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Key Technologies, Practical Validation, and Application Expansion of Full-Ocean-Depth Multi-Channel Fiber-Optic Watertight Connectors

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Abstract This paper focuses on full-ocean-depth multi-channel fiber-optic watertight connectors, providing a comprehensive analysis of their product design, manufacturing processes, testing protocols, sea trials, and scalability. By overcoming a series of critical technological challenges, the research achieves domestic substitution of such connectors, significantly enhancing China's autonomous capabilities in deep-sea equipment. Extensive sea trials have validated the exceptional performance of the developed connectors, demonstrating substantial socioeconomic benefits and offering robust support for the advancement of China's marine engineering endeavors.

Index Terms full-ocean-depth, multi-channel fiber-optic watertight connector, structural design, experimental validation, scalability

I. Introduction

The ocean contains rich resources, and deep-sea exploration and development has become a key area of research in various countries. As the core component of deep-sea high-speed communication system, the performance of full-depth multi-channel fiber-optic watertight connector directly affects the effectiveness of deep-sea operation. In the extreme environment of the deep sea, the realization of stable and efficient optical signal transmission is the key challenge in the development of all-ocean deep multi-channel fiber optic watertight connector. The development of high-performance deep-sea multi-channel fiber optic watertight connector is of great significance to break the monopoly of foreign technology and promote the implementation of China's marine strategy [1].

II. Product design

II. A. Structural design

The all-sea-depth multi-channel fiber optic watertight connector consists of plugs and sockets (Figure 1), with customized adapters to meet the needs of different equipment. When designing, on the basis of guaranteeing the pressure resistance and communication transmission performance of full sea depth, the interchangeability and matching with imported products are ensured to the maximum extent.

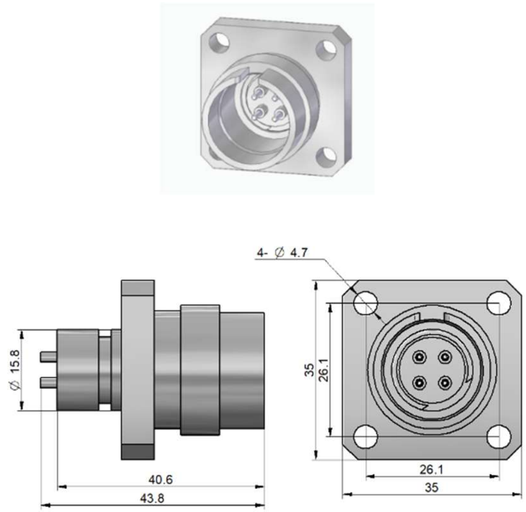
In order to improve the reliability of the system, in the socket and plug interface sealing adapter device (Figure 2, Figure 3). One end of the device is connected to the imported socket on the panel of the equipment, the other end is connected to the domestic plug connector, no longer plugged in and out after the completion of commissioning, effectively avoiding the domestic and imported products interchangeable commissioning repeatedly plugged in and out and matching problems.

II. B. Parameter design

II. B. 1) Structural Mechanics Simulation

The working water pressure of the product needs to reach more than 100MPa, and the test pressure is 127MPa, which is a strict requirement for the strength of the connector shell. Titanium alloy TC4 is chosen to make the shell, which has good comprehensive mechanical properties, high strength, strong corrosion resistance and stable performance [2]. With the help of NX Nastran solver, the structural simulation and verification of the socket shell, the plug front shell and the plug rear shell are carried out (Figure 4), and the results show that under the water pressure of 127MPa, the maximum stress value of the shell is 748MPa, and the minimum value of the coefficient of safety is 1.11, which meets the application requirements [3].

