Optimal design of cylindrical sealed cabin based on simulation module

Wang Zhi\textsuperscript{1a}, Yang Junxian\textsuperscript{1b*}, Zhao Bin\textsuperscript{1c}, Ran Xiangtao\textsuperscript{1d}, Zhao Jie\textsuperscript{1e}, Zheng Wei\textsuperscript{1f}

\textsuperscript{1}Institute of Oceanographic Instrumentation, Qilu University of Technology (Shandong Academy of Sciences), Shandong Provincial Key Laboratory of Marine monitoring instrument equipment technology National Engineering and Technological Research Center of Marine Monitoring Equipment, Qingdao, China

\textsuperscript{a}email: wangzhi@qlu.edu.cn, \textsuperscript{b*}email: yjxwork1@qlu.edu.cn, \textsuperscript{c}email: zbwork1@qlu.edu.cn, \textsuperscript{d}email: rxtqd@qlu.edu.cn, \textsuperscript{e}email: zhaojie83@qlu.edu.cn, \textsuperscript{f}email: zw1983@qlu.edu.cn

Abstract—For the underwater sealed cabin with cylindrical structure, this paper proposes a theoretical design method based on the critical pressure algorithm of the external pressure cylinder combined with the simulation module embedded in Solidworks. Based on the results of FEA, the cabin structure is continuously optimized, and finally designed an economical and reliable cylindrical cabin structure, which can meet the requirements of LR rules. The design method has guiding significance.

1. INTRODUCTION
With the development of marine meteorological observation and marine resource exploration, the development and utilization of the ocean requires the help of a variety of underwater detection equipment, and the underwater sealed cabin is an important guarantee for underwater detection equipment, and its sealing and stability are two important performance indicators [1-3]. Since the sealed cabin needs to be designed according to the actual application, how to design an economical and reliable sealed cabin is particularly important.

The shape of the underwater sealed cabin is mainly divided into cylindrical, elliptical, conical and spherical. Considering the processing economy of the cylindrical structure, the cylindrical cabin structure is the most widely used without special requirements. For the depth area (100m-200m), because the external pressure is small, the cylindrical pressure-resistant shell does not need to be reinforced, and it can be directly designed as a single shell [4]. This paper aims at the structural optimization design of the underwater cylindrical airtight cabin. According to the actual application of the sealed cabin, a design optimization method is proposed, which has certain reference significance for the research of the underwater airtight cabin structure design.

2. STRUCTURAL DESIGN
The sealed cabin designed in this paper is mainly used in the self-contained bottom-mounted profile flow observation system. As shown in Figure 1, the lithium battery is placed in the sealed cabin, and the sealed cabin is fixed on the bracket, and the wave measuring equipment is placed on the top of the bracket, the underwater sealed cabin is powered by the ADCP (Acoustic Doppler Current Profiler)
through a cable, and the acoustic releaser is connected to the bracket through an anchor chain. The entire system is deployed on the seabed for automatic observation. After the observation period is over, the entire observation system is recovered through the acoustic release.

The airtight cabin in this paper is mainly used in the area within 100 meters to place lithium batteries and supply power for the observation system.

The pressure at different depths in the water can be calculated by equation (1):

\[ P = \rho gh \]  

In the formula, \( \rho \) is the density of water, the density of seawater is 1024kg/m³; \( g=9.8N/kg; \) \( h \) is the water depth.

Calculated by formula (1), the pressure at depth of 100 meters is about 1 MPa.

According to the size of the lithium battery, the internal size of the sealed cabin is preliminarily designed to be 150mm in diameter and 200mm in depth.

