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Review

Advances of Complex Marine Environmental Influences on Underwater Vehicles

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Abstract

Underwater vehicles serve as critical assets for global ocean exploration and naval capability enhancement. The marine environment exhibits intricate hydrodynamic phenomena that significantly threaten underwater vehicle navigation safety, particularly in four prevalent complex conditions: surface waves, oceanic currents, stratified fluids, and internal waves. This comprehensive review systematically examines the impacts of these four marine environments on underwater vehicles through critical analysis and synthesis of contemporary advances in theoretical frameworks, experimental methodologies, and numerical simulation approaches. The identified influences are categorized into five primary aspects: hydrodynamic characteristics, dynamic response patterns, load distribution mechanisms, navigation trajectory optimization, and stealth performance. Particular emphasis is placed on internal wave interactions, with rigorous analysis derived from experimental investigations and numerical modeling of internal wave dynamics and their coupling effects with underwater vehicles. In addition, this review points out and analyzes the shortcomings of the current research in various aspects and puts forward some thoughts and suggestions for future research directions that are worth further exploration, including enriching the research objects, upgrading the experimental techniques, and introducing artificial intelligence methods.

Keywords: underwater vehicle; surface waves; ocean current; density stratification; internal waves; fluid dynamics; numerical simulation

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1. Introduction

The 21st century has witnessed global scientific and military communities increasingly prioritize marine resource exploitation and naval infrastructure development. Within this context, underwater vehicles (UVs) have emerged as pivotal platforms for both civilian exploration and defense operations, playing a pivotal role in enabling critical operations ranging from seabed resource extraction to strategic maritime surveillance. Ensuring optimal navigation performance and the operational safety of UVs has consequently become a paramount research focus, particularly given the marine environment's inherently complex and dynamic nature. At present, the most attention has been paid to the impacts of the

four complex marine environments, surface waves, currents, density stratification, and internal waves, on underwater vehicles and their coping strategies [1].

The influence of surface waves on underwater navigation is reflected in the reduction in the stability of near-surface navigation and the increase in the complexity and risk of water entry and exit [2]. At present, scholars have carried out a lot of research on the mechanism of surface wave action, the motion response of the underwater vehicle, and the evolution of the flow field of the water entry and exit through theoretical modeling, experimental validation, and numerical simulation methods.

Currents are common in the ocean, on the one hand, they will affect the motion state of the underwater vehicle [3], resulting in abnormal speed, heading, and attitude angle of the underwater vehicle, and scholars have explored and summarized their influence laws. On the other hand, it will also lead to the failure of the path planning of the underwater vehicle [4]; for this problem, scholars optimize and combine the path planning algorithm on the basis of theoretical research, so as to reduce the influence of the sea current.

Density stratification, as a common phenomenon in the actual ocean, has been studied for a long time, and it mainly affects the hydrodynamic performance and stealth of the underwater vehicle [5]. At present, the research on this complex marine environment has been more mature, and scholars have summarized the mechanism and law of its influence on the underwater vehicle through various research means.

In recent years, a complex marine environment occurring below the water surface, called internal waves, has attracted significant attention from researchers [6], and accidents caused by internal waves are common in engineering practice, which has become a disastrous environmental factor that must be considered in the safe navigation of underwater vehicles and the work of marine structures. Scholars from various countries have carried out many numerical simulations or experimental research on the interaction between internal waves and underwater vehicles by constructing the theoretical model of internal waves, reproducing the interaction process between internal waves and vehicles, and revealing the influence of internal waves on the performance and motion state of vehicles.

The novelty of this review lies in its consolidation of the influences of four common marine environments on underwater vehicles. Through theoretical modeling, experimental verification, and numerical simulation, the current study reveals the influence of four environmental factors on the performance of underwater vehicles. For each environment, it summarizes and analyzes the most critical aspects affecting underwater vehicles' performance. Compared to studies focusing on a single environment, this review enables researchers in related fields to conduct cross-environment comparative analyses of vehicle–environment interactions. Furthermore, beyond the hydrodynamic loads and motion responses typically covered in existing reviews, this work also synthesizes the influences on vehicle guidance and control strategies, path planning, and stealth performance. Thus, it offers broader research perspectives for the scientific community. And it provides solid theoretical support and technical guidance for improving the adaptability, navigation efficiency, and safety of underwater vehicles in complex marine environments. Based on this analysis, directions worthy of further exploration are uncovered, and some thoughts and suggestions are put forward.

2. Influences of Surface Waves

Surface waves represent one of the most prevalent dynamic phenomena in marine environments, yet their hydrodynamic influences were historically disregarded in early underwater vehicle (UV) research. This oversight originated from conventional operational paradigms where UVs predominantly operated at significant depths, rendering surface wave effects negligible through water column attenuation. However, modern UV

applications have substantially expanded operational envelopes, necessitating frequent near-surface navigation for critical missions including communication relay, sensor deployment, and littoral zone operations [7]. Furthermore, all free-launched UVs inherently undergo water entry/exit processes where wave-induced hydrodynamic loading becomes non-trivial. This paradigm shift has driven concerted research efforts to quantify and mitigate surface wave impacts across various operational scenarios. This chapter provides an introduction to the research on surface wave effects on underwater vehicles.

2.1. Near-Surface Navigation in Surface Waves

While deep sea operations constitute specialized mission profiles, underwater vehicles predominantly operate within the near-surface zone where surface waves critically affect three key performance metrics: hydrodynamic stability during navigation, propulsive efficiency under wave-induced perturbations, and depth-keeping precision. These wave-driven disturbances can compromise operational safety through mechanisms such as pitch oscillations caused by asymmetric wave loading. A representative hazard involves wave-induced heave motions creating vertical sea surface displacements that expose propulsion systems to air–water interfaces, triggering propeller ventilation phenomena that induce thrust breakdown during critical maneuvering phases.

In order to determine the range of surface wave effects on underwater vehicles at depth, an experimental study conducted by Khader et al. [8] in 1979 showed that for all axisymmetric objects, the free surface wave effect becomes negligible when the depth of immersion is greater than four times the maximum diameter of the object. However, the effect of waves on an underwater vehicle depends not only on the depth of the water, but also on the Froude number. They modeled the underwater vehicle as an ellipsoid and conducted towing tank experiments. By adjusting the model's speed and dimensions to vary the Froude number, they measured the resistance acting on ellipsoids of different sizes under various test conditions using a force balance. Using f/b (b represents the maximum diameter and f represents the depth of the centroid) as the dimensionless submergence depth, when f/b is less than 4, the drag coefficient increases with the increasing Froude number until the Froude number reaches 0.5. The wave resistance coefficient reaches its maximum value when the Froude number is in the range of 0.5 to 0.55, after which it starts to decrease. This finding provides theoretical support for the scholars' research. Based on this, scholars have conducted numerous experimental studies on the impact of surface waves on underwater vehicles near the surface. Suriben et al. [9] conducted an experimental investigation into the constant drag and oscillating wave excitation longitudinal force on various shapes of underwater vehicles operating near the surface. They discovered that the shape of the head and tail of the underwater vehicle, the wavelength, and navigation velocity had a significant impact on the drag force but only a minor effect on the surge force. For the influence of navigation velocity, Mansoorzadeh et al. [10] investigated the changes in drag and lift coefficients of an underwater vehicle operating near the surface at different water depths and speeds. The study found that changes in drag and lift coefficients were highly sensitive to variations in speed. Figure 1 shows the simulation results of the drag coefficients (CD) of the underwater vehicle at different submergence depths at speeds of 1.5 and 2.5 m/s, where h is the distance between the center of mass and the free surface, and D is the diameter. It can be seen that at lower depths, the surface effect is quite large, and the drag coefficient value is large. On the other hand, the drag coefficient approaches a constant value when the dive depth exceeds a certain value. For example, at an AUV speed of 1.5 m/s, the drag coefficient reached its infinite medium drag coefficient at a relative depth of about 2.6 D, while at a speed of 2.5 m/s, the corresponding relative depth was about 4.35 D.

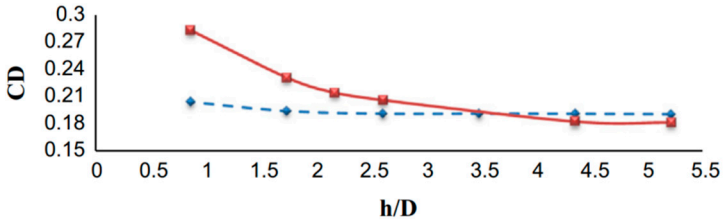


Figure 1. Variation in drag coefficient with relative submergence at v = 1.5 m/s (dashed line) and v = 2.5 m/s (solid line) [10].

