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Collision tests and data acquisition analysis of unmanned underwater vehicles based on multi-sensor monitoring

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Abstract. In response to the safety issues of large-angle collisions faced by unmanned underwater vehicles (UUVs) in marine exploration, this study systematically explores the dynamic response mechanism of underwater large-angle collisions via a "experiment& data&simulation" research system. It adopted a multi-sensor collaborative monitoring experimental scheme and established a fluid-structure coupling simulation model based on experimental data. Results show: 1) During underwater large-angle collisions, axial acceleration drops significantly and impact load transmission path is restructured. Under 60° collision, the shell's near-end axial impact acceleration in air is $29.1g$, strain amplitude nearly 240 $\mu m/m$, wavelength $22.5ms$; underwater, acceleration is unidentifiable, strain amplitude falls to $1/3$ of that in air, and wavelength extends beyond $30ms$; 2) The fluid environment notably optimizes UUV housing's collision response via a synergistic mechanism: "water film lubrication to reduce drag, fluid inertia to extend collision time, and fluid pressure to change collision attitude". This study verified the multi-sensor monitoring scheme's reliability, providing effective technical support for marine equipment's anti-shock design and structural health monitoring. As key marine exploration and monitoring equipment, UUVs require particularly critical collision safety in complex underwater environments.

1. Introduction

1.1. Research background

As a key equipment for conducting marine environmental monitoring and resource exploration tasks, the shell structure of UUV is exposed to significant collision risks in complex underwater environments [1]. Underwater collision accidents are highly likely to cause damage to the shell structure, thereby affecting its integrity and ultimately leading to the failure of the equipment's functionality [2]. This indicates that collision safety of UUV structure is one of the core challenges in ensuring the high reliability operation of marine equipment [3]. However, traditional research on the collision performance of the shell structure mostly focuses on the analysis of structural deformation after the collision or the numerical simulation of the collision process, and generally lacks real-time dynamic data support from the sensors on the equipment itself during the collision process [4]. The absence of such real-time monitoring data makes it difficult to comprehensively reveal the mechanical behavior and the evolution mechanism of shell damage during the collision process, which restricts the improvement of the structural health monitoring and early warning capabilities of marine equipment. Therefore, integrating real-time sensor data with simulation analysis has become an urgent need to

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enhance the structural safety design and intelligent operation level in the development of marine equipment [5].

1.2. Research significance

This research is based on the underwater UUV collision testing device and closely focuses on the core themes of "sensor technology" and "data acquisition and processing" [6]. By deploying various types of sensors (such as acceleration sensors and strain sensors) to simultaneously collect the dynamic responses during the collision process, this multi-source data synchronous acquisition method enables multi-dimensional monitoring of the complex physical phenomena at the moment of the collision [7]. This approach overcomes the limitations of a single sensor and provides key data support for revealing the dynamic response mechanism of the underwater UUV shell. The fusion of multi-sensor information and its application in UUV guidance [8]. The research results offer certain data references for the structural design and safety operation of high-value marine equipment, and help improve their shock resistance performance and reliability in complex marine environments.

1.3. Research content and innovation points

This study has established a complete "experiment - data - simulation" research system. Full-scale air and underwater collision tests of the UUV shell (including the buffer layer) were conducted; multiple types of sensors were finely arranged to achieve synchronous and precise measurement of the dynamic response throughout the collision process; based on the collected multi-source data, in-depth comparative analysis was carried out on the dynamic response of underwater UUV collision processes and the comprehensive influence of the fluid environment on the angle effect and the energy absorption mechanism of the buffer layer [9]. The core innovation of this study lies in using multi-dimensional measured data as the basis for verification and analysis, providing highly reliable data support and research method references for the design of shock-resistant structures and performance evaluation of marine equipment [10].