The materials of the sealed cabin should meet the performance index of anti-corrosion, compression resistance, salt spray resistance, etc. Commonly metal materials is used include stainless steel, aluminum alloy and titanium alloy, etc., and non-metallic materials include organic glass, POM, nylon, etc.[5] . Because POM has excellent electrical insulation, high strength and rigidity, and has good toughness, excellent fatigue resistance and creep performance, high resistance to oxidation degradation and sensitivity to ultraviolet degradation [6-8]. Therefore, POM is selected as the material in this paper, and the performance parameters of POM material are shown in Table 1.

| Table 1 Performance parameters of POM |
|-------------------------------------------------|
| Density/\( \rho \) \((g/cm^2)\) | Yield strength/\( \sigma_s \) \((MPa)\) | Elastic modulus/\( E \) \((Mpa)\) | Poisson's ratio |
|-------------------------------------------------|
| 1.39 | 63 | 2600 | 0.3859 |

According to the instability, the external pressure cylinder is generally divided into three categories: long cylinder, short cylinder and rigid cylinder. Which form the actual external pressure cylinder belongs to should be determined according to formula (2) [9]:

\[ L_n = 1.17D_0 \sqrt{\frac{\delta}{D_0}} \]  

Where \( D_0 \) is the outer diameter of the cylinder, mm; \( \delta \) is the wall thickness of the cylinder, mm;

When the cylinder length \( L \geq L_n \), the cylinder is defined as a long cylinder; when \( L < L_n \), the cylinder is defined as a short cylinder.

According to design requirements, the inner diameter \( d \) of the sealed cabin is 150mm, \( D_0=d+2\delta \), when \( \delta \) is 2-10mm, the cylinder length \( L_n \) ranges from 820.1 to 1581.1mm. According to the design requirements, the length \( L \) of the sealed cabin is approximately 200mm<\( L_n \). Therefore, the sealed cabin is a short cylinder.

The calculation formula of the critical pressure of the short cylinder is shown in formula (3) [10]:

\[ P_n = 2.59E \left( \frac{\delta}{D_0} \right)^{1.5} \left( \frac{L}{D_0} \right) \]
Where $P_n$ is the critical pressure, MPa; $\delta$ is the wall thickness of the cylinder, in mm; $D_0$ is the outer diameter of the cylinder, in mm; $E$ is the elasticity of the cylinder material, MPa;

An important factor that affects the cabin is the safety factor. In the actual design and calculation process, according to the standard, the ratio of the critical pressure of the cabin to the working external pressure is the safety factor $C$, and its expression is as shown in equation (4) Shown:

$$C = \frac{P_n}{P}$$

Where $P_n$ is the critical pressure of the cabin; $P$ is the working external pressure of the cabin.

According to the standard of the German LR Rules: the multiple of the calculated pressure decreases with the depth, and the standard is shown in Table 2 [11]:

| Water depth (m) | 50  | 100 | 200 | 300 | 400 | 500 | 600 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Safety factor   | 2.5 | 2.4 | 2.2 | 2.0 | 1.9 | 1.8 | 1.7 |

According to the standard of the German LR Rules, the safety factor $S$ is 2.4 for a water depth of 100 meters.

The thickness of the cylinder is estimated based on film theory, as shown in equation (5):

$$\delta \approx \beta \cdot \frac{P \cdot R}{\sigma_s}$$

Where $P_c$ is the design failure pressure, MPa, $R$ is the average radius of the cylinder, mm; $\sigma_s$ is the yield strength of the material, MPa; $\beta$ is the reduction factor, usually in the range of 0.7 to 0.9.

This paper takes $\beta=0.9$

Then $\delta=1\text{MPA} \cdot 75\text{mm} / 63 \times 0.9=1.08\text{mm}$

Where, $\delta$ is the minimum thickness of the cylinder, so the thickness is initially estimated to be 2mm, and the trial algorithm is used to calculate according to formula (2):

$$P_n = 2.59 \cdot 2600 \cdot \left( \frac{2.59 \cdot 2600 \cdot 50}{200/154} \right)^{1.5} = 0.099<2.4$$

obviously, if the safety factor standard cannot met, the thickness of the cylinder needs to be increased;

Take the wall thickness $\delta=5\text{mm}$ $P_n = 2.59 \cdot 2600 \cdot \left( \frac{2.59 \cdot 2600 \cdot 50}{200/160} \right)^{1.5} = 0.93<2.4$, and we need increase the thickness of the cylinder;

Take the thickness $\delta=8\text{mm}$ $P_n = 2.59 \cdot 2600 \cdot \left( \frac{2.59 \cdot 2600 \cdot 50}{200/166} \right)^{1.5} = 2.85>2.4$, which meets the standard requirements.