However, physical experimental methods are greatly limited by equipment and environment. With the continuous progress of computer technology, more and more scholars have investigated the effects of surface waves on near-surface underwater vehicles by means of computational fluid dynamics. To accurately describe the operating state of an underwater vehicle near the surface, scholars have optimized the motion model of the vehicle. Thomas et al. proposed a nonlinear, time-dependent motion model based on the energy-based modeling technique for an underwater vehicle maneuvering near the free surface [11]. This model can rapidly simulate the maneuvering of underwater vehicles navigating near the surface in complex environments. Based on this, a simulation model for the depth control of vehicles during near-surface maneuvering was proposed [12]. This model is innovative as it considers free surface suction and nonlinear interactions between maneuvering forces, wave forces, and time-varying free surface suction effects. Fang et al. [13] developed a hydrodynamic motion prediction model for the near-surface maneuvering of underwater vehicles. The model is based on strip theory [14] and time domain simulation techniques [15]. The study investigated the rise and fall control of the underwater vehicle under the action of surface waves in different directions or frequencies. The results showed that beam waves have a more significant impact on vehicle operation. In beam waves, it is easier to control the vehicle's rise than its fall, while in longitudinal waves, the opposite is true. In the case of beam waves, it is easier to control the ascent of the underwater vehicle than its descent, whereas the opposite conclusion is found in the case of longitudinal waves. Pang et al. [16] established simulation models based on the linear AUV kinematic model, under the effect of regular and irregular waves. The study investigated the impact of surface waves on the underwater vehicle's vertical forces and moments, as well as its other degrees of freedom and attitude. The results showed that wave forces had a more significant effect on the AUV's position, attitude, and velocity.

With the maturity of the motion models of near-surface underwater vehicles, scholars' studies have become deeper and more comprehensive. Many scholars [2,17,18] investigated the hydrodynamic characteristics of an AUV for near-surface motion in a wave environment and found that the cruising water depth, wave speed, wave height, and wavelength have an important effect on drag and lift. The average hydrodynamic force increases and seakeeping performance decreases with increasing wave height. The drag coefficient increases with increasing wavelength at the same depth and wave height. When underwater vehicles move near the surface, the propeller loads also increase, reducing propulsive efficiency. One reason for this situation is that wake suction [19] increases the upward vertical force and downward pitching moment of the bow. This effect is further amplified in the presence of surface waves, leading to significant longitudinal rocking that may cause the propeller to float out of the water or the vessel to drop down. Figure 2 shows the free surface and vortical structures as isosurfaces of Q = 50 for the four quarter phases ($\varepsilon = 0°, 90°, 180°$, and $270°$ from top to bottom) of one wave encounter period for different depths. The colors in the graph represent the speeds, where blue is the area with smaller speeds and yellow is the area with larger speeds. The interaction of the hull with the wave-induced pressure

field causes adverse and favorable pressure gradients that result in separation in the deck for the case with the exposed sail.

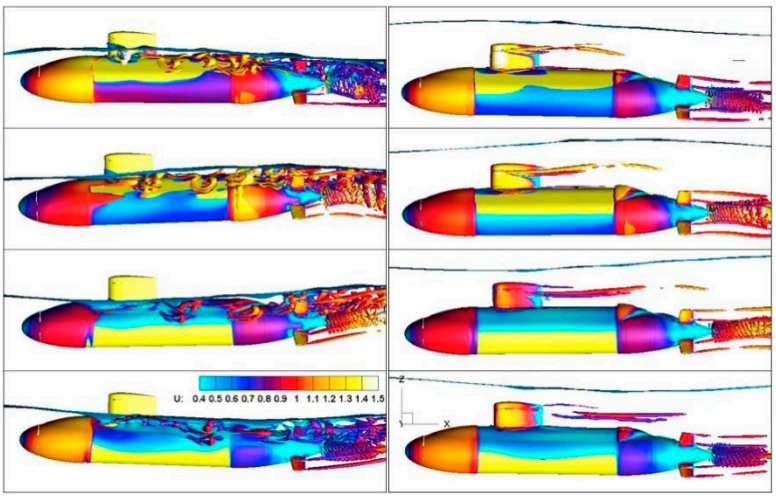


Figure 2. Vortex maps of Q-code isosurfaces of self-propelled state underwater vehicles at $D_0 = -3.9$ m (**left**) and $D_0 = 4.0$ m (**right**) [2]. (D_0 is the distance from the top of the sail to the free surface, such that positive D_0 is used for submerged sail and negative for exposed sail).

It is very important to improve the stability of underwater vehicles in waves. Considering that the underwater vehicle often needs to remain stable at a certain position during underwater operations so as to complete the task, Manimaran [20] conducted a numerical simulation study using OpenFOAM to investigate the impact of surface waves on the hydrodynamic performance of an underwater vehicle that remains stable near the water surface. The study found that the presence of a mooring structure in front of the vehicle reduced the coefficient of lift by 14% and the coefficient of drag by 33%. This provides a reference for improving the stability of the underwater vehicle while hovering. In addition, numerous studies have shown that the shape of the underwater vehicle has a strong influence on the stability. Alvarez et al. [21] optimized the shape of underwater vehicles to obtain the shape parameters that minimize the wave resistance within the considered Froude number, which is important for the design of the underwater vehicle. As shown in Figure 3, the surface waves generated by the original hull and the optimized hull are compared (draft depth of 0.1 m). In the case of the optimized hull, a significant reduction in wave height is observed, indicating a lower wave resistance.

Current research on the influence of surface waves on the load and motion state of the underwater vehicle is abundant. Studies have mainly focused on the influence of surface waves on drag and lift, and different parameters of waves and navigation have also received attention from scholars. However, what deserves more attention is how to reduce or overcome the influence of waves. Pan et al. [22] proposed a wave force prediction formula that can be used as a reference for the maneuvering of underwater vehicles in order to reduce the effects of waves. There have been fewer studies in this area such as this; the majority of studies have been carried out on surface ships, and further work is needed on underwater vehicles. It will improve the safety and stealth of underwater vehicles navigating near the surface in the real ocean.

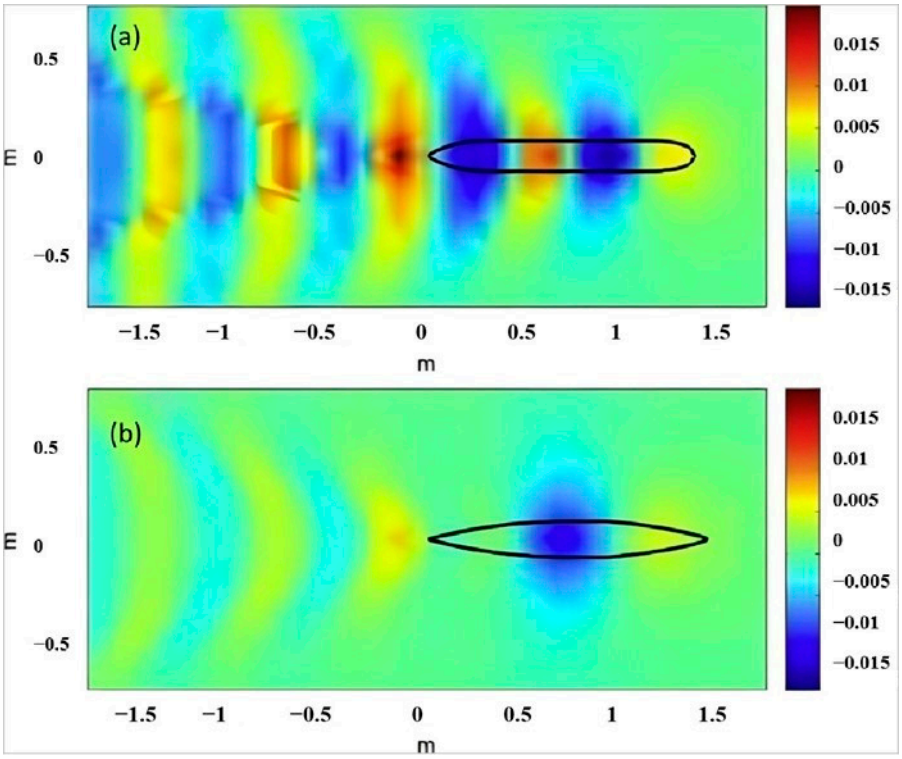


Figure 3. Surface wave pattern generated by (**a**) the original and (**b**) optimized hulls (the black oval is the optimized shape of underwater vehicle) at Froude number = 0.26 (different colors represent different velocities) [21].

2.2. Water-Exit in Surface Waves

Due to mission requirements, various vehicles, such as transmedia vehicles, with submarine-launched missiles need to transition from underwater to the surface. This process can cause significant changes in the vehicle's motion and load due to complex interactions with the free surface [23–25]. The presence of surface waves can further complicate the situation and pose a threat to the safe exit of the vehicle from the water.