2. Test apparatus and scheme

2.1. Parameters of equipment specimens

To accurately simulate the dynamic response of the UUV shell in the underwater environment during collision, this paper fabricated a physical model of the UUV shell and built a matching underwater collision test fixture. The diameter of the UUV shell is 0.32 m, and the total length is 3 m. It consists of the head and the rear cabin. The head part is approximately 0.6 m long and is made of 7075 aluminum alloy [11]. This material can achieve the corrosion resistance and lightweight characteristics of marine equipment [12]. The head and the rear cabin are fixed by a 8-pin gap fit (symmetrical) and are supplemented with O-ring seals and structural adhesives to achieve IP68-level waterproofing. The test fixture is divided into the propulsion system, the water environment system, and the motion limit system. This system enables the UUV shell to complete a collision at a maximum speed of 5.5 m/s at a water depth of 1 m. After verification, the stability and repeatability are excellent [13].

Figure 1. Physical model of UUV shell and test device

2.2. Multi-sensor layout design

In this study, in order to accurately collect the dynamic response data during the collision process of the UUV shell, a multi-sensor collaborative monitoring scheme of "acceleration & stress & vision" was adopted. Pressure-sensitive acceleration sensors, foil-type strain gauges, high-speed cameras, etc. were used to collect real-time data on the acceleration at specific positions of the shell, as well as the deformation images of the overall shell movement. The specific selection is as follows: The acceleration sensor selected is the Endevco 2270 piezoelectric acceleration sensor, with a sensitivity of 2.2 pC/g and a frequency response of 2 - 2000 Hz, used to collect the instantaneous acceleration of the UUV shell head, directly reflecting the instantaneous motion state; the strain sensor selected is the Vishay Micro linear foil strain gauge 500UW, with an accuracy of 0.1% F.S., used to monitor the stress changes in different areas of the shell during the collision. Considering the requirements of underwater tests, the surface of the sensors is encapsulated with epoxy resin, and the external coating is waterproof structural adhesive, achieving an overall waterproof level of IP68 [14], suitable for the humid marine environment; the high-speed camera selected is the NPX-GS650UC camera, with a frame rate of 3000 fps, a resolution of 272×100 PPI, and a lens focal length of 50mm, used to capture the collision movement process from the side observation window, assisting in verifying the rationality of the sensor data. Using a camera to capture high-speed images, the path of the UUV's head features is tracked precisely to measure the speed at the moment of collision. In combination with the structural characteristics and collision force laws of the UUV housing, the specific layout positions of the sensors are as follows:

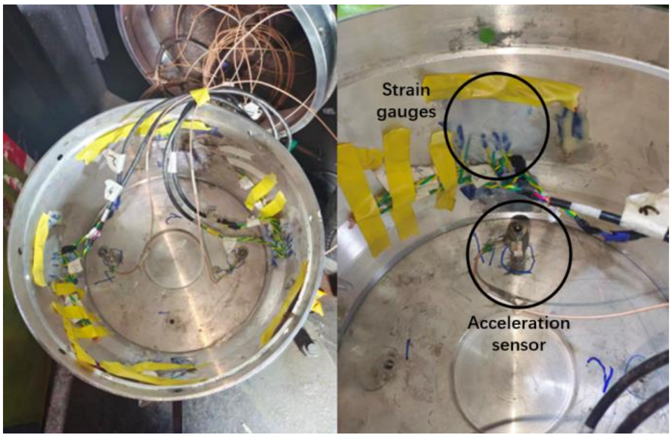


Figure 2. The layout position of the sensor inside the UUV housing

2.3. Construction of the data acquisition system

The core hardware for acceleration data acquisition adopts the LK2019A high-speed acquisition instrument (compatible with stress sensors) and the SDS 1204X-C dynamic response data acquisition oscilloscope (compatible with position acceleration sensors), along with the YE585 charge amplifier. The sampling frequency is uniformly set at 10kHz to ensure the capture of instantaneous dynamic signals during the collision process; the acquisition card is connected to the computer via USB 3.0 and real-time stores the data [15].

