Air Habitat for Detection and Repair of Submarine Oil Pipelines in Complex Sea Conditions*

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***Abstract*—The designed structure in this study can accurately measure defects in underwater oil pipelines that occur during operation. Once the approximate location of the defect in the pipeline is confirmed, the structure can surround the exposed pipeline that needs repair and create a gas environment around the pipeline on the seabed through a sophisticated sealing and inflation system. Then, the motors can scan the pipeline to reconstruct the deformation and defect of the pipeline surface, further developing a targeted pipeline repair plan, which is essential for extending the service life of the pipeline. The study developed a sealing scheme that allows measurement in the large enclosed space surrounding the pipeline on the seabed and can adapt to different angles of the bent pipeline sections. In conclusion, by accurately measuring defects in underwater oil pipelines and developing targeted repair plans, the risk of pipeline failures and leaks can be greatly reduced, thereby improving the service life of pipelines and reducing environmental pollution and human casualties.**

Keywords*—Submarine pipeline, Simulation analysis, External detection

I. INTRODUCTION

With the increasing demand for energy, people have turned their attention to the development of ocean resources, including the exploration and transportation of deep-sea oil and gas resources. Submarine pipelines, as the most important means of transportation for oil and gas resources, have become an important part of modern marine energy industry[1, 2]. However, as the age of submarine pipelines increases, uneven settlement of the seabed terrain will have an adverse effect on them, requiring timely inspection and maintenance to ensure their safety and reliability[3].

Currently, the existing methods for detecting deformation of submarine pipelines mainly include instrument pipeline internal[4] and external inspection[5] and diver observation[5]. Traditional inspection methods, including sonar detectors[6-8], cameras[9], magnetic particle testing[10] and other technologies, are the most widely used. External inspection methods include sonar detection, magnetic instrument detection, and remote sensing technologies. This method is relatively low cost and operationally simple, but it has low sensitivity to pipeline deformation in complex water flow environments, and the test results can have significant errors, making it difficult to detect small deformations. In contrast, diver observation is a more direct and reliable method for detecting deformation of submarine pipelines. By directly observing the surface of the pipeline, divers can more accurately identify deformation issues. However, this method has a high employment cost, requires a lot of manpower and resources for operation, and imposes high demands on the physical fitness and skills of divers, which poses certain safety risks.

Especially in high turbidity and high flow rate sea areas, both traditional internal and external pipeline inspection methods and diver observation methods have significant limitations, making it difficult to carry out underwater in situ pipeline repair operations. Therefore, research on pipeline inspection and repair in complex sea areas is crucial, as the safety and reliability of submarine oil pipelines are essential for energy supply and environmental protection.

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To accurately measure defects in submarine oil pipelines and develop targeted repair plans, it is necessary to overcome the complex conditions of high pressure, strong water flow, low visibility, etc. in the underwater environment. The designed sealing system must also adapt to the different axial states of the pipeline.

In this study, we aim to address the challenges faced in detecting and repairing pipelines under complex water flow conditions. Due to the changes in water flow intensity and direction under such conditions, detection and repair equipment often fail or cannot accurately perform their intended functions. Therefore, we propose a new underwater air chamber design that aims to provide a suitable air habitat for pipeline detection and repair equipment.

II. COMPONENTS OF AIR HABITAT

The design of this scheme is based on two mergeable compartments. Once lowered into the pipeline, these two compartments can be extended by hydraulic cylinders from the top and secured in place by clamping bolts at the bottom to form a sealed space around the pipe. Then, we replace the internal muddy liquid with air to facilitate subsequent experiments. This design provides a good habitat for underwater pipeline maintenance work, allowing pipeline detection and repair equipment to function normally, similar to on land, resulting in higher accuracy in underwater pipeline detective and repair.

The overall structure of this scheme is shown in Fig. 1. It uses innovative design concepts and advanced technological means to effectively address the challenges of pipeline detection and repair under complex water flow conditions. By implementing this scheme, we can provide a more stable and reliable working environment for underwater work, further improving the efficiency and quality of underwater pipeline maintenance work, and providing strong support for the safety and stable operation of underwater engineering.

