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# RESEARCH ON THE RESONANCE FREQUENCY SHIFT OF THE UNDER WATER CIRCULAR CYLINDRICAL SHELLS

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This study investigates the resonance frequency shift of a submerged cylindrical aluminum shell, due to boundary reflections. Utilizing the finite element method, this paper numerically simulates the effects of external loading by the water surface, exploring the dependence of the shell's resonance frequency shift on submerged depth. The experimental and numerical findings consistently demonstrate that the resonance frequency of the shell decreases as the submerged depth increases. Moreover, it is found that the resonance frequency shift weakens when the shell is vertically oriented, with its circumference paralleled to the horizontal plane. Additionally, The work provides a critical submerged depth below which the resonance frequency shift ceases to occur.

*Keywords: underwater experiment, resonance frequency*

## 1. Introduction

Underwater submersibles are often located in bounded flow fields such as shallow water environments, where the presence of fluid boundaries like the free surface significantly influences their vibrational sound characteristics[1]. The interface's reflection of sound waves not only changes the propagation path of the sound but also, through multiple reflections, stimulates the geometric and elastic scattering of the structure. This affects the characteristics of sound radiation and the spatial distribution of the sound field. Therefore, studying the vibrational and acoustic radiation characteristics of cylindrical shells within bounded flow fields is crucial for optimizing the acoustic stealth capabilities of underwater submersibles.

Extensive work has been conducted on the acoustic vibration analysis of cylindrical shells beneath interfaces, predominantly based on theoretical and numerical methods. Wang Bin conducted an in-depth analysis of the acoustic vibration characteristics of cylindrical shells in semi-submerged and fully submerged states. By examining the mean square vibration velocity and acoustic power radiation of the cylindrical shell surface under infinite line excitation, he revealed the differences and connections in acoustic vibration behavior between the two submerged states[2]. Zhao Kaiqi used the method of virtual sources and Graf's addition theorem to establish an analytical model for the acoustic radiation of a spherical shell under point force excitation near an ideal interface, providing a simple formula for predicting interference fringes in the sound pressure frequency spectrum[3]. Yu Dapeng explored the acoustic radiation characteristics of ships in different water depth domains[4], and Wu further optimized the accuracy of sound field calculations in ideal waveguides by combining ray theory with normal mode methods[5]. Seybert addressed the problems of acoustic radiation and scattering within a half-space using the boundary integral method, optimizing the treatment of infinite boundary issues with the Helmholtz integral equation[6]. Ergin[7]and Amabili[8] specifically highlighted the impact of the free surface on the natural frequencies of cylindrical shells, with Ergin noting significant increases in vibration frequency due to the free surface through experimental and numerical methods. Amabili simplified the treatment of partially submerged structures with an innovative sectorial boundary method[9]. Wang introduced modal mass addition to explain the impact of shallow water on coupled modal frequencies, noting significant effects in shallow water depths due to contributions from fluid boundaries[10]. Guo studied the acoustic-structural coupling issues of cylindrical shells within a quarter-water domain, discussing the complex acoustic boundary conditions and their impacts on the shell's vibration and sound radiation[11]. Li utilized the steady-phase method and Graf's addition theorem to obtain analytical expressions for the far-field sound pressure, comparing the results of cylindrical shells in finite and infinite spaces submerged in water, showing that the presence of a free surface significantly affects the far-field sound pressure radiated by the cylindrical shells[12].

Previous research has primarily relied on analytical and numerical methods, focusing on the far-field acoustic radiation characteristics. This paper, using an aluminum cylindrical shell as the subject, explores the effects of external loads induced by the water surface on the shell's resonance frequency through a combination of numerical and experimental research methods. The impact of the shell's submersion depth on its frequency shift is examined, comparing the differences between vertical and horizontal submersions through experimental methods. Ultimately, a critical submersion depth is determined where the shift in resonance frequency ceases, providing valuable insights for the design and operational parameters of underwater cylindrical structures.