The thickness of the cylinder wall is initially set to 8mm, the outer diameter of the sealed cabin cylinder is 166mm, and the inner diameter is 150mm; the thickness of the bilge is the same as the cylinder wall, and is initially set to 8mm.

3. SIMULATION OPTIMIZATION

SolidWorks Simulation is an analysis software based on FEA (finite element technology). As an embedded analysis software, it is seamlessly integrated with SolidWorks. When analyzing the model, the following three steps need to be followed:

a) Preprocessing: define the analysis type (static, thermal conductivity, etc.), add material properties, apply loads and constraints, and divide the mesh.

b) Solving: Calculate the required result.

c) Post-processing: Analyze the results.
Modeling the sealed cabin cylinder in AutoCAD. The model is shown in the following figure 2:

![Model of sealed cabin cylinder](image1)

**Figure 2. The model of sealed cabin cylinder**

Establish a cabin model in SW, establish a new static calculation example, define the model material as POM, impose fixed geometric constraints on the upper end of the cabin, and apply an external pressure of 1 MPa (100 meters water depth) outside the cylinder and the cylinder bottom. Define the grid as high quality, set the grid to a standard grid, the overall size is 4.959mm, the tolerance is 0.2479mm, and the cabin body is meshed, as shown in the figure 3.

![Mesh divided](image2)

**Figure 3. The mesh divided**

After simulation analysis, the cabin stress distribution cloud diagram and the safety factor distribution cloud diagram are shown in Figure 4 and Figure 5. As shown in Figure 4, the maximum stress appears at the center point of the bottom, and the stress value is 6.16e7 Pa; The minimum stress appears on the top surface of the cabin, and the stress value is 3.16e5 Pa; as shown in Figure 5, the minimum safety factor is 1.02, which is less than 2.4 specified by the German LR Rules. so the bottom of the cabin needs to be thickened, until the safety factor of the center point reaches the standard specification.

![Stress cloud diagram](image3)

**Figure 4 the cloud diagram of stress**
When the thickness of bottom is adjusted to 13mm, meshing the cabin again, setting the overall size of the grid to 4.051mm, and the tolerance to 0.2025mm. The final generated grid is shown in Figure 6:

After simulation analysis, the cabin stress distribution cloud diagram and the safety factor distribution cloud diagram are shown in Figure 7 and Figure 8. As shown in Figure 7, the maximum stress value is 3.75×10^7 Pa appearing near the connection between the cabin and the side wall, and the stress value at the center point of the bottom is 2.36×10^7 Pa (the maximum stress value of the bottom). The yield stress of the POM material is 6.3×10^7 Pa; the safety factor at the center point of the cabin bottom is 2.67, which satisfies Standard requirement. As shown in Figure 8, the safety factor of the joint is 1.68 (minimum safety factor), which fails to meet the standard requirements and further optimization of the location is required.
The structure of the cabin is partially optimized as shown in Figure 9. The radius of the chamfer is set to 15mm. The cabin is meshed, and the parameters are set as shown in Figure 10. The grid at the corners is refined, the parameters are set as shown in Figure 11, and the generated grid is shown in Figure 12. Finally, after simulation analysis, the cabin stress distribution cloud diagram and the safety factor distribution cloud diagram are shown in Figure 13 and Figure 14, respectively. As shown in Figure 13, the maximum stress appears at the chamfer of the cabin body and the side wall, and the maximum stress value is 2.43e7 Pa; as shown in Figure 14, the minimum safety factor of the cabin body is 2.59 (>2.4), which satisfies the standard specification requirements.