In recent decades, significant progress has been made in the study of different underwater vehicle water-exit phenomena, and scholars have carried out extensive research by combining experiments and numerical simulations [26–29]. The studies have focused on the loading characteristics of the vehicles out of the water, the deformation of the free surface, and the breaking of the internal vacuole. The huge difference in density between air and water causes forces and moments to be generated during the water-exit process, and when the vehicle comes into contact with air, vacuoles will collapse, which will have a huge impact on the load of the vehicle. This phenomenon can become dramatic in a wave environment. Most of the previous studies of the water-exit problem only considered calm water conditions; however, in the actual process, the influence of surface waves cannot be ignored. However, these results provide valuable references and effective numerical simulation and experimental methods for studying the water-exit process of the vehicles in waves.

In the study of the effect of surface waves on the water-exit process of an underwater vehicle, the physical experiment method has greater difficulties, so numerical simulation has become a favored research tool for scholars. Currently, research has focused on the effects of different wave heights [30] and wave phases [31–34]. Many studies demonstrated that the out-of-water position of the underwater vehicle would be shifted under the surface wave environment [31]. Zhu et al. [32] investigated the influence of wave phase on the hydrodynamic characteristics of an underwater vehicle during the water-exit process.

They discovered that the wave phase causes asymmetry in the spatial geometry of the vacuole of the underwater vehicle, which in turn results in asymmetry in the hydrodynamic distribution on the surface of the underwater vehicle. The evolution of the 3D ventilated cavity of the vehicle as it exits the water at these four distinct water-exit wave phases is illustrated in Figure 4. In the early stages of cavitation, the cavity develops immediately downwards from the surface and assumes a symmetrical shape about the central axis of the vehicle. After that, it gradually exhibits more and more asymmetry over time.

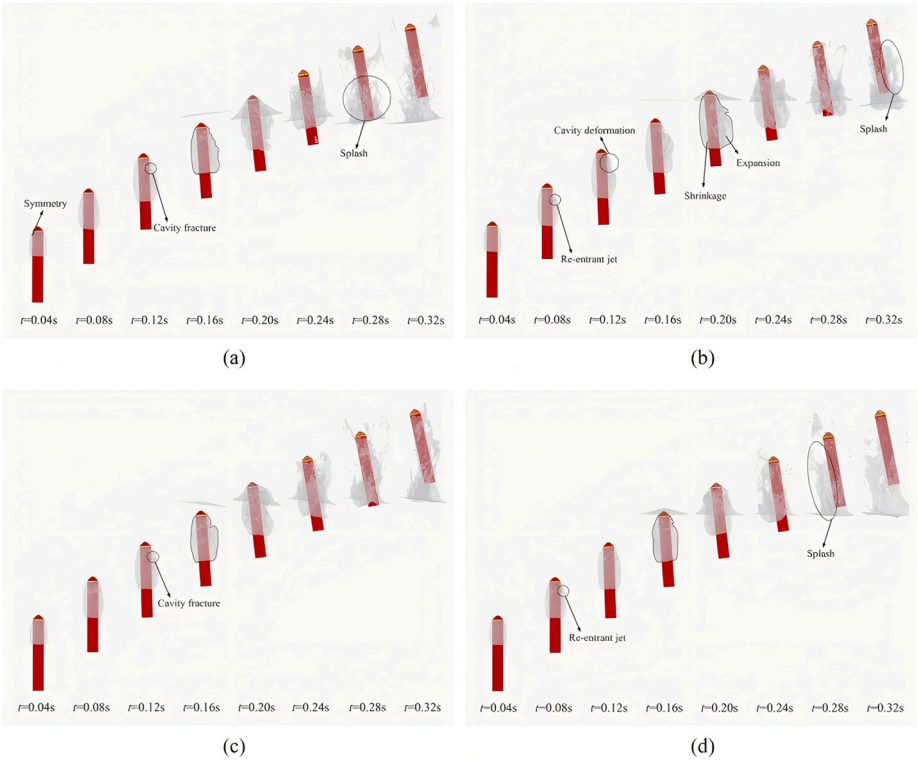


Figure 4. Evolution of the three-dimensional ventilated cavity at different water-exit wave phases: (**a**) node 1, (**b**) crest, (**c**) node 2, and (**d**) trough [35].

On this basis, scholars have conducted extensive research on reducing the impact of surface waves on the process of sailing the body out of water. Compared to the discharge process in the still water, the influence of surface waves was relatively weak at the nodes but significant at the crest and trough [33]. This conclusion was verified by Zhi et al. [34], who established a computational model of an underwater vehicle water-exit attitude based on the boundary element method and investigated the influence of regular wave parameters (wave height, wave direction, period, and phase). The position of the trough has the greatest positive impact on the degree of pitch when against the waves, favoring the successful exit of the underwater vehicle from the water. The above findings provide a reference for the selection of the position and time of the water-exit. In addition, the small size and rapidity of the underwater vehicles are conducive to reducing the disturbing effect of surface waves on the water-exit process [36]. However, these studies still have significant limitations, as their targets are mainly single waves or periodic waves, which are ideal conditions and do not correspond to what happens in the real ocean.

Most of the above studies have focused on a limited number of regular wave environments, while less research has been performed on the effects of random waves. How to quickly predict the motion characteristics of the underwater vehicle out of the water during different surface wave environments has become a hotspot for scholars, which determines how to maximally maintain the stability of the underwater vehicle out of the water. With

the development of artificial intelligence, machine learning technology is applied to this research. Jo et al. [37] accurately predicted the surface loads during the launching process of underwater vehicles based on a CFD-derived database, with a prediction error of less than 0.1%. Zhang et al. [35] developed a machine learning method to predict relevant parameters during the water-exit of the underwater vehicle, enabling the determination of the optimal wave phase for water-exit. The study determined that the optimal position for the underwater vehicle to emerge is at a wave phase of 0.125 pi, while the most dangerous point occurs at a wave phase of 1.1875 pi.

The current methods for the water-exit problem of the underwater vehicle mainly include numerical simulation, physical experiment, and machine learning. Scholars have revealed the law of surface wave influence on the water exit process and instantly realized the rapid prediction of the water-exit characteristics of an underwater vehicle under different surface wave environments provides important theoretical support and practical guidance for the safe and stable water exit of an underwater vehicle. Current control methodologies for optimizing water-exit timing and positioning remain underdeveloped, constrained by limitations in wave prediction accuracy. The future critical research priorities should focus on three key areas: (1) developing comprehensive numerical frameworks for stochastic wave environment water-exit dynamics, (2) advancing adaptive machine learning architectures to enhance wave parameter prediction fidelity, and (3) investigating novel hydrodynamic design paradigms coupled with adaptive control strategies to mitigate wave-induced operational interference.

2.3. Water Entry in Surface Waves

In engineering, the water entry process is more commonly used than the water-exit motion of underwater vehicles. This process is now widely used in military and civil applications, such as missiles, projectiles, torpedoes, spacecraft, and aircraft. In 1897, Worthington et al. [38] recorded the evolution of cavities during the water entry process of a sphere using single spark photography, providing the first study of splash and jet phenomena. Since then, many scholars have conducted experimental and numerical simulation studies on the water entry of underwater vehicles. These studies have provided a comprehensive and in-depth understanding of the process, kinematics, and hydrodynamic properties of underwater vehicles entering water.

Previous studies have mostly been conducted in ideal still water. However, in reality, water surfaces are never completely calm and are always subject to surface waves. These surface waves can alter the shape of cavitations and the trajectory of the underwater vehicle [39]. Additionally, surface waves can also affect variables such as the point of entry, including the current speed and angle of entry [40]. This situation could make the water-entry process of the underwater vehicle extremely complex and may even result in failure. Many studies [41,42] show that it is not reasonable to ignore the surface wave effect unless the Froude number is large enough. A significant effect on the entry process was observed even in smaller waves.

In order to accurately describe the process of water-entry in hydrostatic or surface wave environments, scholars have been investigating theoretical models of underwater vehicles entering the water since the early twentieth century. In 1929, Von Karman [43] introduced an additional mass to calculate the impact load during water-entry according to the potential flow theory and calculated the impact pressure according to the law of momentum conservation during the water entry of rigid structures. And then, Wager [44] improved the theory by introducing a correction factor for the impact of surface waves, which was in good agreement with the experimental results. The model also laid the foundation for the subsequent theoretical studies on water entry [45–47], but the model ne-

glected the compressibility leading to deviations in the results in some cases. To address the liquid compressibility, an improved temperature-dependent Tait equation is utilized [48]. Compressibility induces changes in cavity size, resulting in significant variations in phase composition within the cavity. Lyu et al. [25,49] conducted more detailed water entry experiments in surface waves and observed the evolution and trajectory of the cavity, finding that the waves tilted the cavity and delayed its detachment from the free surface.