## 2. Numerical analysis

To investigate the impact of external loads caused by the water surface on the resonance frequency of cylindrical shells, this section conducts numerical simulations using COMSOL Multiphysics software, as illustrated in the figure 1. The geometric properties of the cylindrical shell are as follows: the length 0.83 m, the diameter 0.25 m, and the wall thickness 0.005 m. The elastic properties of the cylindrical shell include Young's modulus $E = 69\text{Gpa}$ , Poisson's ratio $\mu = 0.33$ , the density of aluminum alloy $\rho_{\text{al}} = 2750\text{kg} / \text{m}^3$ . The water density $\rho_{\text{f}} = 1000\text{kg} / \text{m}^3$ and the sound speed $\mu = 0.33$, with a PML (Perfectly Matched Layer) thickness of 0.25 m. A three-dimensional solid modeling approach is employed, and both the cylindrical shell and the water domain are modeled using free tetrahedral meshes. The maximum mesh size for the cylindrical shell is 0.023 m, and for the water domain, it is 0.23 m. A point excitation is applied at the center of the cylindrical shell's outer surface, with an excitation force of 15 N and a frequency range from 1 Hz to 1000 Hz.

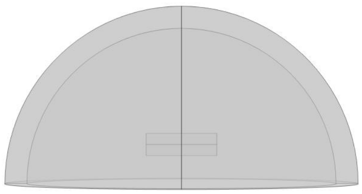


Figure 1: Schematic diagram of cylindrical shell under the interface.

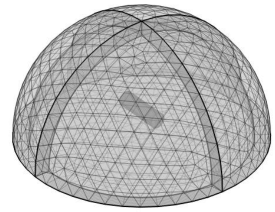
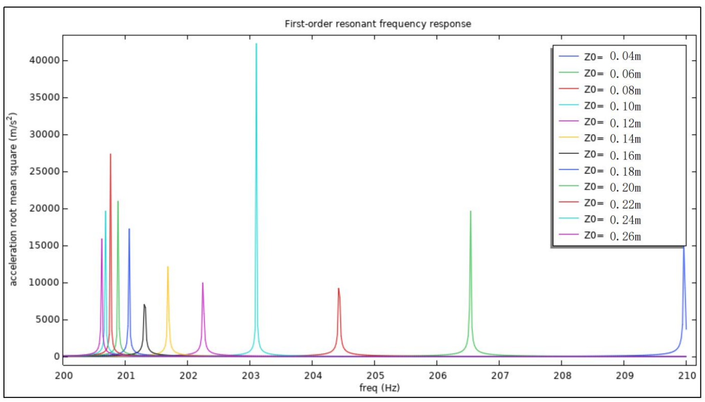
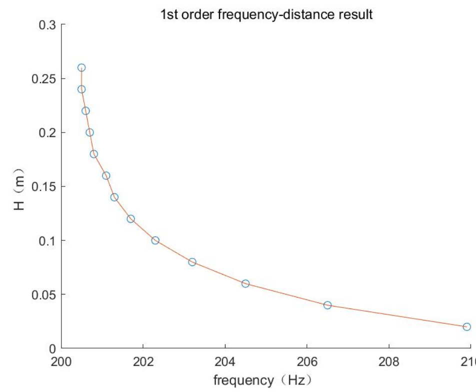


Figure 2: Finite element model.

The initial height of the cylindrical shell from the horizontal water surface is 0.02 m. In increments of 0.02 m, the shell is progressively lowered away from the free surface. The figure3-5 presents the frequency response of the first four resonance frequencies at various depths.

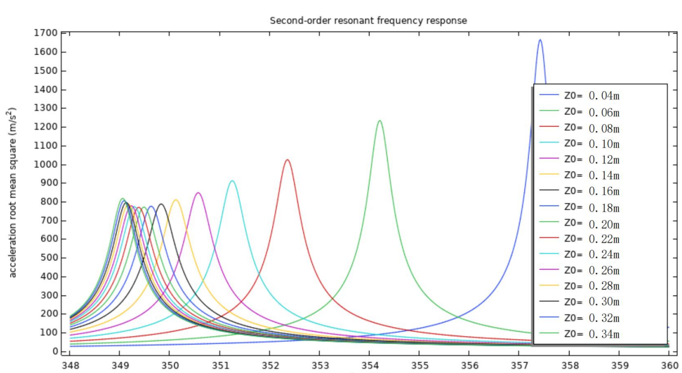



A.First-order resonant frequency response

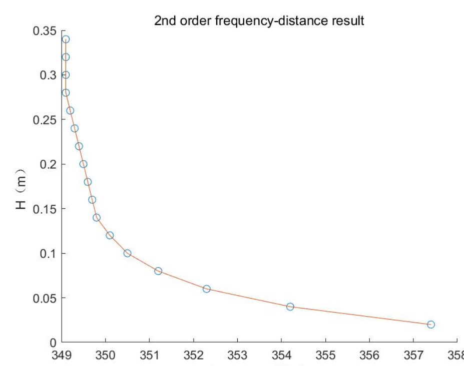



B.First-order frequency versus immersion depth results

Figure 3: First-order resonance frequency shift results.