A silver shielded wire and a shielded twisted pair are used between the sensor and the acquisition card to reduce the influence of electromagnetic interference from water or space on the data; the underwater cable connector uses a dedicated waterproof connector, and is wrapped with polytetrafluoroethylene tape, and the outside is coated with waterproof structural glue to prevent water from seeping in and causing a short circuit; in the acquisition software, a 50Hz low-pass filtering function is added to further eliminate environmental interference signals; the synchronization control of multiple devices is achieved by triggering signals from travel switches, which synchronizes the sensor and the high-speed acquisition instrument to work collaboratively: when the UUV shell moves to the vicinity of the collision position, the travel switch outputs a TTL high-level signal to the high-speed acquisition instrument, synchronizing the triggering of all acquisition devices, ensuring that the stress, acceleration data, and visual images are on the same time axis, facilitating subsequent multi-dimensional analysis [16].

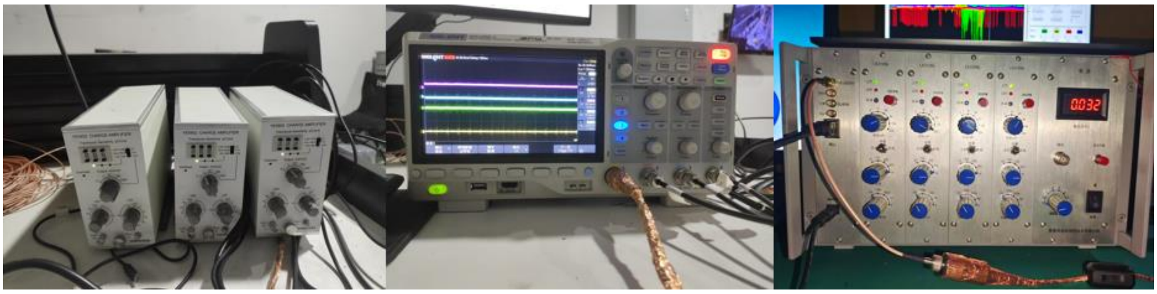


Figure 3. The data acquisition equipment used in the experiment

3. LS-DYNA simulation modeling

3.1. Simulation model construction (Marine Environment adaptation)

Based on HyperMesh and LS-DYNA, a full-scale UUV shell underwater collision finite element model was established [17]. The structural domain includes the shell head, the cabin (7075 aluminum alloy, q235 steel, MAT_PLASTIC_KINEMATIC), and a 50mm thick rubber buffer layer (MAT_MOONEY-RIVILIN_RUBBER). To realistically simulate marine conditions, a 5000×800×800mm³ fluid domain was established, using the ALE algorithm to describe the fluid (MAT_NULL and EOS_GRUNEISEN state equation), and by applying non-reflective boundary conditions to the upper and lower surfaces of the water area and the surrounding areas, as well as using the *INITIAL_HYDROSTATIC_ALE keyword for static water pressure initialization, the environmental loads under different water depths were accurately reproduced, ensuring the consistency of the simulation environment with the real marine conditions. The flow-solid coupling was described using CONSTRAINED- LAGRANGE _IN_SOLID, and the penalty function method was adopted.

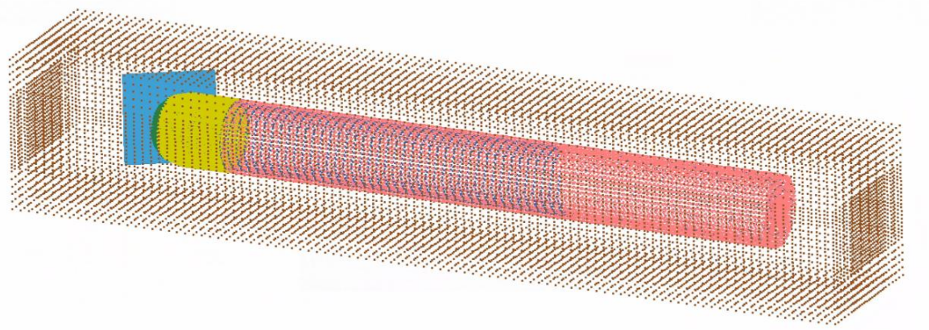


Figure 4. LS-dyna underwater collision model of UUV

3.2. Correlation between simulation and test data

To ensure that the simulation results can be applied to the safety performance assessment of the UUV shell as accurately and reliably as possible, the settings of the simulation output parameters (such as the surface stress inside the shell, the acceleration at key points) must be strictly matched with the positions of the accelerometers, strain gauges and other sensors used in the experiments, as well as the physical quantities collected. The mesh accuracy in the fluid areas near the sensor monitoring positions and near the UUV is locally densified to improve the accuracy of the simulation results in this area, thereby providing a reliable foundation for the subsequent comparison, verification and fusion use of the simulation data with the multi-source signals collected in the experiments.