(a) Multi-channel fiber optic plug connector



(b) Multi-channel fiber optic socket connector

(c) Multi-channel fiber optic connector mating connection state

Figure 1: Schematic diagram of a 4-core fiber optic watertight connector

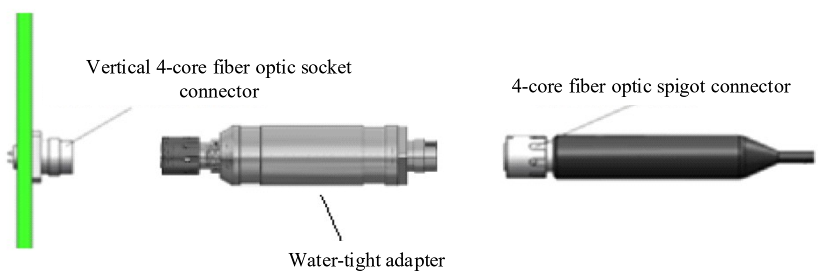


Figure 2: How the watertight adapter is applied

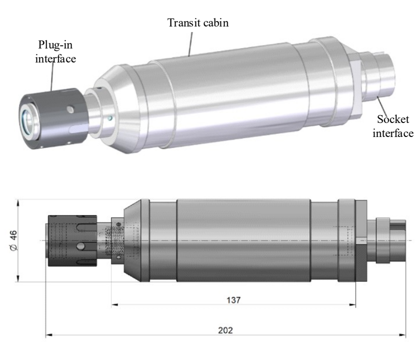
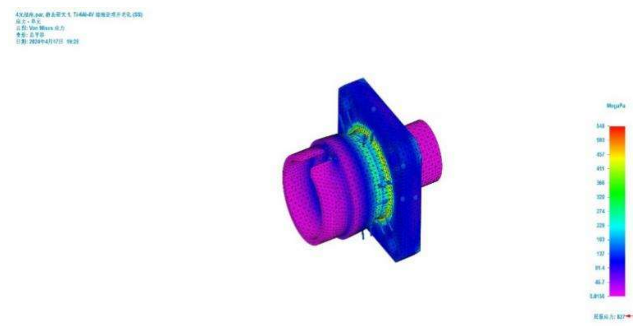
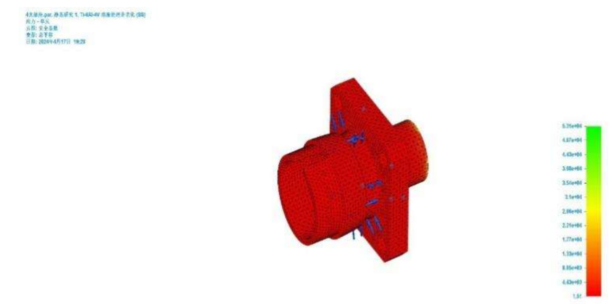


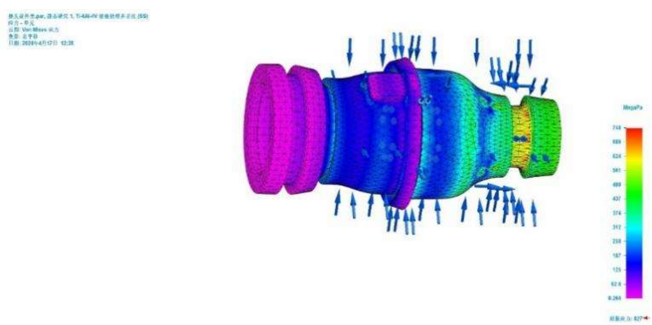
Figure 3: Watertight adapter



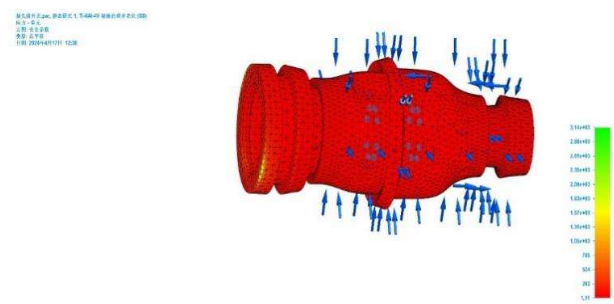
(a) Stress distribution state of socket housing



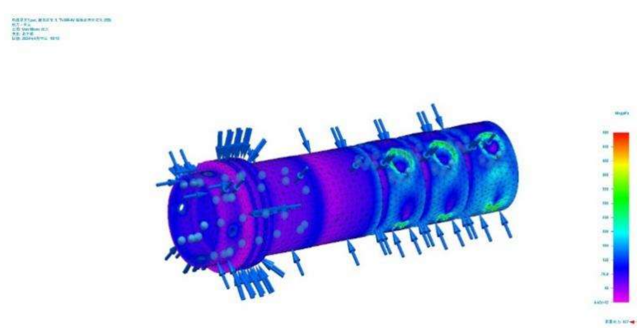
(b) Distribution of safety coefficients for socket shells