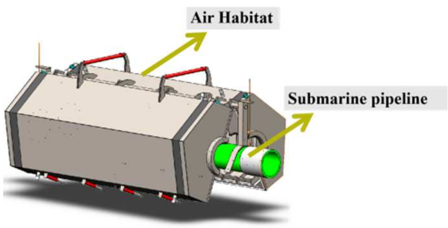

Fig. 1. Overall composition

During the design process, we encountered two key challenges. The first challenge was related to the formation of a large enclosed space. To achieve a seal for the internal air chamber, we needed to design a comprehensive sealing system to ensure that the water inside could be drained. Specifically, we used longitudinal sealing strip, longitudinal sealing strip, middle sealing strips, and lngitudinal sealing strip as the four components, which were fully coordinated with each other to form a complete sealing system. In actual operation, the relative position of the rubber we used is shown in Fig. 2.

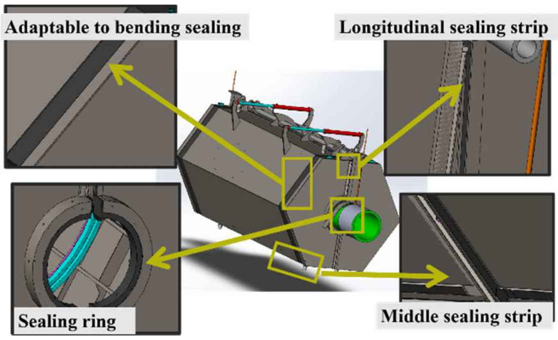

Fig. 2. Overall schematic diagram of the seal

The second difficulty was related to the actual situation of the pipeline. In reality, underwater pipelines are not completely straight, and if the axis of the cross section of the pipeline clamped by our chamber and the axis connecting the two end faces of our habitat are not parallel, the sealed space would fail, resulting in a large amount of water leakage. To avoid this situation, we need to design a certain structure to ensure the variable adaptability between our habitat section and the pipeline interface. Specifically, we used flexible section to solve this problem.

Overall, these two key difficulties are the ones we must overcome in the design process, and our design solution can ensure the expected effect of our underwater air chamber by considering these factors.

III. HABITAT SEALED ENVIRONMENT TO CREATE EACH PART OF THE DESIGN

To ensure the effectiveness of the sealing system, we have used a combination of multiple sealing components. The sealing ring and longitudinal sealing strip are mainly responsible for sealing the ends of the pipeline, while the middle sealing strip is responsible for sealing the middle of the pipeline. These sealing components are all made of special rubber materials, which have good flexibility and corrosion resistance, and can adapt to complex underwater environments. In addition, we have specially designed end rubber to enhance the sealing performance of the end sealing strip and longitudinal sealing strip.

In actual operation, we will design according to the specific size parameters of the pipeline to ensure the matching of each component. For example, the length of the end sealing strip should be equivalent to the outer diameter of the pipeline, and the length of the middle sealing strip should be equivalent to the length of the pipeline. This can ensure the effectiveness and reliability of the sealing system.

A. *Middle sealing strip and longitudinal seal*

The form range of the middle sealing strip and end longitudinal sealing strip is shown in Fig. 3.

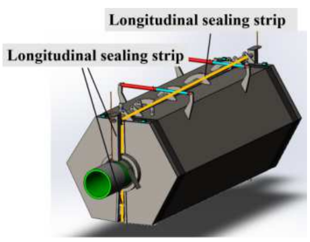

Fig. 3. Schematic diagram of the relative position of the middle seal strip

The central sealing strip and the end longitudinal sealing strip are sealed using the sealing method shown in Fig. 4. The contact part of one side of the half-hull is designed as a protruding steel strip with rounded corners, and the other side is equipped with a matching rubber component. Through the action of hydraulic cylinders, the left and right half-hulls are pressed against each other, and the protruding steel strip will cause deformation of the rubber on the other side, thereby achieving the sealing effect.