4. Result and analysis

4.1. Reliability verification of sensor data

To ensure the reliability of the results and the accuracy of subsequent analyses, the original data collected during the experiment were first verified for reliability. During the data preprocessing stage, in accordance with the common acceleration signal filtering methods used in the field of general mechanical engineering, combined with the electromagnetic interference and mechanical vibration noise existing in the underwater test environment, in order to ensure the consistency and comparability of data processing, this study adopted the filtering method (CFC100 level) specified in the SAE J211/ISO 6485 standard to process the original acceleration signal data [18]. This frequency range can fully retain the main dynamic response characteristics of the structure and effectively suppress high-frequency noise interference, highlighting the effective data during the collision process.

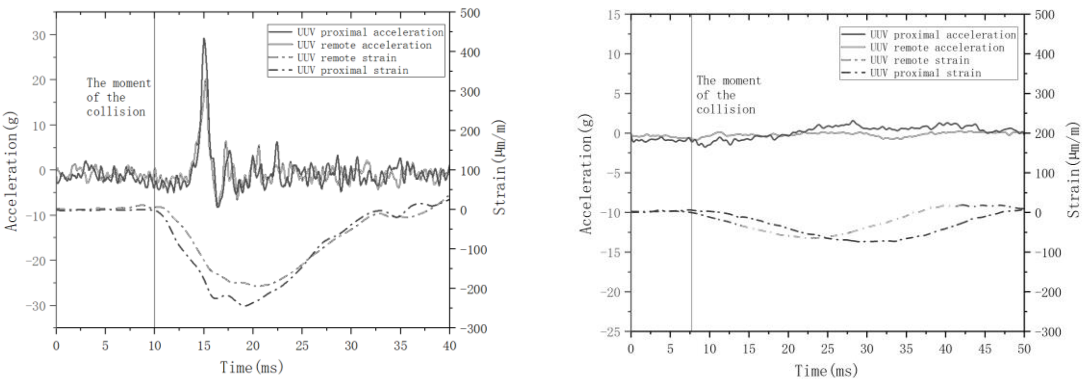
To verify the repeatability and validity of the data, the impact acceleration curves collected by the UUV head acceleration sensor under 5 repeated test conditions were compared. The results show that the appearance time and amplitude of the main characteristic peaks of each test have good consistency, and the degree of acceleration dispersion is within ±4.8% of the average value, proving the stability of the data acquisition system and the consistency of the test data, providing a reliable data basis for subsequent in-depth analysis.

Table 1. The results of five collision tests

Serial number	Velocity (m/s)	Proximal acceleration (g)	Remote acceleration (g)	Proximal strain (μm/m)	Distal strain (μm/m)
1	5.64	29.1	22.1	267	165
2	5.60	27.6	20.9	244	201
3	5.51	26.3	22.1	240	186
4	5.43	26.0	19.7	253	190
5	5.38	25.7	21.5	221	145

4.2. Comparison of air-underwater (Marine environment) collision responses

This study conducted an experiment to compare the collision responses in air and underwater environments, aiming to reveal the unique mechanism of the water body during the collision process of the UUV shell. The test conditions were as follows: collision speed of 5.5 m/s, impact angle (the angle between the shell axis and the normal line of the target plate) of 60°, and the environment was air and 1 meter depth underwater (the water depth where the shell axis was located). The collected data were the acceleration and strain on the inner side of the UUV shell head near the collision point. The results are as follows:



(a) (b)

Figure 5. Test result data graph, collision in air (a), collision in water (b)