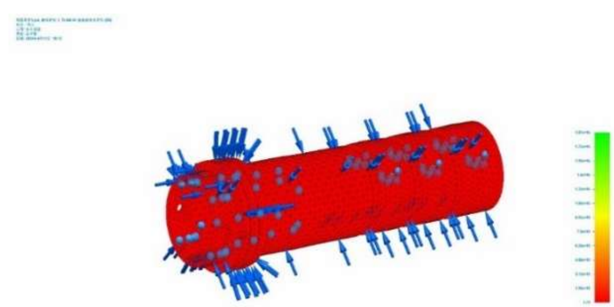
(c) Stress distribution state of plug front housing



(d) Distribution of safety coefficients for the front housing of plugs



(e) Stress distribution state of the shell at the rear of the plug



(f) Distribution of safety coefficients for the rear shell of the plug

Figure 4: Structural simulation and calibration

II. B. 2) Fiber insertion loss

Optical fiber insertion loss is affected by many factors. The use of ceramic cores and C-shaped ceramic sleeves and other precision alignment mechanisms, the use of ceramic thermal stability and abrasion resistance to ensure that the core axis of the two optical fibers are accurately aligned to maintain long-term alignment accuracy [4]. Stable and reliable physical contact is critical. With a single-mode fiber diameter of only 9μm, fiber alignment errors are a key factor affecting insertion loss, including axial misalignment errors, radial offset errors, and angular tilt errors (Figure 5 - Figure 7).

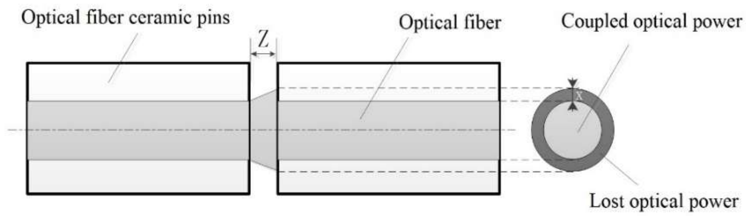


Figure 5: Schematic diagram of coupling efficiency in the presence of axial gap Z for fiber optic connection

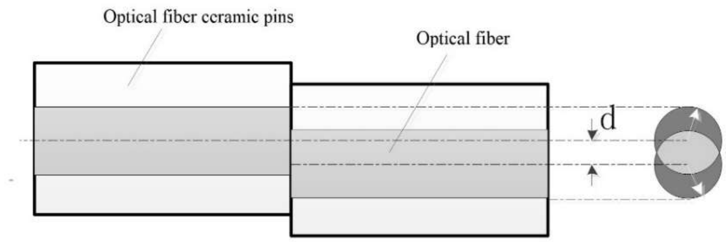


Figure 6: Coupling efficiency of fiber optic connector in the presence of radial offset

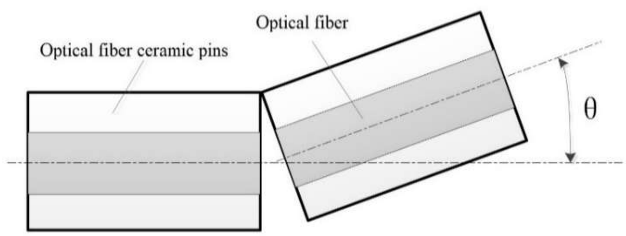


Figure 7: Fiber optic connection with inclination θ Schematic diagram of coupling efficiency

In order to minimize the influence of external forces on the internal optical connection, a “floating pin” structure is used (Figure 8) [5]. This structure can offset processing and assembly errors and reduce the requirements for part processing accuracy, and can achieve a float of ±1.5mm in the axial direction and about ±0.15mm in the radial direction. At the same time, the quality of polishing of the fiber end face is strictly controlled, and precision polishing is performed in accordance with standardized procedures to ensure the efficiency of optical transmission.

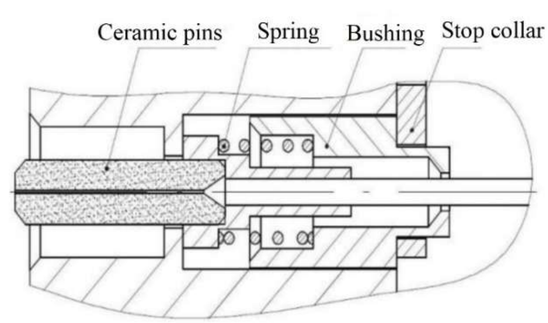


Figure 8: Schematic diagram of the “floating pin” structure

II. C.Sealing element design

The sealing element is the centerpiece of the watertight connector design. Plug sealing structure in the plug shell set a double O-ring seal, and according to the relevant standards set a one-way sealing ring retaining ring and groove (Figure 9), to protect the O-ring and prevent it from being extruded, to ensure that the plug sealing is reliable [6].