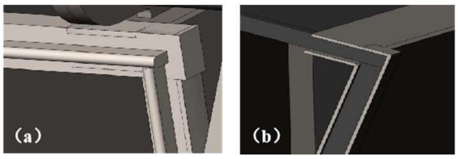

Fig. 4. Connecting form of middle seal strip and end seal strip (a) steel strip connection (b) rubber connection

B. Seal ring

The sealing is divided into two sections, front and back. One end face is shown in Fig. 5, where "D-shaped" rubber strips are distributed at the junction of the left and right half-shells with the pipeline.

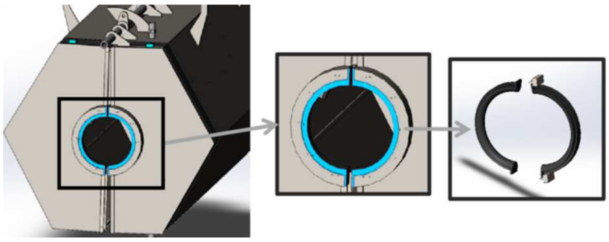

Fig. 5. Schematic diagram of the relative position of the sealing strip

To achieve an effective sealing effect, we have adopted a compression sealing system, the key components of which are the hydraulic cylinder and sealing strip. The sealing strip adopts a D-shaped cross-section design, which has good elasticity and deformability. When the hydraulic cylinder applies pressure, the sealing strip will completely adhere to the pipe wall and deform, thus forming good contact with the pipe surface. The D-shaped design also has good adaptability and can adapt well to the unevenness of the pipe surface, thus achieving an effective sealing effect. In addition, we have also adopted a splicing method at the junction of the sealing strips, splicing the horizontal and vertical rubber together, and the corresponding side is a vertically placed steel bar, thereby increasing the reliability and sealing effect of the sealing strip.

C. Seal design of the end rubber junction

As for the sealing design of the rubber joint at the end, it is divided into two sections, front and rear, and the T-shaped end is set at the middle sealing section and spliced with the original middle sealing strip. On the left and right sides of the end rubber, by embedding a part of the rubber and forming a constraint between the ship's surface and the outer surface of the rubber, and having a rigid support bar to form a constraint on the inner surface of the rubber, as shown in Fig. 6, the left and right sides of the end rubber can also have a sealing effect through loading on both sides.

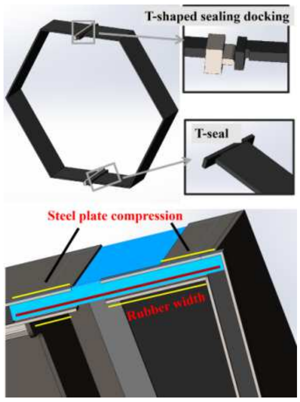

Fig. 6. Seal mode of the rubber joint

IV. FINITE ELEMENT ANALYSIS OF RUBBER SEALS BASED ON THE MOONEY-RIVLIN MODEL

A. Simulation results of T-shaped model section

In this part, we mainly focus on the finite element simulation of the T-shaped sealing method used for the axial sealing endpoint, to obtain the contact stress of the key parts and determine whether it can meet the required sealing requirements.

Since the T-shaped seal is mainly used for axial sealing, and the sealing methods in the axial direction are consistent, we selected a section assembly method for simulation calculation, as shown in Fig. 7.

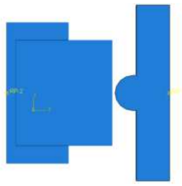

Fig. 7. Type-T sealing structure

Rubber is simulated with Euler body, and the right side represents the T-type structure, which simulates the process of the T-type structure moving to the left at a certain speed on the right side.

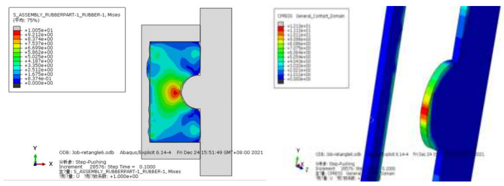

Fig. 8. T-type seal simulation results

B. Simulation results of the circular direction of the sealing ring

In this part, we mainly conduct simulation calculations on the circumferential sealing ring's encircling sealing method to obtain the distribution of contact stress in various parts. Based on the magnitude of the contact stress, we can determine whether the sealing can be achieved or not.