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Data shows that under the 60° large-angle collision condition, the axial impact acceleration of the shell in the air is 29.1g (near end), but it drops sharply in the underwater environment and is unrecognizable. The strain amplitude in the air is close to 240μm/m, with a wavelength of 22.5ms. However, in the underwater environment, the collision strain amplitude is reduced to one-third of that in the air, and the wavelength is extended from 22.5ms to over 30ms. Under the underwater large-angle collision condition, this phenomenon difference of "a significant difference in acceleration and the transformation of short strain waves into long waves" cannot be fully and reasonably explained by the traditional energy dissipation theory and the additional mass theory, thus leading to the conjecture that the fluid may change the load transmission path under the underwater large-angle collision condition. To explain the complex influencing mechanism behind this phenomenon from multiple perspectives, a collision consistent with the test conditions was simulated in the LS-dyna software. After comparison and verification, the relative error of the peak axial acceleration measured by the simulation and the test was less than 5%, and the time-history curves were also basically consistent, which proved the reliability of the simulation data, The simulation results are shown in Figure 6.Some simulation result data were extracted to explain the fluid-structure coupling collision influence mechanism from multiple aspects.

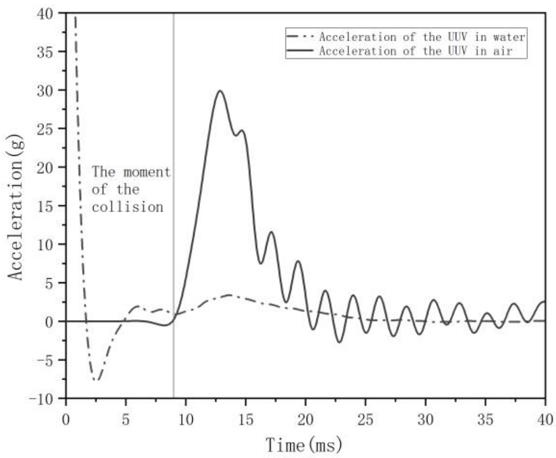

Figure 6. Simulation results: UUV acceleration curves in water and in air

To better reveal the interaction mechanism between the fluid and the UUV shell, the fluid pressure distribution and the projectile movement trajectory in the simulation cloud map were extracted, which can clearly reveal the pressure changes of the water body during the collision process:

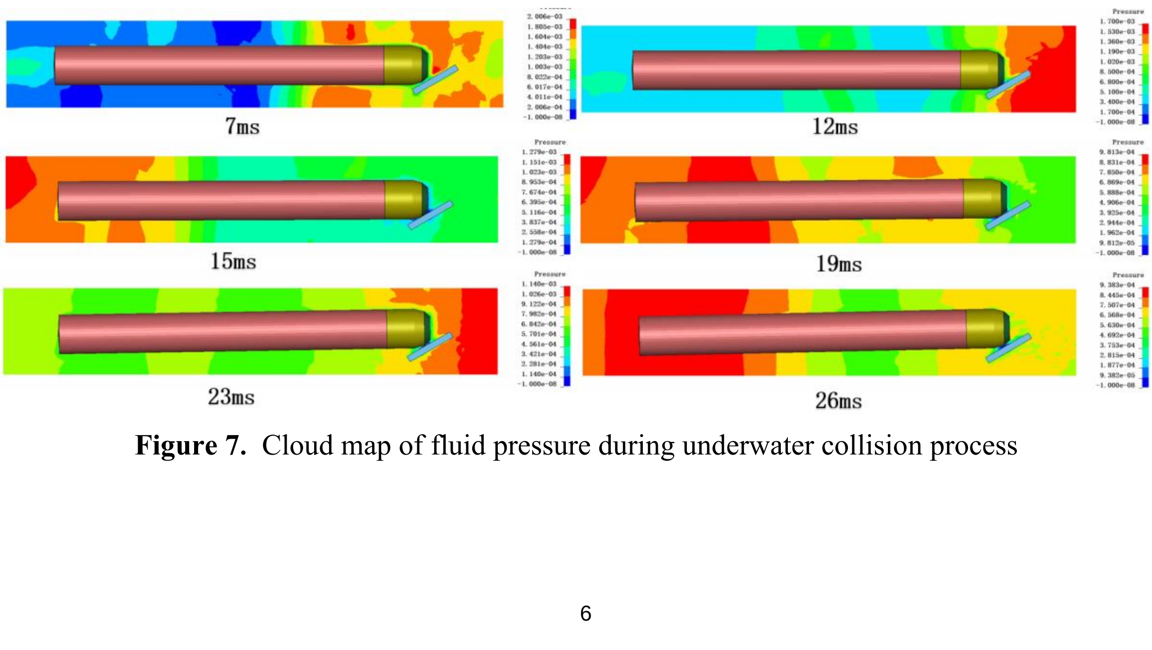

Figure 7. Cloud map of fluid pressure during underwater collision process

By comparing the cloud images, it can be found that at the moment before the collision, due to the water flow being blocked by the target plate, a local high-pressure water area was formed between the head of the uuv shell and the target plate, as shown in Figure 7. The existence of this water area is similar to a high-pressure water film, which greatly reduces the friction coefficient of the contact surface, causing part of the axial kinetic energy to be dissipated through the shear flow of the water film [19]. Rather than all being transferred through solid contact. Moreover, by observing the kinetic energy change in Figure 8, it can be seen that the underwater uuv began to decelerate before the collision, which proves the obstructive effect of the local high-pressure water area on the head of the uuv shell. This directly explains why the deformation of the structure during underwater collisions is smaller than that in the air, and the axial impact overload collected by the acceleration sensor is significantly reduced. The water film dynamic pressure lubrication and load reconstruction effect are important mechanisms that lead to a significant reduction in axial impact force [20]. Meanwhile, according to the time history of the collision force curve in Figure 9, it can be known that due to the existence of high-pressure water film underwater, it plays a role of "blocking" and "driving away" on the uuv head. Therefore, the duration of the underwater collision process is shorter than that in the air.

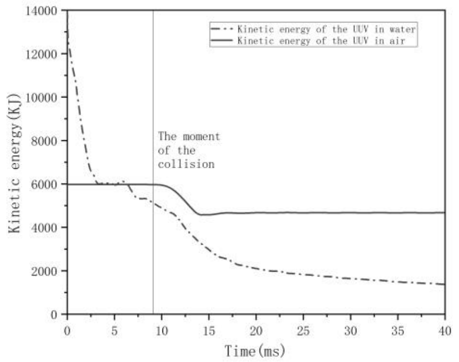

Figure 8. Kinetic energy of the UUV shell in air and underwater collisions

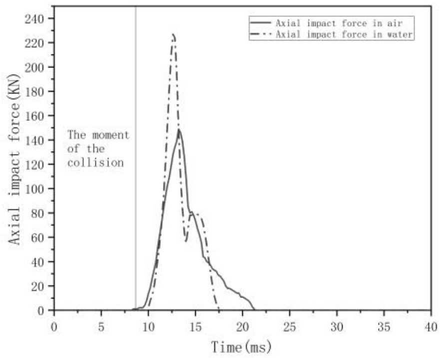

Figure 9. The time-history curve of the collision force between the UUV shell and the target plate

The additional mass effect is a factor that must be considered when analyzing fluid-structure interaction problems. As a continuous medium with a certain mass, water exerts a continuous inertial force (i.e., the additional mass force) on the uuv shell during the deceleration process after the uuv head comes into contact with the target plate, due to the pressure difference between the side wall fluid viscosity and the front and back of the shell. This effect significantly prolongs the duration of the entire collision process, achieving the transfer of part of the fluid kinetic energy to the uuv shell. This conclusion can be verified by comparing the strain curve differences in air and underwater, as shown in Figure 5. From an engineering perspective, the presence of a fluid environment "passivates" a transient violent impact into a gentle load process, reducing the peak while extending the wavelength. This is crucial for protecting the internal sensors and electronic devices that are sensitive to the impact rate.