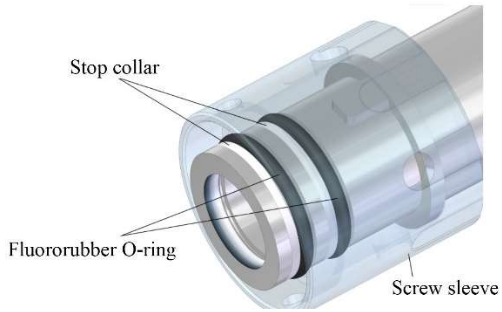


Figure 9: Plug Fit Seal

Fiber optic pin sealing structure designed for special ceramic pin assembly, radial setting of multiple O-rings in the tail shank, the tail end of the potting cavity (Figure 10), the use of double sealing to block the fluid. Fiber optic cable sealing structure adopts composite sealing, the first is pressurized cable sealing, the second is vulcanized sealing, at the same time, set up positioning sleeve and extended cable clamp inside the shell to fix the fiber optic cable, and optimize the shape of the vulcanized tail sleeve to improve the force of the connector's tail (Figure 11) [7].

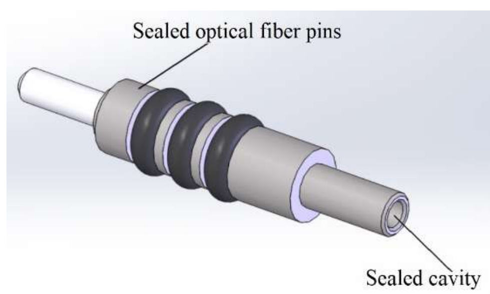


Figure 10: Fiber Optic Sealing Pin

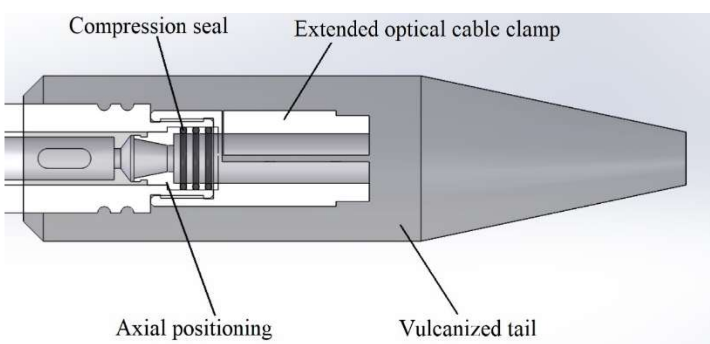


Figure 11: Fiber optic cable sealing structure

III. Product manufacturing

III. A. Process Technology Platform

Based on the previous project experience and years of technical accumulation, the project team has constructed a process technology platform for optical, electrical and optoelectronic hybrid watertight connectors, with a solid process foundation and a rich product portfolio. For the deep water environment, focus on strengthening the sealing process research, around the fiber insertion loss indicators and its consistency to carry out technical research, to build a solid foundation for industrialized mass production, to improve the overall consistency of the product and process stability.

III. B. Process flow

The product process covers a number of complex aspects. Parts machining, the connector shell, electrical contacts and other parts of the processing accuracy requirements are strict, need to ensure that the surface is clean, good fit and interchangeability. Fiber optic pin preparation and polishing process, through the heat curing adhesive fixed optical fiber [8], grinding and polishing process directly affects the temperature performance of optical connectors, is one of the key processes.

Positioning sleeve installation involves aramid combing and epoxy resin adhesive proportioning, modulation and potting. Polyurethane or rubber vulcanization process plays a decisive role in the watertight performance of the product, the selection of rubber, surface treatment, mold design, as well as vulcanization temperature and time are crucial, is also a key process. Insertion and commissioning can improve the consistency, repeatability and interchangeability of the optical insertion loss value of the product.

III. C. Processing and testing equipment

Connector processing and assembly using a variety of advanced equipment. Parts processing, CNC lathe, turning machining center, milling machining center and wire cutting and other equipment to ensure parts processing accuracy; performance testing, light source, optical insertion loss tester, optical power meter, PLC-controlled hydraulic test press and electronic universal testing machine and other equipment, for product performance testing provides a reliable guarantee.

IV. Product testing

IV. A. Standardized Normalized Reliability Test

IV. A. 1) High and low temperature impact test

The high and low temperature shock test (Figure 12) is conducted on the connector using a high and low temperature humidity and heat test chamber to simulate its working condition under different temperature extremes and to verify the reliability and shock resistance. The test is conducted in multiple cycles at specific temperature rise and fall rates and holding times, and the connector is inspected before and after the test for appearance, leakage and optical signal transmission performance.