Based on the gradual maturation of theoretical models, experimental studies of water entry have become an important means for scholars to explore this problem, but there are few experiments on entry in surface wave environments. Analyzing the existing experiments, it is found that the main reasons are: (1) It is difficult to control the underwater vehicle to collide with the surface wave at the specified position. (2) The water surface always fluctuates up and down, and it is difficult to capture the details of the collision between the underwater vehicle and the surface wave. To address the above problems, Wang and Zhao et al. [42,50] developed a physical experimental system to study the entire water entry process of a free-falling sphere into a regular wave. The system has a free-fall device and an asynchronous pulse triggering system to ensure that the sphere enters the water vertically at the specified desired wave phase. As shown in Figure 5, the left figure illustrates the sphere falling into still water, and the right figure illustrates the wave entering in front of the crest. Tang et al. [51] investigated experiments on the evolution of cavitation during the tilted entry of an elongated axisymmetric body in a forward wave. The results showed that the size of the cavitation was largest when the underwater vehicle entered the water at the wave crest. However, the image resolution of the evolution process of this experiment is low, and the description of the details of the water entry is not clear enough. Overall, the experimental study of water entry in a wave environment still needs to be further explored.

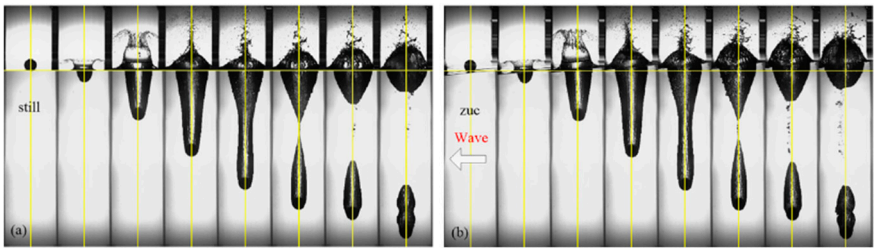


Figure 5. Mosaic images of the water entry process at different times in a surface wave: (**a**) Still water. (**b**) The sphere enters the water in front of the wave crest. The yellow vertical and horizontal lines indicate the position of the still water and the free-falling trajectory of the sphere [50].

Compared with other experiments, numerical simulation can not only obtain more detailed information about the flow field, but can also significantly reduce the cost of experiments, so the main means for scholars to study the problem of water entry in surface waves is numerical simulation technology. The current research mainly focuses on the influence of parameters such as the shape of the underwater vehicle, entry velocity, angle of attack, and wave height and phase [52–54]. These studies can maintain the stability of the underwater vehicle during water entry. If the initial velocity is increased from 100 m/s to 400 m/s, the maximum values of ballistic deflection, drag coefficient, and lift coefficient are reduced by 41.1%, 27.1%, and 34.1%, respectively, and the velocity attenuation is reduced by 0.6%. In addition, a body with a positive attack angle provides better stability. The maximum deflections of underwater vehicles with attack angles of -2° and -4° were reduced by 13.6% and 6.62% compared to positive attack angles of the same size. Therefore, the motion stability in surface waves can be enhanced by appropriately increasing the speed and maintaining a positive angle of attack during water entry. It is suggested that

the initial speed of water entry is greater than 300 m/s, and the angle of attack is less than 2°. In addition to the influence on the stability of the vehicles, the waves may cause the vehicles to experience re-entry or even failure to enter the water. Re-entry may occur when the entry angle is smaller than the maximum wave inclination. Li [55] identified two critical angles for the occurrence of re-entry phenomena: one where re-entry is likely to occur, and another where re-entry is inevitable. The study innovatively provides a quantitative description of the range of surface wave influence, which can serve as a reference for safe water entry of underwater vehicles under actual wave conditions.

3. Influences of Ocean Currents

Currents are relatively stable, large-scale flows of seawater generated under the action of geostrophic bias force and gravitational tidal force, which are some of the natural phenomena existing in the marine environment. In the real marine environment, there are various forms of ocean currents, such as a uniform velocity field, stepped velocity field, and even a shear velocity field. Although the velocity amplitude of the current velocity field is not very large, the depth of influence of the current field ranges from tens of meters to thousands of meters, which has a great influence on the motion state, load, response, positioning, communication, and other aspects of the underwater vehicle, so it is of great importance to study the influence of the current environment on the underwater vehicle in order to improve the performance of the underwater vehicle and ensure the navigational safety of the underwater vehicle.

3.1. Influences on Navigation State

Ocean currents alter the initial flow field around the underwater vehicle, which in turn affects the force on the underwater vehicles. This can cause changes in the trajectory and attitude of the vehicles, and in extreme cases, may result in significant deviation from the intended heading or even lead to the wreck of the underwater vehicle. In addition, ocean currents can alter the pressure distribution of the flow field, leading to an uneven distribution of hydrodynamic pressure on the underwater vehicle [56], which can also cause changes in the dangerous cross-section of the underwater vehicle, resulting in damage to its local structure. Since the simulation of the real flow environment requires high experimental equipment requirements and is difficult to achieve, current research focuses mainly on numerical simulation. Many scholars have simplified the ocean currents as a homogeneous fluid and investigated the influence of the currents on the loads and motion states of the navigating vehicles in both two- and three-dimensional cases [57,58]. In reality, ocean currents have complex and variable forms. The impact of different ocean currents on the underwater vehicle can also vary significantly. Fang et al. [59] studied various regional currents to obtain the current velocity distribution in each navigation region. They then simulated the motion performance and attitude change in a direct sailing AUV under the influence of different current velocity magnitudes and directions. The study compared the conditions with and without currents and established the relationship between current speed, direction, and the AUV's heading, roll, and longitudinal inclination angles. This provides a theoretical foundation for exploring control strategies and motion performance of the underwater vehicle in current environments.

A more notable situation is the phenomenon of convection in ocean currents. In the ocean, the current form is a closed-loop process due to internal waves and other factors. This allows convective phenomena to occur in ocean currents, such as tidal currents. When a vehicle moves through a convection area, the flow direction of the ocean current will be reversed along the direction of the vehicle. The reverse flow field distribution will cause uneven pressure distribution along the underwater vehicle's direction of movement,

making it more difficult to control the underwater movement attitude of the underwater vehicle [60]. In convection currents, the transverse load of the body undergoes an abrupt change. The larger the gradient of the sudden change in the velocity of the ocean current, the more drastic the sudden change in the transverse load; the larger the mean velocity of the convection current, the more the sudden change in the transverse load will be aggravated, and the underwater vehicle will be subjected to a larger negative torque so that the pitch angle of the underwater vehicle will increase, accelerating the process of the underwater vehicle overturning.

In the previous section, the effect of waves on the entry and exit process of an underwater vehicle has been discussed. It is important to note that in the real ocean, currents can also influence the process. Therefore, it is necessary to consider the influence of current loads on the underwater vehicle, as well as the motion of the currents and the nonlinear variation in the wave surface during the process. Yang [61] revealed that the difference between the current velocity and wave current velocity vector significantly affects the velocity and trajectory of the structure's water entry motion. Note that in the real ocean, waves and currents often coexist. Considering that ocean currents exhibit significantly larger spatial scales relative to the dimensions of the underwater vehicle and demonstrate minimal variation along the water depth, the researchers in this study simplified the current as a uniform flow. The study revealed that the vehicle undergoes pitch motion about its center of mass in a clockwise direction under waves alone, currents alone, and combined wave–current conditions. However, the entry characteristics of the structure change under the joint action of waves and currents. When waves and currents are in the same direction, the cylinder's pitch and yaw angles are further amplified. Conversely, when waves and currents are in the opposite direction, the cylinder's entry attitude is inhibited. If the directional vectors of the ocean current (simplified as a uniform flow) and the waves are non-collinear, particularly when the current direction is orthogonal (90°) to the wave direction, the cylinder produces a two-direction pitching and yawing motion. Compared to the in-water motion of the underwater vehicle, ocean currents have a more significant effect on the out-of-water motion of the underwater vehicle, particularly during the upward motion and out-of-water attitude of the underwater vehicle; as the current speed increases, the yaw angle of the underwater vehicle also increases significantly [62].

The stability of the underwater vehicle's motion attitude and heading under the influence of ocean currents has become a research focus for many scholars. To improve this stability, it is necessary to enhance the underwater vehicle's ability to perceive and predict the sea current. Inertial measurement units (IMUs) are commonly used to measure the total acceleration experienced by the underwater vehicle. However, they cannot distinguish whether the acceleration is caused by ocean currents or the propulsion system of the underwater vehicle. Aguiar and Pascoal [63] proposed a scheme for estimating the current based on the planar motion of an underwater robot. They designed a kinematic observer that predicts current velocities with small errors. However, this observer requires known parameters of the underwater vehicle, such as real-time position and relative velocity, making it less practical. Refsnes et al. [64] proposed a less restrictive measurement method to estimate the velocity of the ocean current. This method requires only the known real-time position of the underwater vehicle, reducing the a priori conditions. However, ocean currents can interfere with the effectiveness and accuracy of the underwater vehicle's positioning, as described in the next section. Borhaug et al. [65] designed a six-degree-of-freedom observer to monitor the velocity of ocean currents based on a dynamical model of the underwater vehicle and measurements of its own linear velocity. The observer considers the UGAS error dynamics to ensure that the current estimates converge asymptotically and consistently to their true values. This study is highly practical as it only requires known

kinematic parameters of the underwater vehicle itself, such as linear velocity, angular velocity, and attitude, and does not depend on external ocean environment parameters.