At the moment before the contact occurs, the water in the high-pressure area of the uuv head exerts a trace but crucial pre-compression on the polyurethane buffer layer, as shown in Figure 10. This phenomenon causes the buffer layer to enter the energy-absorbing state in advance. At the same time, the high-pressure water area near the target plate surface exerts a unilateral force on the head of the uuv shell, changing the initial contact posture between the uuv head and the target plate, inducing a slight deflection away from the target plate, and further reducing the severity of the collision. Meanwhile, due to the presence of the fluid, the flow field and pressure changes generated by the attached water driven by the movement of the uuv shell interact with the target plate before the shell and the target plate. Even after the shell and the target plate separate, the fluid still exerts a continuous force on the target plate. Therefore, the energy absorption process of the target plate begins earlier

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than in the air during underwater collisions, but the peak appears later than in the air, as shown in Figure 11.

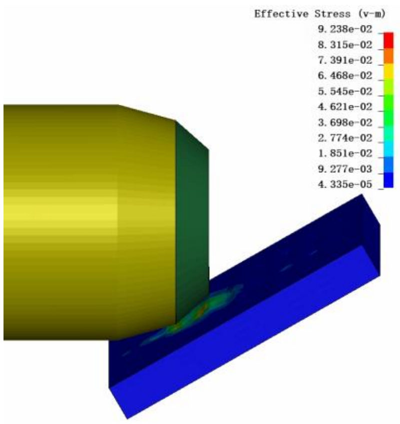

Figure 10. The target plate undergoes pre-compression before collision

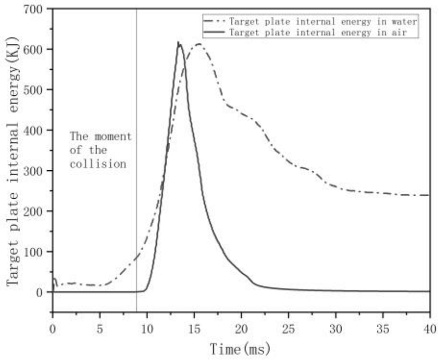

Figure 11. Comparison of energy absorption of target plates in air and Underwater

Based on the above conclusions, the experimental and simulation data jointly prove that in the underwater high-angle collision condition, the UUV shell completes the contact with the target plate in a manner similar to "sliding friction". During this process, the marine environment does not simply act as a damping medium to absorb energy, but rather through the synergistic mechanism of "water film lubrication for reduced resistance, fluid inertia to prolong the impact time, and fluid pressure to change the contact posture", fundamentally reconstructs the transmission path and time course of the collision load. This new discovery supplements the traditional understanding in the field of fluid-solid coupling high-angle collisions, clearly indicating that in the design of shock-resistant structures for marine equipment, it is necessary to fully consider and actively utilize the lubrication and inertia effects of fluids in order to achieve more precise and efficient protection for the equipment and its internal core components.

5. Conclusion

5.1. Core research conclusion

This study, through a combined research system of "experiment&data&simulation", has reached the following core conclusions: Firstly, the multi-sensor collaborative monitoring scheme based on standard filtering processing demonstrates excellent reliability (RMSE of repeated experiments < 5%) in marine equipment collision tests, providing a reliable technical path for equipment structural health monitoring. Secondly, the research reveals that in underwater large-angle collision conditions, the UUV shell undergoes a significant change in collision response through the collaborative mechanism of "water film lubrication and drag reduction, fluid inertia delay, and fluid pressure changing the posture", which reduces the collision impact overload. This proves that in this condition, the marine fluid environment has a positive effect on equipment collision safety. Finally, the verified simulation model is highly consistent with the sensor measured data, indicating that this high-fidelity numerical model can effectively simulate complex marine conditions and can provide highly reliable analysis tools and design basis for the shock resistance design and safe operation of marine equipment.

5.2. Suggestions for the Design and Application of Marine equipment

Based on the research findings, the following suggestions are proposed for the development of marine equipment: In the design of the UUV shell, the fluid pre-compression effect should be fully considered, and the material parameters and layout of the side wall buffer layer should be optimized to better utilize the water medium to improve the large-angle collision load. The multi-sensor monitoring scheme and verification method established in this study can be further extended to the collision safety assessment and structural health monitoring system of similar high-value marine equipment such as underwater robots and autonomous submersibles, providing technical support for improving the intelligent operation and maintenance level of China's marine equipment.

