Research on the underwater echo characteristics by hollow coaxial cylinder-cone assembled elastic shell

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Abstract: For the purpose to research the underwater echo characteristics of elastic shell, the numerical expressions of surface sound pressure and particle vibration velocity are derived based on finite element and boundary element theories. The echo characteristics of hollow coaxial cylinder-cone assembled elastic shell are calculated with simulation and experiment methods to obtained the azimuth angle and frequency characteristics. It´s shown in the results that the more quantity of mesh point, the higher precision of calculation. Meanwhile, the magnitude of mirror reflection wave is largest in the echo wave between 20 and 40 kHz, and increases as the scattering cross-section. The backscatter sound pressure of elastic shell has the obvious frequency characteristic.

Key words: elastic shell; finite element; boundary element; echo characteristic

1 Introduction

Under the effect of sound waves, the object being detected underwater can be excited out the scattering acoustic field with its own physical properties which is necessary in some practical engineering applications. Generally, the analytical method and numerical method are used to calculate the scattering acoustic field of elastomer. The former is mainly aimed at the simple objects with regular geometrical shape, such as Helmholtz integral equation and separation of variables[1~4]. As to the irregular geometrical objects, the latter can calculate the acoustic properties with the advanced computer, such as physical acoustic method, T-matrix method and FEA +BEA[5~8], which get the wide application prospects in engineering.

Based on FEA and BEA theories, this paper will deduce the equations for calculating the surface sound pressure and particle vibration velocity of elastic shell under the plane wave excitation to obtain the underwater echo characteristics of elastic shell. On this basis, the azimuth angle and frequency characteristics of scattering sound pressure are simulated and experimentally analyzed in the anechoic tank to acquire the causes of echo characteristics.

2 Calculation of scattering acoustic field for elastic shell

The FEA and BEA equations are respectively used todescribe the elastomer's vibration state and the relation between the surface sound pressure and particle vibration velocity. Hence the numerical equation of scattering acoustic field can be deduced[9].

The FEA equations are established based on the principle of minimum potential energy, and isoparametric element method is used to solve the definite integration in irregular region. Then the BEA equations areestablished with Helmholtz integral formula to solve the integral singularity. Finally, the equations for calculating the surface sound pressure and particle vibration velocity of elastic shell under the plane wave excitation are deduced.

Firstly, in order to transform the vibration effect of elastic structure into the load vector in the finite element equation, the acoustic-structure coupling matrix L is adopted. The expression of this matrix is

$$L = \sum^{e} \int_{S} N \cdot \{\vec{n}\} \cdot N^{T} dS \quad (1)$$

where, $\{\vec{n}\}$ is the outward normal vector, N is interpolation function.

Then the finite element equation for calculating the acoustic-structure coupling is

$$[K\text{-}\omega^2 M]D + [L]P = 0 \quad (2)$$

where, K is global stiffness matrix of elastic structure, M is global mass matrix, ω is radian frequency of the incident sound wave, D is particle displacement, L is acoustic-structure coupling matrix, P is surface sound pressure which includes the incident and scattering sound pressure.

After transformed, Eq.(2) is

$$\begin{cases} D = -(K\text{-}\omega^2 M)^{-1}[L]P \\ P = -[L]^2(K\text{-}\omega^2 M)D \end{cases} \quad (3)$$

When the viewpoint is located onsurface S and the incidence plane wave is existed, Helmholtz integral formula can be expressed as[10].

$$2\pi P\text{-}4\pi P_i = \int_{S} \frac{-ikr\text{-}1}{r^2} e^{-ikr} \cos(\vec{n},\vec{r}) \cdot P\text{-} \rho\omega^2 \frac{e^{-ikr}}{r} \vec{n} \cdot \vec{D} dS \quad (4)$$

where, k is wave number, r is the distance between viewpoint and integral infinitesimal, $\vec{r}$ is radius vector from integral moving point to site, ρis density of fluid media.

In order to obtain the equation of surface sound pressure P and particle displacement D in each node, Eq.(4) will be discretized into the integration summation of every element[11-13]. As to the closed curve, each node is shared by the adjacent element, then Eq.(4) can be simplified as

$$2\pi P\text{-}4\pi P_i = \sum_{j=1}^{M} [\alpha_{kj} + \alpha_{lj} + \alpha_{mj} + \alpha_{nj}] P_j + [\beta_{kj} + \beta_{lj} + \beta_{mj} + \beta_{nj}] D_j \quad (5)$$

Hence, the relation of sound pressure and displacement between nodes can be converted to the matrix form, which is

$$[C]P\text{-}4\pi P_i = [H]P\text{-}[G]D \quad (6)$$

Substituting Eq.(4) into Eq.(6), then eliminating particle displacement D and surface sound pressure P to get