With the maturity of current monitoring and prediction techniques, scholars have carried out studies on the stability of the motion and heading of the underwater vehicle in a current environment. Figure 6 illustrates the spiral motion trajectory of Petrel-II UG under the influence of ocean currents with a velocity of $[0.4, 0, 0]^T$ m/s and $[-0.4, 0, 0]^T$ m/s. It is concluded that the UG will drift away along with the ocean current when their velocity has the same magnitude as the speed of ocean current in the axial directions, which decreases the UG's maneuverability [66]. Wang et al. [66] developed a dynamic model of an underwater vehicle that considers the effect of currents. The model calculates the relative velocity between the currents and the submerged body and then uses the relative velocity and hydrodynamic coefficients to obtain the hydrodynamic force and moment. This model is more accurate than that used by Merckelbach et al. [67], which computes vessel velocity by adding vector sum of flow to vessel velocity in still water. The proposed parameter in this model is a combination of stability, maneuverability, and cruising ability, which can be used to evaluate the kinematic performance of different hulls in a current environment. Currently, research on vehicle stability under current conditions primarily focus on optimizing control algorithms and adjusting attitude angles. Poorya Haghi et al. [68] elaborated on the influence of sea currents on the position and attitude angle of the underwater vehicle in the horizontal plane. They proposed an adaptive controller and a linear feedback algorithm that effectively control the navigational direction and trajectory of the underwater vehicle. Antonio et al. [63,69] proposed a nonlinear adaptive controller for the uncertain parametric modeling of AUVs under the interference of ocean currents. They simulated the trajectory to verify the effectiveness of the controller. The proposed controller enables motion control of AUVs under current disturbance. The aim of the above studies was to counteract the influence of currents through the design or optimization of the control algorithm of the underwater vehicle. Adjusting the attitude angle of the vehicle is also an important means of reducing the influence of ocean currents, which can be achieved by steering the rudder and adjusting the gravity. Fan [70] analyzed the effect of currents on the attitude angle and current speed of an underwater vehicle by establishing a multi-system motion model of the underwater vehicle under the influence of currents. The author used adjustable weights and rudders, according to the observation data, to realize the dynamic model of attitude angle adjustment of the underwater vehicle, achieving the desired attitude adjustment. However, the overall design of the underwater vehicle may be complicated by the addition of weights. In a simulation experiment, Hu [71] simulated the drifting motion of AUV under the influence of flow and loaded the rudder motion module and the counter-flow UDF, relying only on the rudder to maintain the AUV heading in the simulation experiments. This may provide a reference for the operation against ocean currents in real current environments.

It is important to note that sea currents can both hinder and assist the navigation of a vessel. For instance, Wang [66] et al. discovered that positive axial currents or negative vertical currents can significantly improve the cruising capability of underwater robots. Clearly, a potential area for future research is the effective utilization of ocean currents.

Most current studies have limitations due to the variability of ocean currents in time and space, which are difficult to measure. Whether it is to reduce the influence of currents or to utilize them, the first thing needed is to monitor, sense, and predict the currents, and the accuracy and timeliness of the technology needs to be further improved. The development of deep learning algorithms has provided new solutions in this field, but deep learning requires a large amount of real and experimental data, which is currently

lacking. To improve the accuracy of related studies, more precise current observations and sea experiments are recommended in the future.

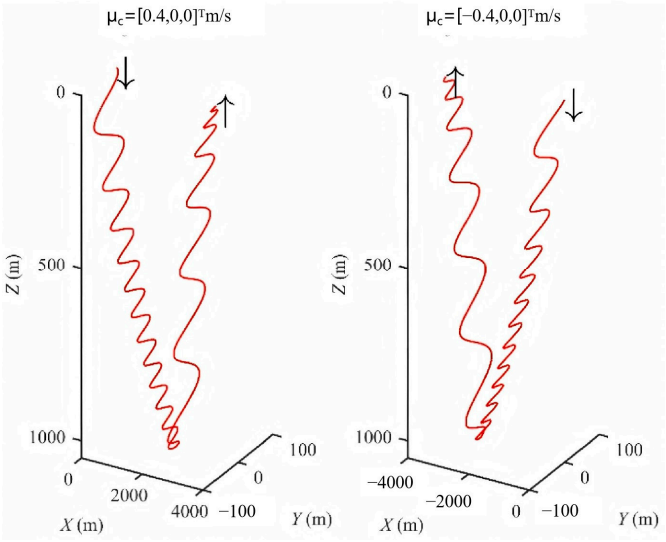


Figure 6. Spiral motion trajectory of the Petrel-II UG (an underwater glider) with an axial ocean current (The arrow indicates the direction in which the glider moves along with the ocean current) [66].

3.2. Influences on Path Planning

Trajectory planning is an important task for an underwater vehicle during the execution of a mission, as it largely determines the success or failure of the mission. The presence of sea currents can cause the flow field in which the underwater vehicle is located to become quite complex, which in turn has a major impact on the trajectory of the underwater vehicle, and if these effects are not considered in the design, the performance of the path planning can be seriously affected [72]. One of the hotspots of current research, which is of great importance for improving the performance of the underwater vehicle, is how to maximize the use of currents to speed up the vehicle and save energy during path planning, so that the underwater vehicle arrives at the destination in an efficient and energy-saving manner. Figure 7 shows the critical technologies of UG for path planning. This mainly involves marine environment reconstruction, path planning, path decision-making, and precise navigation techniques. Accurate environmental reconstruction helps to analyze the effects of current fields, temperature, and salinity on the motion of underwater vehicles.

The current AUV route planning methods under the consideration of ocean currents can be mainly classified into traditional algorithms, intelligent optimization algorithms, and hybrid algorithms [73]. Commonly used algorithms include the A* algorithm, wave matrix algorithm, level set algorithm, artificial potential field method, mathematical model-based algorithm, genetic algorithm, ant colony algorithm, particle swarm algorithm, etc. In this section, the research on path planning for underwater vehicles using various types of algorithms in a sea current environment is presented. By investigating the literature in this field, we have summarized the principles, advantages, and disadvantages of the currently used algorithms, as shown in Table 1.

(1) A* algorithm: The A* algorithm is an effective method for solving the shortest path in static road networks. Perdomo proposed a CTS-A* (Constant-Time Surfacing A*) algorithm based on the A* algorithm [74]. The advantage of this algorithm lies in its ability to handle current information effectively, but its limitations are severe, and the algorithm fails in dynamic current settings. Redondo et al. [75] further improved this algorithm by introducing time into the algorithm and integrating the time-varying trajectory of the underwater vehicle using the time-varying 2D current field provided

by the regional ocean model. The improved method ensures the optimality of the paths obtained when uncertainties such as current eddies are taken into account. Also in the 2D case, Josep Isem et al. [76] proposed a low-energy underwater path planning method based on the A* and ND algorithms. The advantage of this method is that it is suitable for complex environments such as strong currents and can effectively avoid static or dynamic obstacles to obtain an optimal path. All of the above algorithms are limited to two-dimensional conditions. They are not applicable to three-dimensional situations. In contrast, Zhou et al. [77] applied the CTS-A* iterative algorithm to the path planning of an underwater vehicle based on the constructed current field. This has been demonstrated in sea trials with single and multi-path currents.

(2) Wavefront Algorithm: This method is based on the graph search theory. It is a blind search algorithm for solving the shortest path problem from the start point to the end point on a known map. Soulignac et al. [78] proposed a sliding wavefront expansion method based on the wave matrix algorithm. The advantage of this algorithm is that it ensures accuracy, efficiency, and global optimality of the path by combining an appropriate cost function with successive optimization techniques, but the algorithm is not applied to the 3D case. Chinmay and Pierre [79] proposed a wavefront algorithm for time-varying current path planning in a current environment. This algorithm takes into account the unknown and real-time nature of currents in the real ocean environment, which provides better accuracy and adaptability.

(3) Level set algorithm: Level set is a numerical technique for interface tracking and shape modeling, which has the advantage of allowing the numerical computation of evolving curved surfaces on Cartesian grids without parameterizing the curved surfaces. Tomaszewski et al. [80] investigated the problem of efficient path planning for an underwater vehicle traversing a current field in a real ocean by using the level set method. The method can effectively reduce the time and energy consumption of traversing paths. However, the traditional level set method is slow, so Liu [81] improved it and proposed an improved narrowband level set method suitable for path planning. Based on the improved level set, a two-dimensional and three-dimensional path planning method considering the influence of ocean currents is developed. It is characterized by its ability to effectively utilize the downstream currents, avoid the strong currents and obstacle areas in the reverse direction, and reach the target point in the shortest time. But the limitations of this algorithm are clearer: Its planned route considers only the time-optimal route without considering the path length and energy consumption, while the time-varying characteristics of the current are not considered in the three-dimensional path planning.

