QUASI-FAR FIELD CRITERION OF UNDERWATER ELASTIC STRUCTURE FOR RADIATED SOUND POWER MEASUREMENT

Yan Xiao\textsuperscript{1,2}, Dejiang Shang\textsuperscript{1,2}, Qi Li\textsuperscript{1,2}, Chao Zhang\textsuperscript{1,2}

1. Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin, China 150001; 2. College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin, China 150001

e-mail: xiaoyan_0220@126.com

This paper derives a method for determining the quasi-far field criterion for measuring the radiated sound power from underwater elastic structures by method of mean squared sound pressure. A numerical experiment is presented for a finite elastic cylindrical shell excited by a point force in the water using finite element method (FEM). The radiation noise field at points on the acoustic axis of the shell is simulated. The phase difference between the pressure and velocity on those field points, as well as the attenuation law of sound pressure amplitude with the testing distance, are analyzed to determine the quasi-far field criterion. The simulation results show that the radiated sound power from the cylindrical shell can be precisely measured by method of mean squared sound pressure according to this quasi-far field criterion, which is much less than the classic criterion of far field $L_2/\lambda$ for sound sources in general. This means that sound pressure can be measured at points nearer to the elastic structure to determine its radiated sound power by method of mean squared sound pressure, which is very valuable for sound source level measurements when the signal-to-noise ratio is low.

1. Introduction

The measuring distance for radiated noise of large-scale underwater vehicle is about several hundred meters determined by the classic far-field testing criterion\textsuperscript{1}. However, at the far-field, the multi-path interference of test environment could not be avoided. And more, the signal to noise ration could not meet the requirements at the far-field\textsuperscript{2}, so that the near-field measurement must be considered. At present, aiming at the radiation noise measurement for submarines or other underwater vehicles, the structure is often deemed as a point sound source, and the source level is estimated by spherical wave attenuation. When the measurement distance is reduced, the measurement will be up against the problem that point source assumption is whether rational or not. Therefore, how to determine the measurement distance is a major problem. This paper has researched on the measuring distance criterion for underwater structure radiated noise from the perspective of energy measurement. A concept of quasi-far field measuring criteria is derived respondent to the far-field criterion of the traditional acoustic theory. When the phase difference between the pressure and particle normal velocity on wave front is close to zero, the radiation
pressure at this distance is satisfied the spherical wave attenuation law and the structure radiation sound field is similarly reached far field state. In this paper, this distance is definite as quasi-far field distance for the structural radiation pressure measurement.

2. The radiated sound power by mean squared sound pressure measurement

In the free space, if the radiation sound pressure is attenuated with $1/r$ ($r$: the distance from the measuring position to the structure), as well as the acoustic impedance is similar to plane wave impedance, the sound field is reach the far field. Scholars has taken the radiation sound field on the sound axis of a circular piston places on an infinite plane hard baffle for example, carried out a detailed derivation of the near field and far field acoustic characteristics, and presented the classic far-field testing criterion\(^1\):

\[
Lr \geq \frac{\lambda^2}{L}, \quad r \geq L
\]

Where, $L$ is the maximum line length of the structure, $\lambda$ is wavelength.

For underwater acoustic measurement experiment, when the scale of transmitting transducer is small, the criterion is relatively easy to meet. But for the large-scale underwater elastic structure measurement, it is difficult to achieve the requirement. For example, when measuring the axial pressure of a structure which length is 30m, the critical distance is so far as 300m at 500Hz that the SNR could not be enough. And more, the far-field measurement criterion above is used for measuring the radiated sound pressure on the sound axis. Only the uniformity of transverse amplitude distribution could be ensured, but not the other directions.

A far-field criterion $r \geq 10 \times L$ is put forward for the transducers which radiation surfaces are not uniform. But this requirement is also inapplicable for large-scale underwater elastic structures. When the size of underwater elastic structure is larger, and the internal sound source is complex, the sound field distribution is not uniform at near field. Thus the radiation noise is difficult to be evaluated by the acoustic radiation pressure at limited points.

The structure radiated sound power can be obtained by the integration of sound intensity on a closed surface surrounding the structure. It is a constant value regardless of the measurement distance. Therefore, it is considered that using the radiated sound power to evaluate the radiation noise of structure. The radiated sound power is calculated as follows.

\[
W = \int_s Ids
\]

Where, $I$ is the sound intensity.

$I$ is determined by pressure amplitude $p_0$, velocity amplitude $u_0$, and the phase difference between the pressure and velocity $\varphi_0$:

\[
I = \frac{1}{2} p_0 u_0 \cos \varphi_0
\]

When pressure and velocity are in phase, the sound field will meet the requirement of plane wave, then:

\[
I' = \frac{p_0^2}{2 \rho c}
\]

Where, $\rho c$ is the medium impedance.