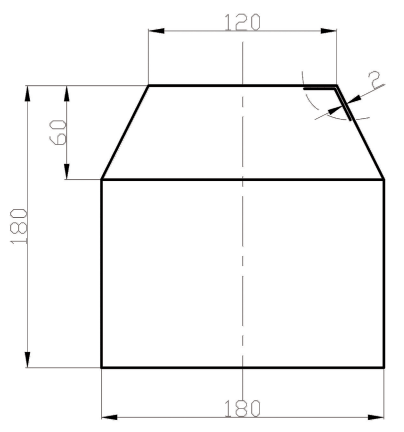
$$\begin{cases} P = 4\pi([C\text{-}H]\text{-}[G][K\text{-}\omega^2 M]^{-1}[L])^{-1} P_i \\ D = 4\pi(\text{-}[C\text{-}H][L]^{-1}[K\text{-}\omega^2 M] + [G])^{-1} P_i \end{cases} \quad (7)$$

where, G is Green function, C and H are transform items.

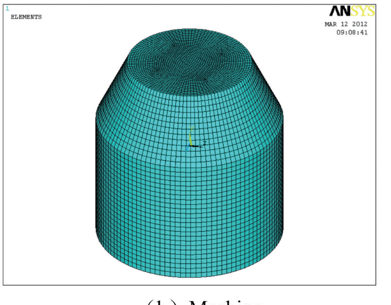
Hence, the surface sound pressure and the particle displacement can be obtained with Eq.(7), as well as the external scattering sound field will be calculated by Helmholtz integral formula.

3 Echo characteristics simulation for hollow coaxial cylinder-cone assembled elastic shell

The azimuth angle and FRF properties of inverse scattering sound pressure for a steel revolving shell in the case of monostatic are calculated out with the numerical equation of scattering acoustic field. The model parameters are: Young modulus E is 2.06×10^{11} Pa, Poission ratio σ is 0.28, density ρ is 7800 kg/m^3. The dimensions and meshing are shown in Fig.1.



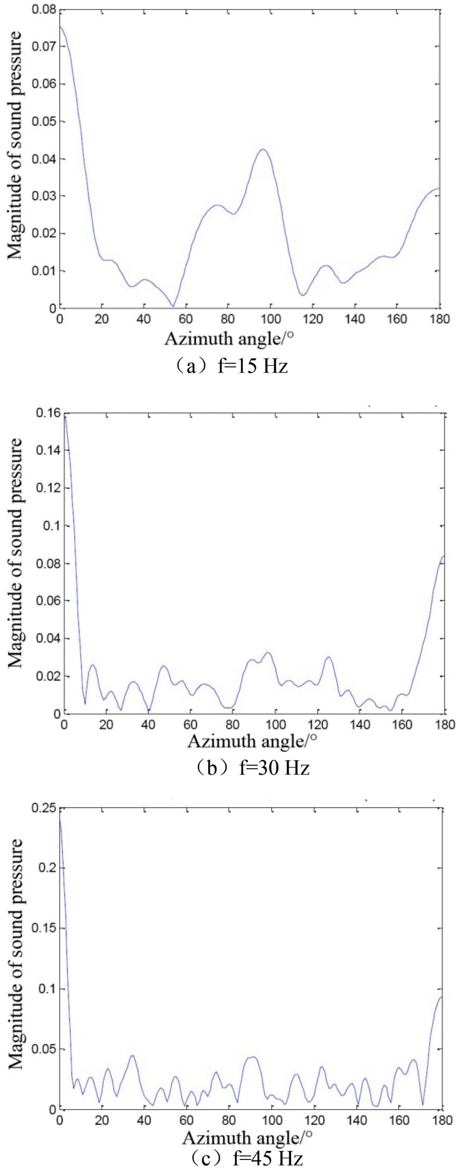
(a) Dimensions



(b) Meshing

Fig. 1 Dimensions and meshing of simulation model

The azimuth angle calculation results of inverse scattering sound pressure when frequencies are 15 Hz, 30 Hz and 45 Hz are shown in Fig.2.