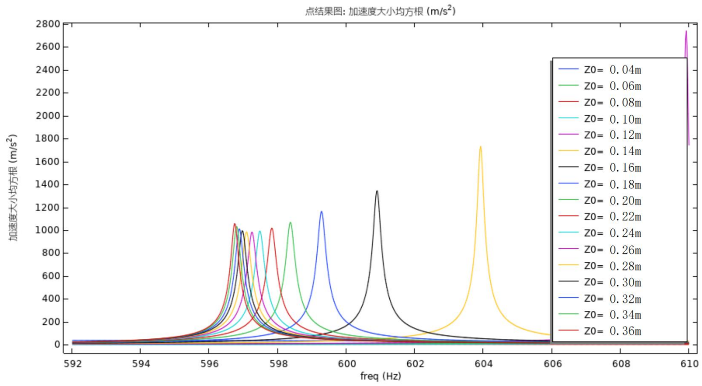



A.Second-order resonant frequency response

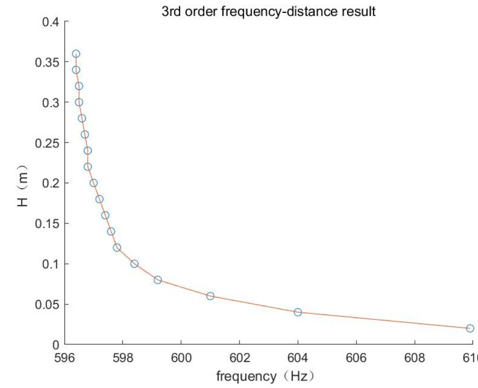



B.Second-order frequency versus immersion depth results

Figure 4: Second-order resonance frequency shift results.




A.Third-order resonant frequency response




B.Third-order frequency versus immersion depth results

Figure 5: Third-order resonance frequency shift results.

The figure3-5 demonstrates that when the cylindrical shell is near the surface, the shift in resonance frequency is quite pronounced. As the shell is progressively lowered from the free surface in 0.02 m increments, the shift in resonance frequency gradually diminishes. Upon reaching a certain depth, the shift in resonance frequency essentially disappears, indicating that the influence of the free surface on the resonance frequency of the cylindrical shell can be considered negligible.

Table 1: Frequency total offset statistics.

| | 1st order resonance frequency(Hz) | 1st order resonance frequency(Hz) | 1st order resonance frequency(Hz) |
|---|---|---|---|
| frequency offset | 750 | 800 | 870 |

## 3. Experimental Research

### 3.1 Experimental equipment and layout

Resonance frequency shift experiments on submerged cylindrical shells were conducted at the acoustics pool of Shanghai Jiao Tong University. The experimental model was an aluminum cylindrical shell, with a length of 0.8 m, a diameter of 0.25 m, and a thickness of 0.005 m. The shell was equipped internally with a signal collector and an exciter. The signal collector was rigidly attached to one end cap, while the exciter was elastically mounted on the other end cap. Five accelerometers were arranged in the middle of the cylindrical shell to collect vibration signals. The internal structure of the cylindrical shell is depicted in the figure 6. The experiments involved suspending and lowering the cylindrical shell model to various depths underwater using a crane located above the pool.

Figure 6: Schematic diagram of test model.

The placement of the signal input and output ends is illustrated in the figure 7. During the experiment, a broadband white noise signal, covering the first three characteristic frequencies of the cylindrical shell, was selected as the input for the exciter, with a bandwidth of 0-2000 Hz. The cylindrical shell model was lowered to various depths both vertically and horizontally using a crane, as depicted in the figure. The vibrational response of the cylindrical shell was measured using five accelerometers.