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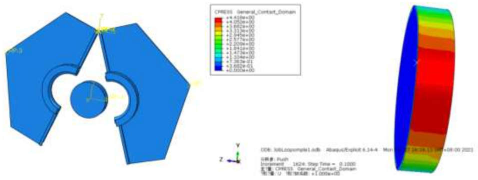

Fig. 9. Simulation results of weekly seal structures and weekly seals

We adopt direct contact sealing, mainly judging the sealing performance based on the contact pressure between the sealing surfaces. Based on the simulation results, we can see that the sealing has good sealing pressure and will not cause leakage of water or gas. It can achieve a good closed environment for the encircled pipeline to form a habitat.

V. FLEXIBLE SECTION DESIGN

A. Design principles and basis for different axis design of pipeline

In this design, different axis design conditions at both ends of the pipeline are considered. In the inspected section of the pipeline, local bending occurs, and the air chamber can fully cover and wrap around the bent section. However, there may still be a problem of the air chamber clamping the pipeline at different axes at the two ends of the air chamber, as shown in Fig. 10.

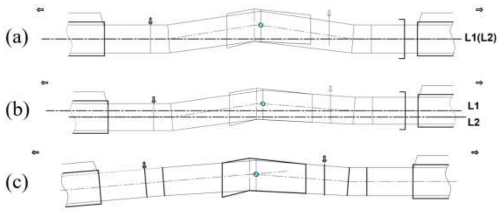

Fig. 10. Schematic diagram of the curved tube segment

As shown in Fig. 10(a), the pipe still maintains a coaxial state after bending, while Fig. 10(b) shows the pipe with different axes caused by the offset of the two end faces after bending, and Fig. 10(c) shows the small angle deviation caused by the bending of the two end faces, resulting in different axes. If there is a different axis phenomenon, the use of rigid fixtures to clamp the pipe may damage the connection between the pipe and the surrounding pipes, resulting in cracks or even fractures on the surface of the pipe. Therefore, after comprehensive consideration, a flexible material needs to be added in the design to adapt to the above phenomenon.

The rubber to be used in this design is widely used and has good pressure resistance, water resistance, air tightness, and flexibility, making it a basic flexible material for making components that can adapt to deformation.

B. Adaptation to Different Axis Working Modes

To solve the problem of the pipeline not being completely straight, we have designed a variable adaptation structure. Specifically, we have designed the section of the habitat to be rotatable, which can be adjusted according to the inclination angle of the pipeline interface, thus ensuring the integrity and sealing of the sealed space. This design is very critical and can effectively avoid problems such as water leakage, as shown in Fig. 11.

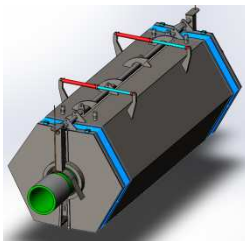

Fig. 11. Schematic diagram of the rubber distribution position at the end

The working principle of the end rubber added in this design to eliminate or reduce the impact of the airbag fixture on the pipeline in response to the phenomenon of different axes is shown in Fig. 12.

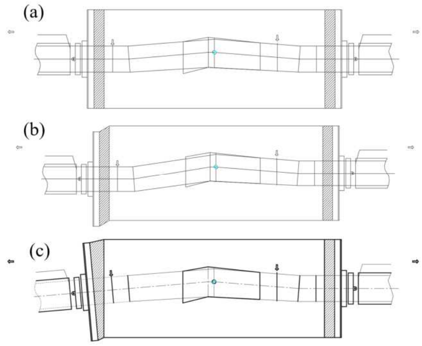

Fig. 12. Adaptation of the air habitat to different axes

As shown in Fig. 12(a), in the case of left and right end faces being coaxial, the rubber only exhibits sealing performance and does not show adaptability. As shown in Fig. 12(b), for pipelines with front and back dislocation after bending, the left rubber is deformed by overall stretching, so that the clamping point can coincide with the pipeline end face. As shown in Fig. 12(c), when the pipeline has a small angle deviation at both ends, the left rubber can be deformed by upper rubber stretching and lower rubber compression to achieve complete contact between the clamping point and the pipeline end face and ensure sealing.