(4) Artificial potential field method: This method was first proposed by Khatib [82]. He applied it to the field of path planning for mobile robots. The underwater vehicle moves to the target point under the joint action of gravitational force and repulsive force. The gravitational field is generated by the target point and the repulsive field is generated by the obstacles. However, the traditional artificial potential field methods are not easy to obtain the optimal path; for example, such methods suffer from the local extreme value problem and are ineffective or even invalid in complex current environments [83]. Therefore, for the path planning problem under the influence of sea currents, most of them adopt the improved or hybrid artificial potential field method. Cao et al. [84] combined the artificial potential field method and ant colony algorithm and then proposed a path planning algorithm under a sea current environment. This algorithm can effectively avoid the local extreme value problem of the artificial potential field method. Yang et al. [85] introduced the velocity potential field function into the artificial potential field method, transforming the static potential field into a

dynamic potential field, and combined with the kinematic properties and constraints of the underwater vehicle to obtain an expression for the obstacle influence radius, overcame the limitations of local extremes and target unreachability.

(5) Ant colony algorithm: Italian scientists Dorigo et al. [86] proposed this algorithm inspired by the characteristics of foraging behavior of ant colonies in nature, which is a kind of intelligent bionic optimization algorithm. Liu et al. [87] improved the ant colony algorithm by considering the role of factors such as sea currents and used the energy consumption of sailing to guide colony evolution. Compared to the unimproved method, the navigation time was significantly improved. The traditional ant colony path planning method has the disadvantage of slow convergence speed. To overcome this disadvantage, Fu et al. [88] introduced artificial potential field heuristic factors into the ant colony algorithm to obtain the Artificial Potential Field Ant Colony Algorithm (APF-ACO). The method uses the cell to reflect the regional physical elements and quantifies the physical ocean phenomena in the form of a cost function to realize the extensive use of the ocean sound velocity environment, the ocean density environment, and the current environment, on the basis of which the optimal path is designed. As a result of this improvement, the convergence speed of the algorithm is effectively enhanced. Furthermore, the integration of the Delaunay triangle decompositions into the ACO optimization algorithm can also achieve the effective use of current information [89] and has a faster convergence rate.

(6) Particle Swarm Optimization Algorithm: This is a simulation algorithm based on the flock aggregation model used to solve the problems of how birds avoid collision and adjust neighboring birds' speed. Compared with the particle swarm algorithm, the quantum particle swarm algorithm shows better ability in the ocean current environment [90]. Based on the quantum particle swarm algorithm principle, Zou et al. [91] proposed an ocean current path planning method suitable for high-dimensional situations. However, the method fails when there are complex obstacles and currents in the environment. In fact, the marine environment is constantly changing, so there is a high probability that the underwater vehicle will encounter new obstacles while tracking the global path. To solve the multi-objective path planning problem for underwater vehicles under uncertain sea currents and uncertain hazard sources, Gu [92] proposed an interval-based multi-objective quantum particle swarm algorithm, which works well for route planning by interval optimization under constant current conditions, changing current conditions, and dynamic obstacle conditions.

Path planning in static currents is now relatively mature. However, research on the path planning of underwater vehicles in the current environment is basically carried out on the basis of constant currents or precise information about the currents. As soon as the environment changes, the effectiveness of the algorithms is greatly reduced. Therefore, further research needs to be performed to achieve the goal of making the algorithm better adapted to the current environment. On the other hand, due to the complexity and uncertainty of the current environment, it is often difficult for a single path planning method to successfully find the optimal route, and even the problem of direct failure occurs. In addition, some algorithms can obtain the shortest path, but the optimization efficiency of the algorithms is low in the three-dimensional planning space, and the planned path is not smooth, which is not conducive to the control of the underwater vehicle. Integrating different algorithms in a certain way and synthesizing the advantages of different algorithms are effective ways to improve the efficiency and performance of path planning. The integration of multiple algorithms, the introduction of deep learning and other technologies, and the development of multi-algorithm collaborative models are the main directions for the development of the path planning problem of the underwater vehicle under the general

trend of the development of artificial intelligence. When navigating near the pycnocline, disturbances of the underwater vehicle will result in fluctuations at the inner interface.

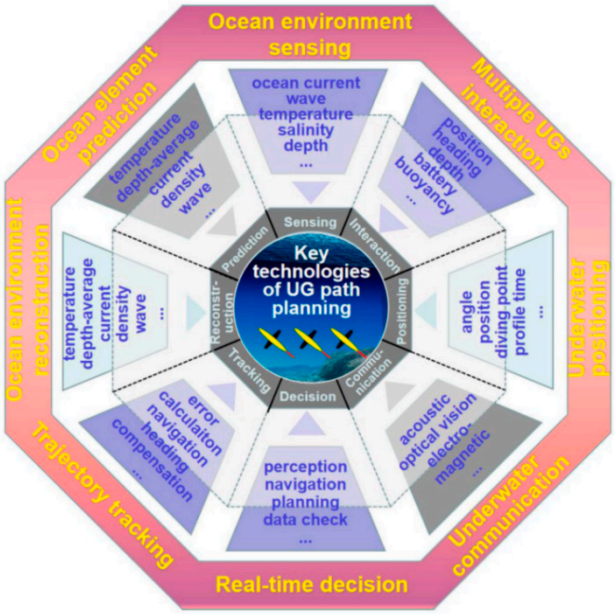


Figure 7. The critical technologies of UG for path planning [73].

Table 1. Path planning methods applicable in ocean currents.

Method Name	Principle or Technology	Advantages	Disadvantages
A* algorithm	Maintenance of actual and predicted distances	Fast convergence and high stability	May fail under dynamic conditions
Wavefront Algorithm	Graph search theory	Good accuracy and adaptability	Requires known maps
Level set algorithm	Categorize and compare	Interface tracking and shape modeling	Slow convergence
Artificial potential field method	Gravitational and repulsive field interactions	Simple principle	Existence of localized extremes
Ant colony algorithm	Foraging behavior of ants	More Intelligent	Slow convergence
Particle Swarm Optimization Algorithm	Bird Aggregation Modeling	Simple structure, easy to implement	May fail under dynamic conditions

4. Influences of Ocean Stratification

In the actual marine environment, the density is not completely homogeneous and varies due to factors such as temperature, salinity, and pressure, resulting in seawater showing a steady succession of pycnoclines. Pycnocline, as a special phenomenon in the marine environment, has a crucial impact on the navigational state of underwater vehicles and its navigational safety. At present, for the underwater vehicles moving in the pycnocline, the research mainly focuses on the effects on the hydrodynamic performance and stealth performance of vehicles. On the one hand, it will increase the drag of the submerged body; on the other hand, disturbances at the inner interface can interact with the free water surface to form a special surface wake, affecting the submarine's stealthiness. In this chapter, the progress of these two parts of the study will be presented.

4.1. Influences on Navigation State

The existence of the density stratification causes some special phenomena in the motion of the underwater vehicle, which are not found in the uniform flow. According

to the different trends of the stratification, the density stratification can be divided into two categories: positive stratification and inverse stratification [93]. If the density has the depth of a positive gradient change, it is often referred to as the "liquid seabed". The buoyant force on the underwater vehicle as it moves downwards will become greater and greater, as if the underwater vehicle was becoming lighter and lighter. Similarly, the buoyancy force as it moves upwards becomes less and less. Eventually this will lead to the phenomenon that the underwater vehicle can neither dive down nor float up. This phenomenon has a major impact on the vehicle's maneuverability. If the density of the seawater changes with depth in a negative gradient, the situation is reversed. The vehicle moves downwards with less and less buoyancy, which accelerates its dive. It is for this reason that the negative gradient layer is often referred to as the "sea cliff", which can easily cause the submarine to fall deep or be lifted out of the sea. Although the positive layer has a significant effect on the submarine's maneuverability, it also helps to maintain the submarine's depth stability, which is particularly useful for hovering maneuvers. In the actual marine environment, the inversion layer is more common and more dangerous, therefore it is also the main research object of scholars. Figure 8 is a schematic representation of the "sea cliff". When an underwater vehicle enters low-density fluid from heavy-density fluid, it will suddenly sink, posing a fatal threat to the vehicle. This chapter focuses on the inversion layer.