Figure 12: High and low temperature humidity and heat test chamber

IV. A. 2) Corrosion tests in the marine environment

Marine environment corrosion test (Figure 13) is carried out on the offshore test float, and the connector is placed in the offshore environment for at least two months to assess its long-term corrosion resistance. Environmental monitoring and data collection are carried out during the test, and the connector is thoroughly inspected and performance tested after the test.

Figure 13: Offshore test floats

IV. A. 3) In-line pressure test

The on-line extreme high pressure test system (Figure 14) and cyclic fatigue hydrostatic tester (Figure 15) are utilized for the pressure test. The online extreme high pressure test simulates an ultra-high pressure environment to verify the connector's performance under deep-sea working pressure; the cyclic fatigue hydrostatic tester conducts multiple full-depth up-and-down pressure cycling tests on the connector [1], monitors the strain data, and evaluates its pressure-resistant performance and ability to recover from the pressure.

Figure 14: In-line extreme high voltage test system (left) and connections (right)

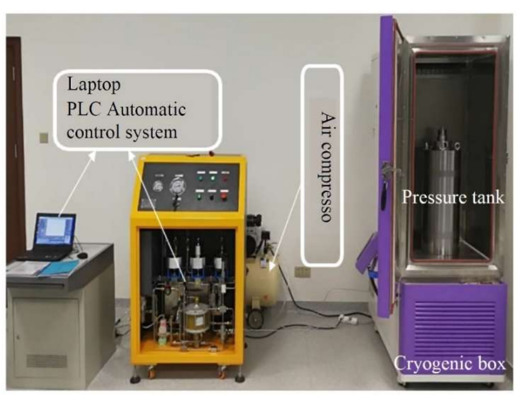


Figure 15: Cyclic Fatigue Hydrotester

IV. A. 4) Pool Tests

The connector will be equipped with deep-sea operation equipment in the pool for joint testing (Figure 16), simulating deep-sea operation scenarios and verifying its functional stability. The test process covers equipment connection, testing, inspection before launching, underwater testing and data comparison to ensure that the connector meets the requirements of practical applications.

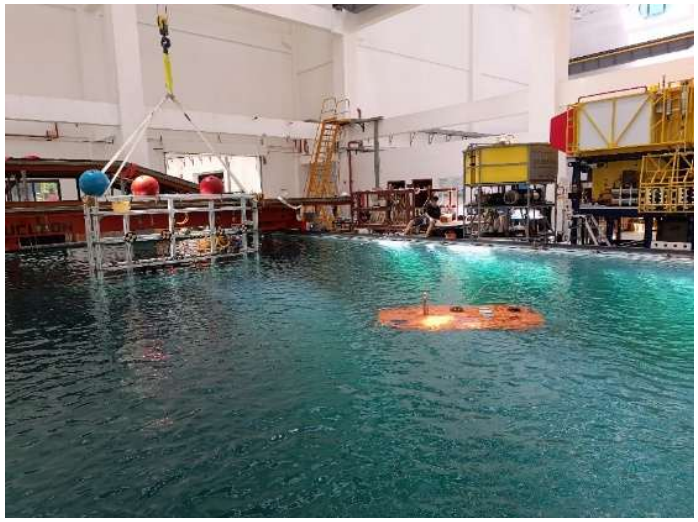


Figure 16: Pool test site

IV. B. Post-test analysis

If the sample is damaged or fails during the test, microstructural observation and compositional analysis of the failed part are carried out by X-Ray (Figure 17) and scanning electron microscope (Figure 18) to investigate the cause of failure and provide a basis for product improvement [4].

Figure 17: X-Ray inspection equipment

Figure 18: Field Emission Scanning Electron Microscope

V. Product sea trials

V. A. Preliminary sea trials

The 4-core fiber optic connector samples developed by the project were carried on the "Struggler" full-depth manned submersible for the sea test, after 25 dives, with a maximum depth of 7,180.4 meters, of which 14 times exceeded 6,000 meters, and were in good condition during the process of use, with no failures [9], and were applied in a variety of ways (Figure 19).

