \), then \( D = 2.3\text{m} \), which is basically impossible in actual operation. Therefore, the reflector definitely has transmission, which is specifically calculated by the expression of transmission coefficient. The incident angles \( \theta_i \) of the
entire multi-segment linear reflector are (for each straight line, only take the point angle parallel to the x-axis in the reflection direction): 27.86°, 36.19°, 40.41°, 42.93°, 45.00°, 47.07°, 49.59°. Where, air medium parameters are: \( \rho_1 = 1.21 \text{kg/m}^3 \), \( c_1 = 344 \text{m/s} \).

The reflector is made of different materials, so the critical angle of total internal reflection is different. The material density, sound velocity, thickness and sound wave frequency will all affect the transmission coefficient. Figure 4 shows the change of the transmission coefficient with the incident angle under different material parameters and sound wave frequencies.

\[ I_t \]

Based on the above analysis, it is concluded that the transmission coefficient \( I_t \) is inversely related to the reflector material thickness \( D \), frequency \( f \), and material density \( \rho_2 \), and is positively related to the incident angle \( \theta \). That is, for better effect of the reflector, material with larger material density \( \rho_2 \) and structure with higher thickness \( D \) should be selected. Based on comparison of different thickness \( D \) and different material density \( \rho_2 \), one with larger product of the two should be selected. Finally, in view of the actual processing and production conditions, nylon materials are selected for the production of multi-segment linear reflectors.

3. Experiment and results

In this paper, an elliptical cylindrical flexextensional transducer was used, and the designed and manufactured multi-segment linear reflector was tested for radiated sound pressure. The specific test of sound pressure is as follows: the audio signal generator generates sinusoidal signals of different frequencies which are amplified by the power amplifier and loaded on the input end of the transducer to drive the transducer operation and externally radiate sound waves. The microphone (B&K4193) placed in the front of the transducer detects sound wave signal, and the signal is amplified, collected
and stored by the level recorder or data acquisition device. The microphone needs to be calibrated with a sound calibrator before use.

Through test, we obtain the sound pressure waveforms at 10 m in front of the transducer with and without the installation of multi-segment linear reflector, and the variation of the sound pressure level with frequency is derived through further calculation, as shown in Figure 5. It can be seen from the figure that as the frequency increases, the sound pressure level basically maintains an increasing trend, and the installation of reflector does not alter the overall variation trend with frequency. Without the reflector, the maximum sound pressure level is 100.2dB (100Hz). After installation of the reflector, the sound pressure level of the entire test frequency band of the flexextensional transducer is greatly improved, with the maximum sound pressure level up to 110.4dB (100Hz). Compared with the case without the reflector, the maximum gain occurs at 70Hz, reaching 11.2 dB. This proves that the design method of multi-segment linear reflector proposed in this paper is feasible with significant gain effect.

If we further study the gain effect of the multi-segment linear reflector, especially the gain effect relative to the parabolic reflector, considering that the large-size reflector used in this experiment will increase the production cost and difficulty of the parabolic reflector, we can adopt numerical simulation to carry out further research.

4. Conclusion

This paper proposes a multi-segment linear reflector design method. Through the normal vibration radiation analysis of the flexextensional transducer shell, the reflector interface reflection is optimized to improve reflection effect and reduce the reflector size. The transmission theory is used to analyze the impact of different material parameters and sound wave frequencies on the transmission coefficient, so that reflector materials and parameters can be selected under its guidance. Finally, the gain effect of the multi-segment linear reflector was experimentally tested. Studies have shown that the reflector has significant gain effect in the frequency range of 20~100Hz, with the maximum gain at 70Hz, reaching 11.2dB.

The multi-segment linear reflector proposed herein is applicable to the production of large-size reflectors, which can provide technical reference for related needs.

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