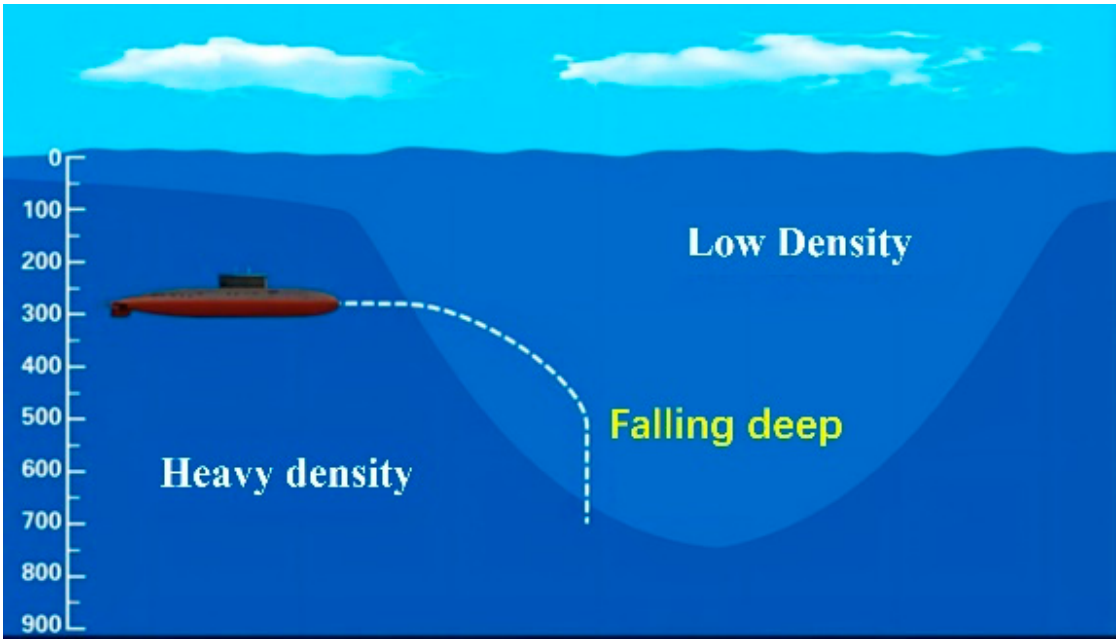


Figure 8. "Falling depth" phenomenon.

In 1983, Nansen experienced the phenomenon of "dead water", which attracted the attention of scholars. The "dead water" effect refers to the phenomenon of slowing down or even stagnation of navigational objects entering the region when there is density stratification in the fluid [94]. The experimental study of Ekman [95] found that this was a consequence of the presence of density stratification, which was further confirmed by the study of Grue [96]. When navigating in a two-layer fluid, the drag on an underwater vehicle in the low-speed region first increases with speed, peaks, and then decreases. Afterwards, scholars have carried out theoretical, experimental, and numerical simulation studies on the effect of density stratification on the underwater vehicle. In order to investigate the influence mechanism of density stratification, it is necessary to establish the force model of the underwater vehicle first. Hudimac et al. [97] established formulas for solving the

resistance of surface and internal waves. Motygin [98] used the potential flow theory to obtain a formula for the wave resistance resulting from the motion of a two-dimensional object in a density stratification fluid. Miloh et al. [99] used the Green function method to obtain the wave drag of a semi-submersible oblate sphere and hull. When the drag reaches maximum value, the corresponding vehicle velocity is always less than the critical speed c, where c refers to the limiting wave velocity of the internal waves that may be generated in a two-layer fluid.

While theoretical studies lay the groundwork for exploring the influence of density stratification, experimental studies show more intuitively how density stratification influences the motion of underwater vehicles. Most of the earliest experimental studies simplified underwater vehicles to simple geometries, such as point sources. Yeung [100] experimentally investigated the motion process of a point source in pycnocline at certain depths and found that the depth of the fluid has an effect on the resistance as well as on the generation of waves. Sturova [101] discovered that negative damping can occur in a two-layer fluid, even when a moving object is traveling at a low speed. With the development of experimental techniques and equipment, experimental research has become more intensive. Mercier et al. [102] employed novel techniques to revisit Ekman's "Dead Water" studies, simulating a more accurate two-layer flow in a water tank, subsequently measuring a vehicle's trajectory and characteristic behavior. The underwater vehicle will be in a dynamic state of force equilibrium under the action of a certain critical constant force, i.e., its speed will maintain a regular fluctuating change, but its mean value will remain basically unchanged. Gou et al. [103] conducted a model experiment to investigate the drag characteristics of box structures when dragged in a two-layer flow and compared the results with those in a single-layer flow.

However, experimental studies have limitations in the information they can obtain due to scale and measurement accuracy. Additionally, most experiments are conducted on simple geometries, and it is difficult to simulate real-world situations. Fortunately, numerical simulation technology has matured, providing a solution to this problem. Computational fluid dynamics (CFD) is currently the main tool for studying the hydrodynamic performance of underwater vehicles in pycnocline. Mehdi et al. [104] again investigated the "dead water" problem using CFD methods. The total drag coefficient increased by almost an order of magnitude under the most unfavorable conditions. When strong density stratification occurs, the pressure resistance may suddenly increase by several times [105]. As shown in Figure 9, it shows free surface profiles in the vicinity of the submarine at different density stratification. Fr in Figure 9 refers to the internal Froude number, which is usually used to describe the stratification degree of density. The smaller the internal Froude number, the larger the density gap. Two distinctive features can be discerned: One is a bulge at the head of the underwater vehicle, which is due to the fact that the dynamic pressure is greatest at this position, creating a blocking effect. Secondly, there is a crest in the tail which increases as the Froude number decreases. When Fr = 1, the wave breaks. This is likely the cause of the sudden change in the drag and pitching moment in this case. Considering that conditions such as density stratification parameters, underwater vehicle state, and position affect the hydrodynamic characteristics, scholars have carried out a series of numerical simulation studies for different working conditions. The Joubert BB 2 [106] and SUBOFF submarine models have been used in most of the current studies. The drag coefficient increases by about 30% per cent for an underwater vehicle located above the inner interface and by about 42% for it located below the inner interface, compared to movement in a homogeneous fluid. Different navigational speeds, relative interfacial positions, submergence depths, and upper and lower fluid density ratios will influence hydrodynamic characteristics of underwater vehicles. It was found that the resistance of the

underwater vehicle was lowest when it was at the interface of density stratification [107]. The reason for this is that the rising waves at the inner interface will increase the resistance of the submarine to navigation. The speed and depth of the underwater vehicle have a significant effect on its hydrodynamic performance. The effect of density stratification on the drag increases when the forward speed increases and the position distance from the free water decreases. The density of the lower layer and the distance from the inner surface have little effect on the state of motion [108]. In addition, the shape and attachment of the vehicles may also have an effect. Zhang et al. [109] calculated the resistance of box structures in stratified fluids. For attachments, the effects are related to the high and low speeds. Attachments can cause large pressure changes due to the sudden curvature of the submarine's surface. The wave resistance coefficient of the submarine is highest near a Froude number of 0.5 [110].