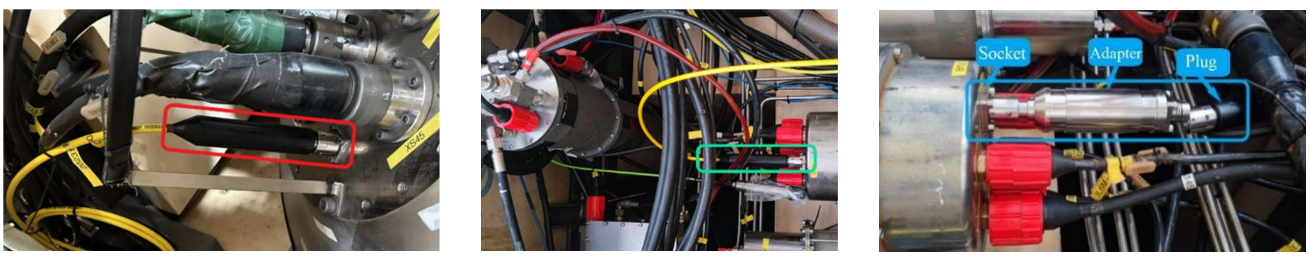
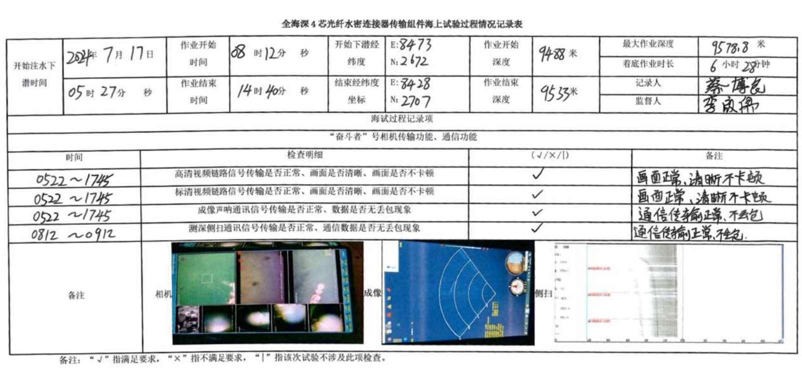


Figure 19: Application of project products on board the manned deep-submersible Striver

V. B. 10,000-meter sea trials

In July-August 2024, the product participated in the Exploration 1/"Striver" TS-42 voyage and carried out two sea tests above 9000 meters in the Chiba-Kamchatka Trench, with the maximum depth of 9580.8 meters. During the sea test, different channels of 4 optical fibers were connected to the observation and communication system and equipment of the manned submersible, the video transmission of the camera was normal and clear, the communication of the equipment was normal and the data transmission did not lose any packet, and the insertion loss satisfied the assessment standard (Figure 20 and Table 1).



全海深 4 芯光纤水密连接器传输组件海上试验过程情况记录表

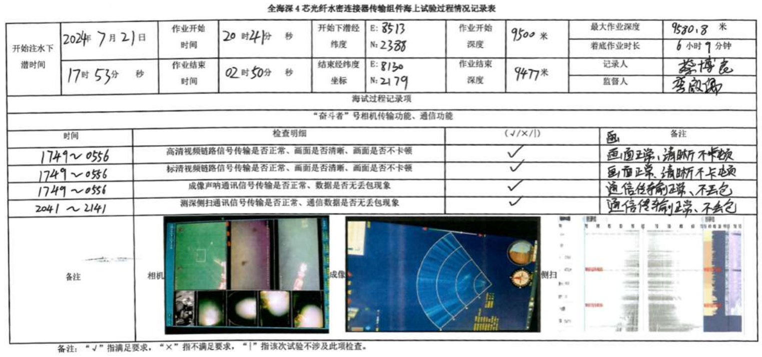
开始注水下潜时间	2024年 7月 17日	作业开始时间	08 时 12分 秒	开始下潜经纬度	E:8473 N:2672	作业开始深度	9488 米	最大作业深度	9578.8 米
								着底作业时长	6 小时 28分钟
	05 时 27分 秒	作业结束时间	14 时 40分 秒	结束经纬度坐标	E:8428 N:2707	作业结束深度	9533米	记录人	蔡博[illegible]
								监督人	李[illegible]

海试过程记录项

"奋斗者"号相机传输功能、通信功能

时间	检查明细	(√/×/|)	备注
0522～1745	高清视频链路信号传输是否正常、画面是否清晰、画面是否不卡顿	✓	画面正常，清晰不卡顿
0522～1745	标清视频链路信号传输是否正常、画面是否清晰、画面是否不卡顿	✓	画面正常，清晰不卡顿
0522～1745	成像声呐通讯信号传输是否正常、数据是否无丢包现象	✓	通信传输正常，不丢包
0812～0912	测深侧扫通讯信号传输是否正常、通信数据是否无丢包现象	✓	通信传输正常，不丢包
备注	相机 / 成像 / 侧扫		