In summary, the end rubber can adapt to the different axis phenomenon to a certain extent and range by its deformation, regardless of the relationship between the two ends of the pipeline.

C. Simulation results of the flexible deformation segments

In this section, we conducted finite element simulation and analysis to determine whether the flexible deformation section can adapt to a 15-degree deformation. The main criterion for judgment is whether the contact stress at the contact point of the flexible section after the 15-degree deformation is greater than the pressure inside the container, in order to determine whether the sealing can be achieved.

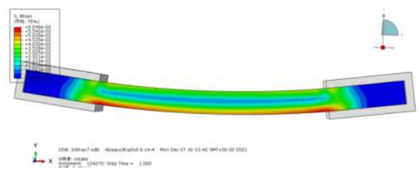

Fig. 13. Simulation analysis of flexible deformation section

D. The structure of the end surface rubber strengthens

In order to meet the requirement of the end rubber's load bearing capacity under the pressure difference between the inside and outside when the internal space is filled with air, a transverse reinforcement bar is added to the cantilever extending from both sides of the air chamber, which is equipped with reinforcement on both the inside and outside. On one hand, this component can restrict the normal deformation of the end rubber and improve its load bearing capacity under pressure. On the other hand, by setting the cantilever, the axial deformation of the rubber is not affected, and it will not have any impact on its adaptation to small angle bending, as shown in Fig. 14.

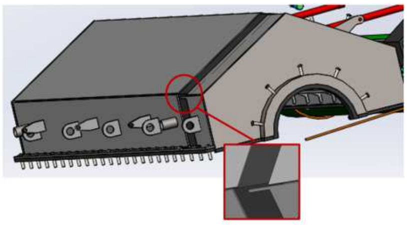

Fig. 14. Section rubber reinforced cantilever

VI. OFFSHORE TEST

After the manufacturing and assembly of submarine pipeline inspection equipment, commissioning and testing were carried out in the sea area with a depth of 40 m.

Fig. 15. Offshore test

The equipment we have ultimately designed, as illustrated in Fig. 15, has demonstrated excellent overall sealing performance in underwater environments with extremely high sediment concentration. Moreover, it is capable of creating a gas shelter underwater, as evidenced by its ability to operate within a bent pipeline with an angle of up to 12 degrees, as shown in Fig. 16. This equipment enables us to carry out underwater inspection and repair work effectively, and its design reflects a high level of professionalism.

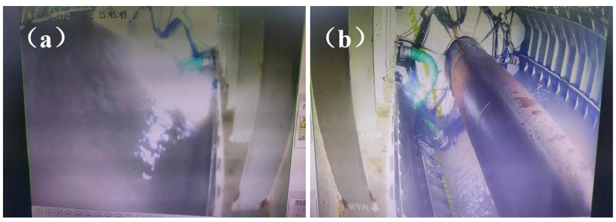

Fig. 16. Clamping a 12-degree bent pipe in a pipeline underwater air habitat (a) sub-aqueous semi-aqueous state (b) underwater air state.

VII. CONCLUSION

In conclusion, the device was tested under complex oceanic conditions, including a high flow rate, high turbidity, and low visibility at a depth of 40 meters. The overall system operated smoothly, and the well-designed sealing system ensured that there was no water leakage during the underwater clamping of the pipeline, forming an air shelter. Furthermore, we used artificially curved pipes with angles of up to 12 degrees for underwater clamping and to empty the seawater from the chamber. The condition of the pipe surface could be clearly observed, and the practicality of the adaptable rubber for bending angles was verified. Through the air shelter, the detection and maintenance of pipelines in complex oceanic conditions were achieved effectively.

Overall, the analysis and simulation results suggest that the transportation and installation process of the chamber and pipeline are feasible, and the safety requirements have been met. However, further studies on the long-term safety and stability of the structure under various environmental conditions are necessary. The findings of this study can provide a valuable reference for the engineering design and construction of similar structures.

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