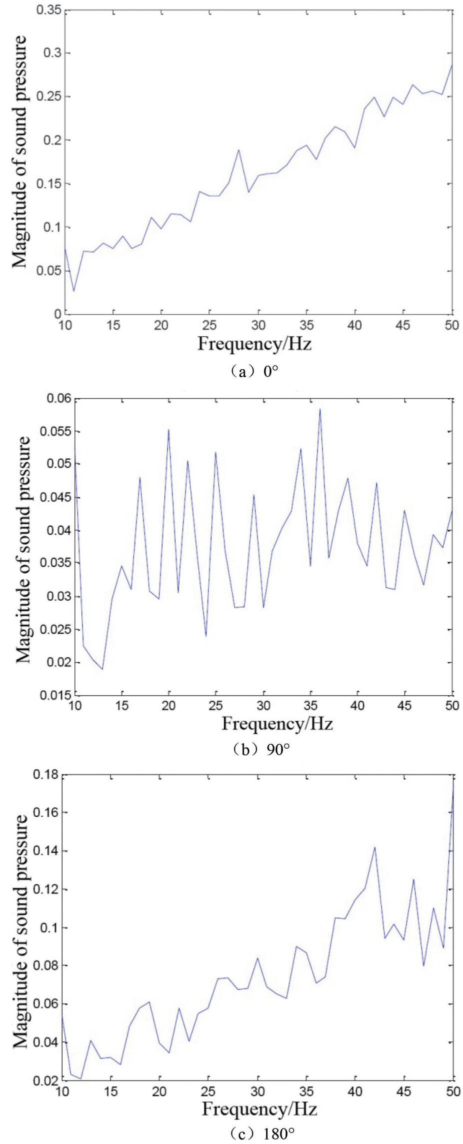
(a) f=15 Hz
(b) f=30 Hz
(c) f=45 Hz

Fig. 2 Variation of inverse scattering sound pressure with azimuth angle

It's shown in Fig. 2 that the value of inverse scattering sound pressure is largerwhen the azimuth angle is 0°, 90° and 180°. Mean while, the sound pressure is related to the scattering cross section. Moreover, there are more peaks in the curves as the frequency increasing.

The FRF results ofscattering sound pressure when azimuth angle are 0°, 90° and 180° are shown in Fig.3.

Fig.3 shows the magnitudes of sound pressure increase with frequency when azimuth angle is 0° and 180°, meanwhile the curves are more smooth. The reason is that the mirror reflection will happen when the azimuth angle is at the value of 0° and 180°, and hence the magnitude of sound pressure increases obviously to take a main part in the echo component. As the frequency increases, the energy of diffraction sound wave decreases but the reflection energy increases, therefore the magnitude of inverse scattering sound pressure increases.



(a) 0°
(b) 90°
(c) 180°

Fig. 3 FRF curves of inverse scattering sound pressure in different azimuth angle

Moreover, there are more irregular peaks in the FRF curve when azimuth angle is 90°, which is caused by the increment of wave number as frequency increases. Since the phase difference of sound pressure between different surface areas will increase with the wave number, the influence of surface sound pressure and normal practical vibration on scattering sound pressure increases, and leads to the irregular variation of FRF results.

4 Experimental analysis and verification

The azimuth angle and FRF properties of inverse scattering sound pressure for monostatic transducer are tested in the anechoic tank, and the experimental results are compared with the simulation.

The test target is hung in a turnplate by two soft ropes which can make it rotate freely and horizontally. Test arrangement is shown in Fig.4.

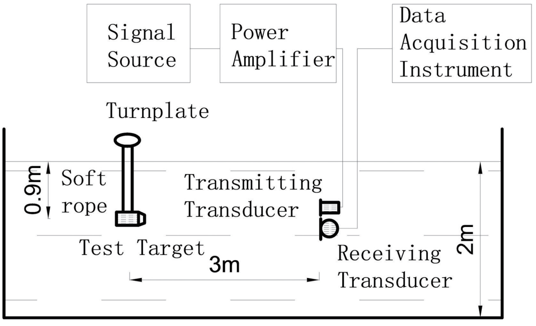
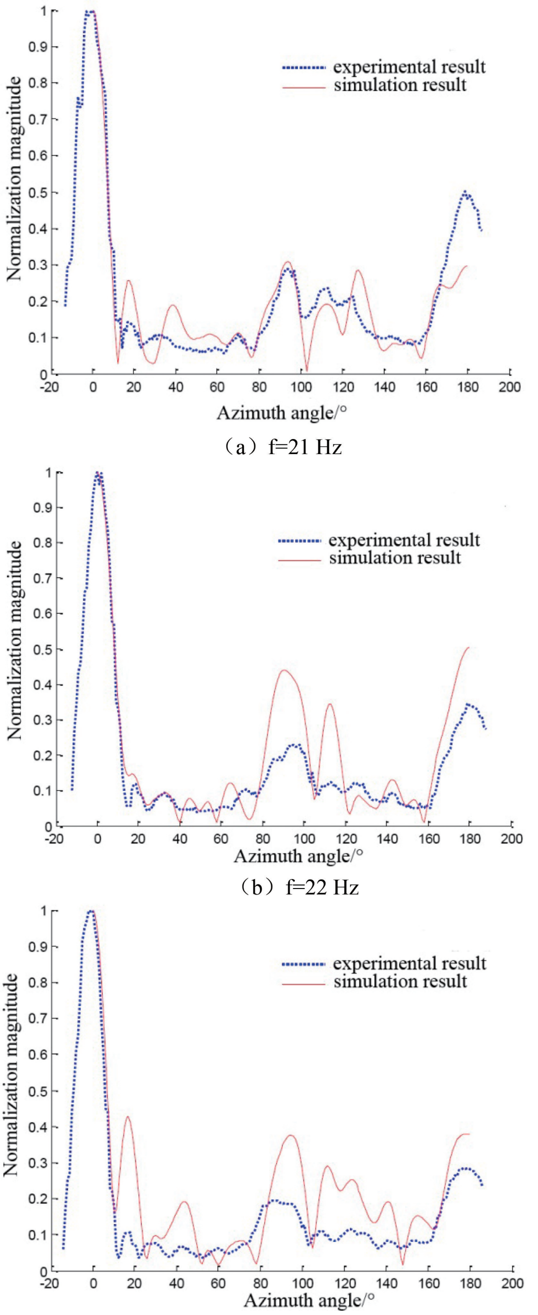