备注："√"指满足要求，"×"指不满足要求，"|"指该次试验不涉及此项检查。



全海深4芯光纤水密连接器传输组件海上试验过程情况记录表

开始注水下潜时间	2024年 7月 21日	作业开始时间	20 时 41分 秒	开始下潜经纬度	E: 8513 N: 2388	作业开始深度	9500 米	最大作业深度	9580.8 米
								着底作业时长	6 小时 9 分钟
	17时 53分 秒	作业结束时间	02 时 50分 秒	结束经纬度坐标	E: 8130 N: 2179	作业结束深度	9477米	记录人	蔡博良
								监督人	李殿涵

海试过程记录项

“奋斗者”号相机传输功能、通信功能

时间	检查明细	(√/×/|)	备注
1749～0556	高清视频链路信号传输是否正常、画面是否清晰、画面是否不卡顿	√	画面正常，清晰不卡顿
1749～0556	标清视频链路信号传输是否正常、画面是否清晰、画面是否不卡顿	√	画面正常，清晰不卡顿
1749～0556	成像声呐通讯信号传输是否正常、数据是否无丢包现象	√	通信传输正常、不丢包
2041 ～ 2141	测深侧扫通讯信号传输是否正常、通信数据是否无丢包现象	√	通信传输正常、不丢包
备注	相机 / 成像 / 侧扫		

备注：“√”指满足要求，“×”指不满足要求，“|”指该次试验不涉及此项检查。

Figure 20: Sea trial product camera screen transmission, equipment communication test records

Table 1: Insertion loss of specimens before and after sea trial

Channel number	Insertion loss before test		Insertion loss after test	
	1310nm	1510nm	1310nm	1510nm
1	0.31dB	0.3dB	0.27dB	0.16dB
2	0.23dB	0.13dB	0.28dB	0.23dB
3	0.25dB	0.23dB	0.27dB	0.24dB
4	0.14dB	0.15dB	0.16dB	0.23dB

VI. Product scalability study design

VI. A. Design of functional extensions

On the basis of the original product, a small pressure compensation structure and implantation of fiber optic sensors are added to improve product performance. Small pressure compensation structure in the fiber optic connector cable ends set up inlet and outlet holes and integrated small pressure compensation system (Figure 21), the use of oil in the form of a bladder to achieve pressure compensation, improve the overall stability and reliability of the structure.

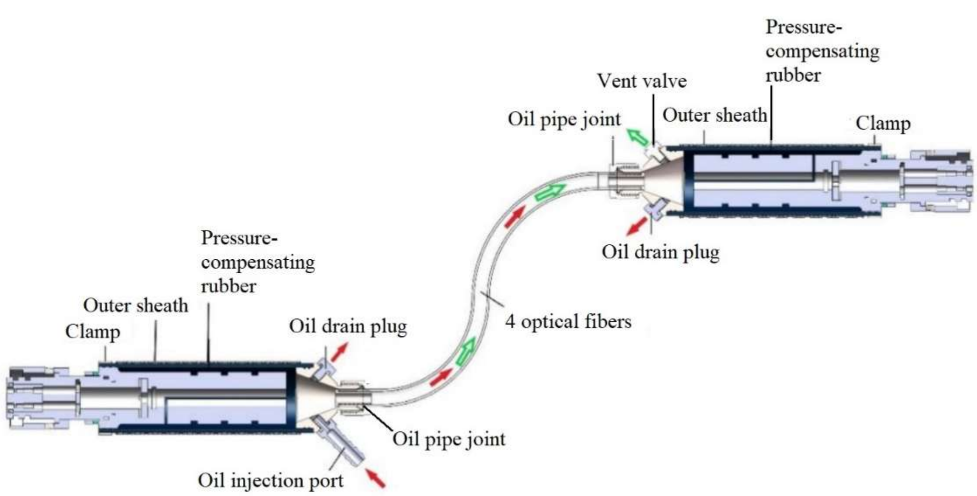


Figure 21: Schematic diagram of oil filling and venting

Implanted fiber optic sensors, including deformation sensors and moisture sensors (Figure 22 - Figure 25), are used to monitor stress changes and micro-leakage during inspection and application. By implanting these sensors in watertight connectors, real-time condition monitoring is achieved, providing data to support product development and assisting in the creation of failure modeling databases [10].