Therefore, at the position where the pressure and velocity are in phase, the sound intensity could be obtained by measuring mean squared sound pressure, and the sound radiation power could be calculated by Eq. (2). Thus the problems, that the phase measurement is difficult, the accuracy is low, and so on, could be avoided effectively.
3. **Numerical simulation of underwater single cylindrical shell radiation sound field**

The radiation sound field of underwater single cylindrical shells is simulated by finite element method and boundary element method\(^3\text{-}^5\). Cylindrical shells are modelled with shell elements, Young's modulus \(E = 2.06 \times 10^{11} \text{ N/m}^2\), Poisson's ratio \(\sigma = 0.3\), density \(\rho = 7800 \text{ kg/m}^3\).

The scales of three cylindrical shell models\(^6\):

- **model1**: \(L = 1 \text{ m}, D = 0.16 \text{ m}, h = 0.005 \text{ m}, \Delta l = 5 \text{ cm}\).
- **model2**: \(L = 2 \text{ m}, D = 0.80 \text{ m}, h = 0.005 \text{ m}, \Delta l = 5 \text{ cm}\).
- **model3**: \(L = 5 \text{ m}, D = 1.50 \text{ m}, h = 0.005 \text{ m}, \Delta l = 10 \text{ cm}\).

Where, \(L\) is the length of shell, \(D\) is the diameter, \(h\) is the thickness, \(\Delta l\) is the element length. The models are as shown below:

![Finite element models of cylindrical shell](image1)

**Figure 1.** The finite element models of cylindrical shell.

An excitation is loaded at the position that the centre of a generating line, the intensity is 1N, and the direction is radial outward. The pressure and velocity are numerical calculated at the annular field points in the three coordinate planes that radius are 0.5m~200m.

The model and the field points are as shown below:

![Finite element model and the field points](image2)

**Figure 2.** The finite element model and the field points.

The sound intensities at different distances on the excitation direction away with the shell are calculated by Eq. (3) and Eq. (4) respectively. The results calculated by the two methods are compared. The result of Eq. (3) is used as the reference value. The error curves of mean squared sound pressure calculated results of model1 are shown as follows:
(1)distance: 0.5m~200m  
(2)frequency: 10Hz~50Hz  
(3) frequency: 100Hz~5000Hz

**Figure 3.** The errors of sound intensity calculated results at different distance

It can be seen from the results above that the critical distance, where the error of mean squared sound pressure calculated result is less than 1dB, is decreased as the measurement frequency increased. However, the far-field measurement distance according to the classical criterion is increased as the frequency increased. In order to illustrate the problem in detail, $\phi_0$ on a circle round of the structure in the three coordinate planes are compared and analyzed. When the pressure and velocity are in phase, $\cos \phi_0 = 1$. So, $\cos \phi_0$ are shown as follows for analyzing conveniently.

![Figure 4. $\cos \phi_0$ at different positions in the three coordinate planes ($f=200Hz$)](image)

As it can be seen from Fig. 4 and Fig. 5, the phase differences between the pressure and velocity in the three coordinate planes are varied greatly. When $f=200Hz$, at the positions further than 9m, the phases of pressure and velocity are same in all of the three planes. When $f=2000Hz$, the distance is decreased to 1.5m.

Accordingly, the critical distances of mean square pressure sound pressure measurement are variable at different frequencies. In the following table, there are the analysis results of the three models at partial frequencies, where $d_0$ is the critical distance.
The critical distances at different frequency in the table are analyzed, and a preliminary regularity could be summarized as:

\[ d_0 = \frac{6\lambda}{\sqrt{L/D}} \quad (L < \lambda) \]  
\[ d_0 = \frac{6L}{\sqrt{L/D}} \quad (L \geq \lambda) \]

For the cylindrical shell, the critical distance is relative to the ratio of length and diameter, and it is almost a constant when the wavelength is smaller than the length. In order to verify this conclusion, the radiation sound power on the external spherical enveloping surface is calculated. The reference value of radiation sound power \( W_{\text{ref}} = 0.67 \times 10^{-18} \text{W} \).

The results of model 1 are as follows:

![Graphs and data](image.png)
4. Conclusion

In the near field, the phases of pressure and velocity are different. When using mean square sound pressure instead of sound intensity, the calculate error of the radiation sound power could not be neglected. The radiation sound fields of the three models with different scales are simulated in this paper. A quasi-far field criterion is preliminarily put forward by comparing the phase difference between pressure and velocity. At the position determined by the criterion, it could not be ensured that the radiation sound is attenuated with $1/r$, but the radiation sound power could be accurately obtained by the mean square sound pressure measurement method. Because the phase is not need to be measured, the problem caused by the poor accuracy of phase measurement could be avoided.

However, the simulations are just at several frequencies, the number of models is very limited, and the models are all axis symmetric. Thus, in order to verify whether the criterion presented in this paper is universal or not, the intensive theoretical researches and sufficient calculations are required.

ACKNOWLEDGMENTS

This work was partially supported by the National Natural Science Foundation of China (11274080); The Foundation of Science and Technology on Underwater Acoustic Laboratory, Harbin Engineering University (9140C200203120C20083).

REFERENCES