Fig. 4 Test arrangement in the anechoic tank

Since the resonant frequency of transmitting transducer is 22 kHz, three frequency test points which are 21 kHz, 22 kHz and 23 kHz are chosen to obtain the higher SNR. The trigger period of CW pulse is 1s, and the number is 10. The reference azimuth angle is along the outer normal of test target bottom. The model is rotated from 0° to 180° and the data is recorded every one degree.

The azimuth angle of inverse scattering sound pressure is tested in three frequency points as above, and the results are shown in Fig.5.

It's indicated from Fig.5 that the variation tendency of azimuth angle is similar between the experiment and simulation. The reason for these echoes is the angular wave and Lamb wave[14~15]. From the test, when there is the mirror reflection happened, the maximum value of inverse scattering sound pressure is from the target bottom is largest, and the minimum is from the lateral.



(a) f=21 Hz

(b) f=22 Hz

(c) f=23 Hz

Fig. 5 Comparison of experiment andsimulation result for inverse scattering sound pressure varying with azimuth angle in different frequency

The FRF properties of inverse scattering sound pressure when angle is 0°, 90° and 180° are shown in Fig.6.

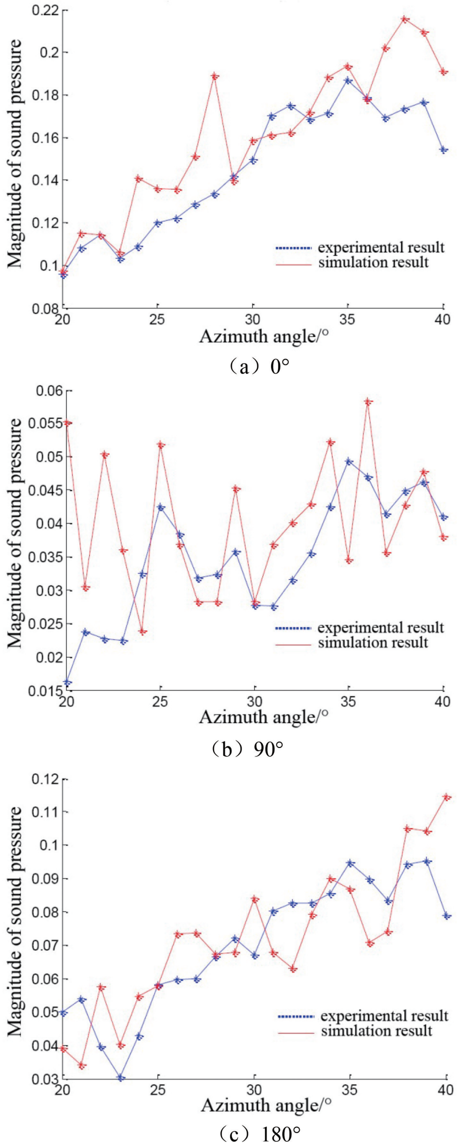


Fig. 6 Comparison of experiment andsimulation result for FRF curves of inverse scattering sound pressure in different azimuth angle

As shown in Fig. 6. (a) and Fig. 6. (c), the sound pressure increases with the frequency in the bottom and top of test target, but the difference is larger in Fig.6. (b). There are three reasons for the discordance between experiment and simulation.

1) The models between experiment and simulation exist difference;

2) The calculation procedure adopts Gaussian elimination method which has the higher computation speed but less precision.

3) The distance between test target and transducer is not large enough for the restraint of tank dimension.

5 Conclusion

The echo characteristics of hollow coaxial cylinder-cone assembled elastic shell areanalyzed with the scattering acoustic field numerical model established based on FEA and BEA theories. As well as the experimental verification is carried out in the anechoic tank. Some conclusions are summarized that the echoes of elastic shell have the mirror reflection wave, angular wave and scattering wave, and among them the inverse scattering wave has obvious frequency characteristics.

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