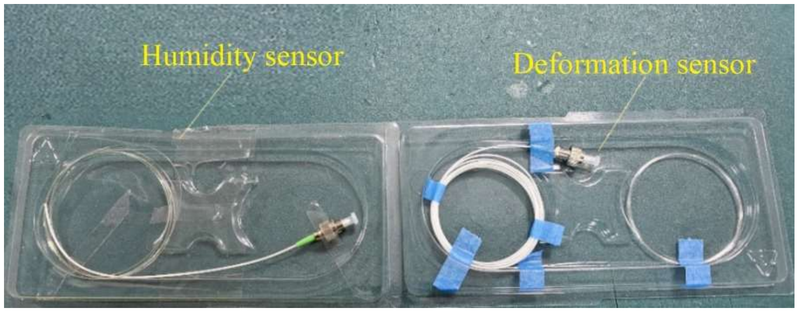


Figure 22: Deformation Sensor and Humidity Sensor

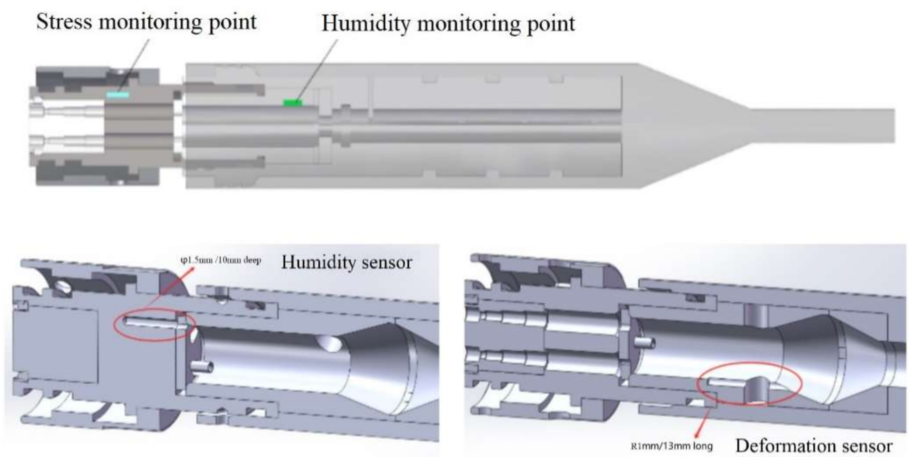


Figure 23: Watertight Connector and Sensor Integration Design Solution

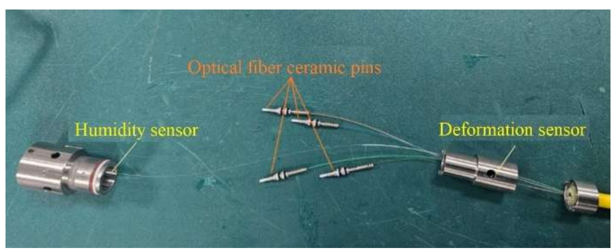


Figure 24: Actual Installation Diagram

Figure 25: General Installation Diagram

VI. B. Technological innovation drives expansion

High-pressure-resistant and high-compatibility miniaturized and modularized structure compensation technology enables the product to ensure pressure-resistant sealing while realizing high compatibility and interchangeability with foreign products, which enhances the versatility and fault-tolerance of the product in the application of the whole deep-sea engineering. Small modular overall integrated pressure compensator technology, which skillfully combines the pressure compensator with connectors and transmission components, realizing the upgrade of pressure resistance and stability without increasing the volume and quality burden.

Multi-source data monitoring and analysis method and performance standardization evaluation method, which collects and analyzes data through implanted sensors to derive the product performance degradation law, provides scientific basis for product optimization and quality control, and promotes continuous product improvement and innovation [11], [12].

VII. Concluding remarks

The development of full-depth multi-channel fiber optic watertight connector is a complex and systematic project, involving many key aspects such as product design, manufacturing, testing, sea trial and scalability. Through continuous technological innovation and practical verification, significant results have been achieved in this field, and the product performance has reached the international advanced level, providing strong support for deep-sea exploration and resource development [5].

In the future, with the continuous deepening of ocean development, higher requirements will be put forward for the performance and function of all-ocean depth multi-channel fiber optic watertight connector. It is necessary to further strengthen the technical research and development, improve the reliability, stability and expandability of the product, expand the application fields, promote the development of related industries, and contribute more power to the vigorous development of China's marine industry.

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