6. References

[1] Han E, Yuan S, Chen L. Study on the Performance of Anti-Collision Sandwich Structure forUnderwater Vehicles[C]//*International Conference on Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers*, 2024, 87790: V002T02A097.
[2] Glenn, S., Moline, M. Robot Explorers Lose One of Their Own. *American Scientist*. 2015.
[3] Weijermars R. Comprehensive assessment of deep-water vessel implosion mechanisms: OceanGate's Titan submersible failure sequence explained[J]. *International urnal of Pressure Vessels and Piping*, 2025, 213: 105340.
[4] Treloar A, Hunter J, Blondel P, et al. Real-time passive acoustic beamforming and detection from the AutoNaut USV and Manta XLUUV[C]//*Underwater Acoustics Conference and Exhibition. IACM, Foundation for Research and Technology-Hellas*, 2023: 249-256.
[5] Sreenath S, Malik H, Husnu N, et al. Assessment and use of unmanned aerial vehicle for civil structural health monitoring[J]. *Procedia Computer Science*, 2020, 170: 656-663.
[6] Thurman E, Riordan J, Toal D. Approach to the Real-Time Adaptive Control of Multiple High Frequency Sonar Survey Systems for Unmanned Underwater Vehicles[J]. *IFAC Proceedings Volumes*, 2008, 41(1): 61-66.
[7] Zhou H, Lynch J, Zekkos D. Autonomous wireless sensor deployment with unmanned aerial vehicles for structural health monitoring applications[J]. *Structural Control and Health Monitoring*, 2022, 29(6): e2942.
[8] Jyothi V B N, Shakeera S, Vedachalam N, et al. EM and Vision aided Multi-Sensor Fusion Homing Guidance System (MSF-HGS) for Intelligent AUVs[J]. *IEEE Sensors Journal,* 2024.
[9] G Guo , L Min Dynamic Response and Prediction of Underwater Cylindrical Shell Collision[J]. *Journal of Southwest University Natural Science Edition*, 2025, 47(7): 168-184.
[10] Ma S, Tang X, Ma S. Integration of multi-sensor marine environment monitoring system for hybrid-power USV [C]//*Fourth International Conference on Geology, Mapping, and Remote Sensing (ICGMRS 2023). SPIE*, 2024, 12978: 520-528.
[11] Xie C, Wang L, Yang N, et al. A compact design of underwater mining vehicle for the cobalt-rich crust with general support vessel part a: Prototype and tests[J]. *Journal of Marine Science and Engineering*, 2022, 10(2): 135.
[12] Zhang P, Yue X, Jiang X, et al. Research on the seawater corrosion resistance mechanism of 7075 aluminum alloy based on combination strengthened gradient surface construction[J]. *Materials Characterization*, 2025, 223: 114964.
[13] Liu P, Kaewunruen S, Zhao D, et al. Investigation of the dynamic buckling of spherical shell structures due to subsea collisions[J]. *Applied Sciences*, 2018, 8(7): 1148.
[14] HY/T 0394-2024, Technical Requirements for Anti-corrosion and Anti-fouling of Underwater Structures of Marine Observation Equipment[R],2024.
[15] GB/T 7714,Talmadge R D, Radmand M. High Speed Data Acquisition Systems[R]. 1988.
[16] International Electrotechnical Commission. Precision clock synchronization protocol for networked measurement and control systems[J]. *IEC 61588: 2004 (E)*, IEEE 1588-2002 (E), 2004.
[17] Min L. Influence of ambient water currents on collision dynamic response characteristics of unmanned underwater vehicles. Wuhan University of Technology, 2025.
[18] S. J211-1 instrumentation for impact test—Part 1—Electronic instrumentation[J]. *SAE International*, 2007.
[19] Shao S, Gotoh H. Simulating coupled motion of progressive wave and floating curtain wall by SPH-LES model[J]. *Coastal Engineering Journal*, 2004, 46(02): 171-202.
[20] Runhua Litwin W. Water: An Extraordinary, Ordinary Lubrication Liquid. Influence of Water Salinity, Pressure and Temperature on Water Lubricated Bearings Properties [C]//*International Joint Tribology Conference*. 2010, 44199: 103-105.