![Figure 7 the cloud diagram of stress](image7.png)

![Figure 8 the cloud diagram of safety factor](image8.png)

![Figure 9 The structure optimized](image9.png)
Table 1: Mesher parameters

| Parameter          | Value            |
|--------------------|------------------|
| Mesh type          | Solid Mesh       |
| Mesher Used        | Standard mesh    |
| Automatic Transition | Off             |
| Include Mesh Auto Loops | Off             |
| Jacobian points   | 4 points         |
| Mesh Control       | Defined          |
| Element size      | 0.0000 mm        |
| Tolerance         | 0.0000 mm        |
| Mesh quality      | High             |
| Total nodes       | 703514           |
| Total elements    | 499320           |
| Maximum Aspect Ratio | 6.4693          |

Figure 10: The mesh parameters

Figure 11: The grid parameters

Figure 12: The mesh divided

Figure 13: The cloud diagram of stress
CONCLUSION
Cylindrical tube structure is a commonly used structure for airtight cabin. In this paper, the overall structure of airtight cabin is optimized by a combination of theoretical calculation and FEA.

a) According to the results of FEA and the critical pressure formula of the short cylinder, combined with the safety factor standard of LR Rules, the calculated thickness of cylinder wall can meet the standard requirements.

b) For the thickness of the bilge, the thickness of the cylinder wall has no reference meaning, and the final ideal value can be obtained through FEA.

c) Structural optimization is needed near the contact between the wall and the bottom to further reduce the stress value.

ACKNOWLEDGMENT
In this paper, the research was supported by National Key Research and Development Project (2017YFC1405604) and Shandong Provincial Natural Science Foundation (ZR2018LD008).

REFERENCES
[1] Wang Guangyue, Lai Jianyun. “Structural Optimization and Selection Design of Deep Sea Pressure Tank.” MECHANICAL ENGINEER, 2019(06):80-82.
[2] LUO Shan, WANG Weibo. “Status and prospects on the pressure shell structure of submersible.” SHIP SCIENCE AND TECHNOLOGY, 2019,41(19):7-16.
[3] Yogang Singh, S.K. Bhattacharyya, V.G. “Idichandy. CFD approach to modeling, hydrodynamic analysis and motion of a laboratory underwater glider with experimental results.” Journal of Ocean Engineering and Science, 2(2017),90–119.
[4] Dai Zhiguang. “Body structure design and hydrodynamic simulation for small underwater robot.” YANGZHOU University,2012.
[5] YING YI. “Deep-sea Pressure Hull Robustness Optimization.”,2018
[6] Zhang Lei. “Preparation and Properties of PP/POM Composites Filled with Modified Natural Clay.” Plastics Science and Technology,2020,48(07):5-7.
[7] LIU Bin, WANG Yuxiang, LIN Ziwei, “Research on Forming Quality of 316L/POM Composite Parts Fabricated by Fused Deposition Modeling.” Plastics Science and Technology, 2020, 48(04):32-35.
[8] Gong H J, Snelling D, Kamran K. “Comparison of stainless steel 316L parts made by FDM and SLM-based additive manufacturing processes.” The Journal of the Minerals, Metals & Materials Society, 2019, 71(3): 880-885.
[9] XIN G H, FENG D Z, PAN R N. "Design and Implementation of Shallow Observation ROV." Computer & Telecommunication, 2015(4):71-73.

[10] Liu Tao. “Analysis and Design of Deep-Sea Submersible Structures.”. China Ship Scientific Research Center, 2001.

[11] Teerbusiho, O. 1. “Satbility of stiffened and anisotropic shells, Trans-7th All-Union Conf. on Theory of Plates and shells,” Dneproteotrvsk, Ukrainian SSR, Sept. 1969.