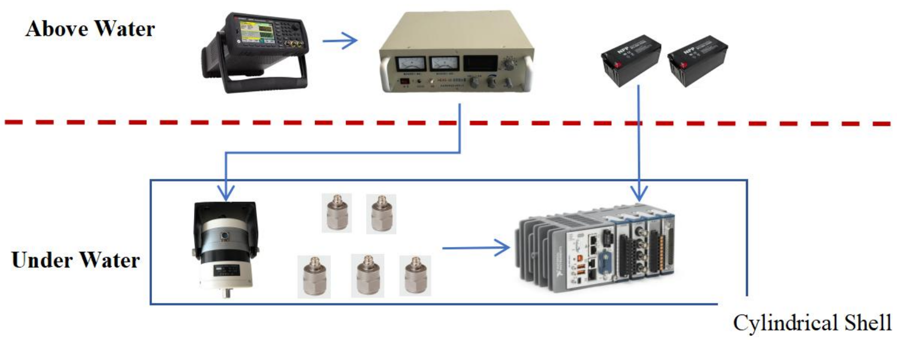



Figure 7:Equipment layout diagram.

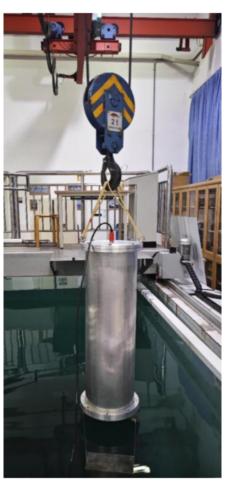


Figure 8: Vertical hanging diagram of cylindrical shell.

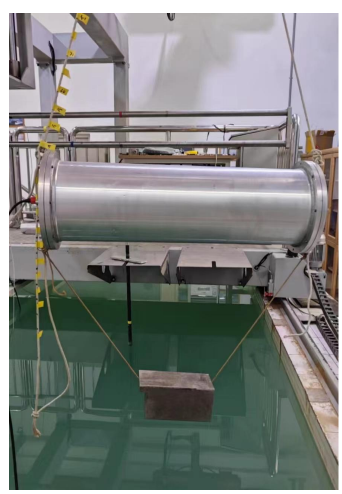


Figure 9: Horizontal hanging diagram of cylindrical shell.

### 3.2 Discussion of results

When the cylindrical shell was submerged vertically and horizontally into the water, the positions of the first, second, and third-order resonance peak frequencies at various depths were organized, as shown in the table 2-3. It was observed that when the end caps of the cylindrical shell were parallel to the free water surface, the shift in resonance frequency was weaker. Conversely, when the end caps of the cylindrical shell were perpendicular to the free water surface, the shift in resonance frequency was more pronounced.Additionally, there exists a critical submersion depth; when the cylindrical shell is submerged deeper than this depth, the shift in resonance frequency ceases to occur.

Table 2: Frequency shifts of each order when the cylindrical shell is suspended vertically.

| Depth(cm) | First-order frequency point(Hz) | Second-order frequency point(Hz) | Third-order frequency point(Hz) |
|---|---|---|---|
| 5 | 189.8 | 346.9 | 664.8 |
| 10 | 189.1 | 346.9 | 664.8 |
| 15 | 189.1 | 346.1 | 664.8 |
| 20 | 189.1 | 346.9 | 664.8 |
| 25 | 189.1 | 346.9 | 664.8 |
| 30 | 189.1 | 346.1 | 664.1 |
| 40 | 189.1 | 346.1 | 664.1 |
| 50 | 189.1 | 346.1 | 664.1 |
| 80 | 188.1 | 346.1 | 664.1 |
| Experiment result offset | 1.7 | 0.8 | 0.7 |

Table 3: Frequency shifts of each order when the cylindrical shell is suspended horizontally.

| Depth(cm) | First-order frequency point(Hz) | Second-order frequency point(Hz) | Third-order frequency point(Hz) |
|---|---|---|---|
| 5 | 197.7 | 353.1 | 668.0 |
| 10 | 191.4 | 347.7 | 664.8 |
| 15 | 190.1 | 346.9 | 664.8 |
| 20 | 189.8 | 346.1 | 664.1 |
| 25 | 189.1 | 346.1 | 664.8 |
| 30 | 189.1 | 346.1 | 664.8 |
| 40 | 189.1 | 346.1 | 663.0 |
| 50 | 189.1 | 346.1 | 663.0 |
| 80 | 189.1 | 346.1 | 663.0 |
| Experiment result offset | 8.6 | 7 | 5 |
| Finite element result offset | 6 | 5.1 | 7 |

When plotting the time-frequency spectrum of the cylindrical shell as it was horizontally submerged, as shown in the figure10-13, it was observed that due to limitations in the experimental setup, the cylindrical shell's submersion depth could not approach infinitely close to the free water surface. Therefore, the shifts in resonance frequency were primarily concentrated within 5 cm of the water surface. This finding is in good agreement with the results obtained from finite element analysis.

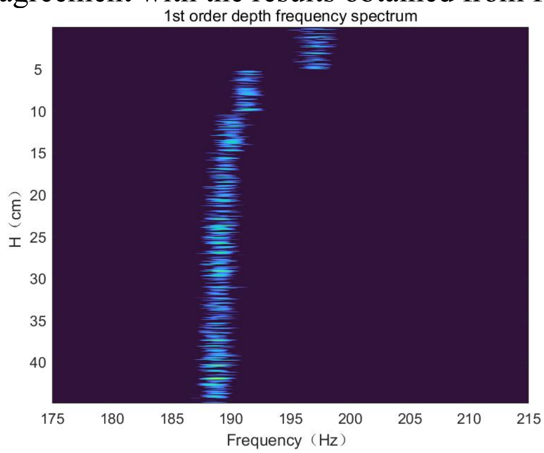



Figure 10: 1st order depth frequency spectrum

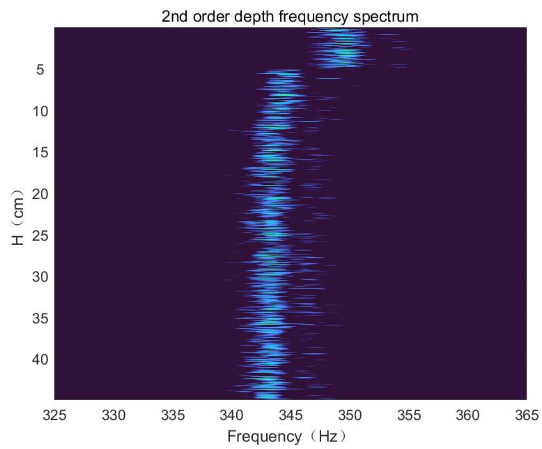



Figure 11: 2nd order depth frequency spectrum

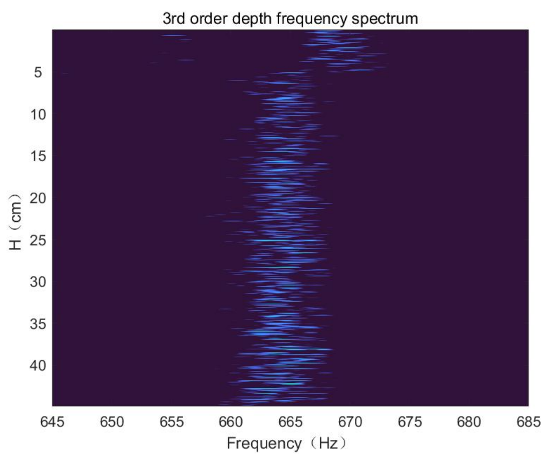



Figure 12： 3rd order depth frequency spectrum

## 4. Conclusion

This paper investigates the resonance frequency shift of an aluminum cylindrical shell caused by boundary reflections, utilizing both finite element analysis and experimental methods. The discussion focuses on the dependency of the shell's resonance frequency shift on the distance from the free water surface:

1. Both experimental and numerical results consistently demonstrate that the resonance frequency of the shell decreases with increasing submersion depth. The frequency shift is more pronounced when the shell is placed horizontally, suggesting that the shift is related to the area of the shell projected onto the free water surface. Furthermore, the closer the shell is to the water surface, the more significant the frequency shift.

2.The study identifies a critical submersion depth; beyond this depth, the resonance frequency shift ceases to occur when the cylindrical shell is submerged deeper into the water.

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