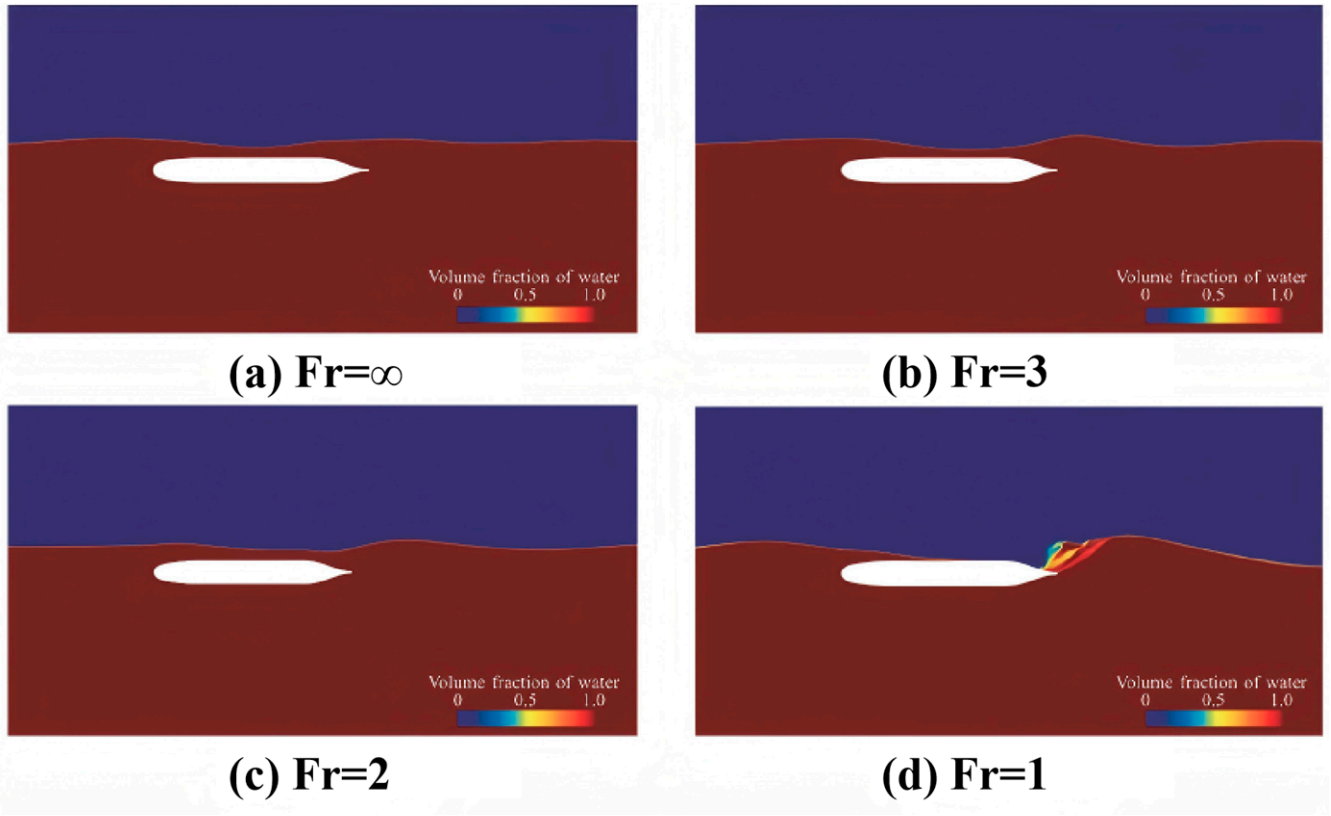


Figure 9. Free surface profiles near the submarine hull at different internal Froude numbers [105].

According to the current research, the influence of pycnocline on the hydrodynamic performance of the underwater vehicle has been relatively clear, and the influencing factors mainly include the motion parameters and positions. However, there has been little research on how to reduce the influence of density stratification on underwater vehicles, and control methods to avoid the vehicle being dragged to the seabed have not been studied. This is essential to ensure the safety of the underwater vehicles, especially submarines, and is one of the issues that needs to be addressed urgently. In addition, it can be found that the shape and attachments also have effects on the vehicles moving in the stratified fluid, but there are few experimental and numerical simulation studies in this regard. Future research can be carried out to address this issue, thus informing the optimal design of the underwater vehicle.

4.2. Influences of Stealth Performance

The movement of an underwater vehicle in density stratification results in the formation of "hydrodynamic wake" and "cold wake" in the wake field and leads to changes in the geometry and temperature distribution of the free surface, which differ from the situation when moving in a homogeneous fluid, such as upstream blockages [111], the generation of internal waves [112], and pie-shaped vortices in the far-field wake [113]. These special phenomena can make underwater vehicles a target for non-acoustic detection [114], thus causing a serious threat to the concealment of the vehicle. In order to improve the stealth performance of underwater vehicles in density stratification, scholars have carried out a large number of studies on the morphological characteristics, evolutionary processes, and developmental laws of the wake and free surface.

Since the generation principle and evolution process of wake fields in stratified fluids are very different compared to those in uniform flows, theoretical studies of the hydrodynamic wake of underwater vehicles in density stratified fluid is needed first. The initial theoretical research was mostly based on simplified models (point sources, spheres, and ellipsoids). Hudimac [97] constructed a theoretical model of surface and interfacial waves after perturbation by using a stationary moving point as a source of disturbance in a stratified flow. The Fourier transform is applied to derive the velocity potential of a moving point source in a stratified fluid, thus enabling a qualitative analysis of the relationship between transverse and dispersive wave systems and the velocity of the point source. Keller and Munk [115] derived the near-field and far-field rough waveforms of the wake by solving the wake equation for a moving wave source in an anisotropic medium. A further study was carried out by Voisin [116], who derived analytical Green's function-based expressions for pulsating point sources in stratified fluids with and without the Boussinesq assumption. However, the above studies only focused on the wake of moving objects and did not consider the effect of the free surface. On this basis, Zhu [117] introduced the effect of the free surface into the analysis of moving point sources to derive the wave states for different free surfaces and internal interfaces. Radko [118] derived far-field waveforms due to the motion of an underwater vehicle in a multilayered fluid on the basis of perturbation theory.

Experimental methods can visualize the evolution of the wake field of an underwater vehicle, and with the support of theoretical models, scholars have begun to study the characteristics of the wake and free surface in density stratification by experimental methods. Similarly to the theoretical studies, most of the early experimental studies were on wakes generated by moving objects with simple geometries [119–121]. All these studies verified that the wake flow in stratified fluids is significantly different compared to it in homogeneous fluids, especially in turbulent conditions. With the continuous progress of experimental technology, the objects and contents of research are gradually diversified. Zhao [122], Wei [123], and Wang [124] experimentally investigated the wake generation in linear density stratified fluids by underwater vehicles with spherical, hemispherical, and elongated shapes, respectively. Experimental results show that in the density of a linearly stratified fluid, the towing hemisphere generates wakes and internal waves that affect its stealthiness. Body-generated internal waves also occur. The critical internal Froude number for the conversion of these two is 1.6, a value that is 2/3 times higher than that of a sphere. The wake-generated internal waves possess similar variation tendencies, but the wave speed is about 2/3 that of the spheroid model. Ma et al. [125] conducted physical experiments on the motion of a Rankine ovoid in stratified fluid and investigated the effect of the velocity and shape of the object on the free surface. Amin A et al. [126] studied the wake flow of a moving three-dimensional airfoil in a finite depth tank with stratified fluid, by means of flow field shadowing maps.

However, many studies have demonstrated that the wake field of an underwater vehicle in density stratification is quite complex, and it is difficult for existing experimental equipment to fully capture the evolution of the flow field and wake trajectory. But the numerical simulation technique can aptly solve this problem by recording all the information of the flow field, therefore numerical simulation is the main research tool nowadays. Continuously stratified fluid is closer to the real situation, so most of the current studies use this environment. In the numerical simulation study, the first step is to realize the background environment simulation of the density of the continuously stratified fluid. Cao et al. [104] introduced a thermocline model based on the Boussinesq assumption to simulate continuously stratified fluids under free surface conditions. The more commonly used density stratification model is the continuously stratified fluids model, based on mixed multiphase flow models and the thermal density current model [127], and the model achieves the continuous stratification of density by specifying the distribution of temperature in the flow field and the functional relationship between density and temperature. They also made a comparative analysis of the applicability of various turbulence models for different Reynolds number ranges [128]. Based on the establishment of density stratified fluid, scholars have carried out a series of studies on the effects of stratified structure, attitude, speed, position, and shape of the underwater vehicle on wake flow and waveforms on free surface. Ma et al. [129,130] found that the layered structure has an effect on the distribution of velocity dispersion at the free surface, which in turn affects the degree of "Convergence and divergence" at the free surface. They also quantitatively analyzed the effects of the velocity, depth, and density gradient on the free surface wave characteristics in stratified fluids. Although the submarine sailing at low velocity can generate a divergence field with a maximum intensity of about 10^{-5} magnitude, it will be swamped in the background of the wind waves. As the Froude number of the submarine increases, the surface divergence field starts to be affected [131]. Figure 10 shows a schematic of the waves on the free surface with and without stratification, which reveals that when there is no density stratification (Fr = ∞), the submarine near the free surface exhibits a regular Kelvin wave shape. But the typical Kelvin wave pattern no longer exists in the case of strong density stratification. The overall wave pattern is more diffuse, with greater anisotropy between peaks and troughs. A typical phenomenon under the influence of density stratification is the appearance of crests at the head of the underwater vehicle. This phenomenon is unique to stratified wakes and is called an upstream blockage. Huang et al. [106] numerically simulated the motion of the Joubert BB2 submarine model in homogeneous fluid and stratified fluid, respectively. The special characteristics of the wake and free surface in stratified fluids are discussed. In the case of the Joubert BB2 submarine model, for example, when it moves in a density stratified fluid, the region of influence of the free surface becomes longer and wider, the longitudinal propagation distance increases by 7.9%, the transverse propagation distance increases by 13.2%, and the Kelvin wedge angle increases by 15.4%. The above studies have mainly considered the wake generated by the linear motion of the underwater vehicle in the stratified fluid, while the wake generated by the maneuvering motion has been less studied. Shi et al. [132] numerically simulated the wake and surface wave trajectory of the SUBOFF model in a stratified fluid at different drift angles. With the increase in drift angle, the kinematic wake still exhibits obvious Kelvin wave characteristics. Figure 11 is a comparison chart of the calculation results of the SUBOFF wake feature at drift angles of 2°, 4°, 6°, 8°, 10°, and 12°. The depth and speed of the underwater vehicle were kept constant at 1.2 m and 11.83 kn, respectively. It is clear from the figure that the Kelvin wave system features are always evident even under different conditions.

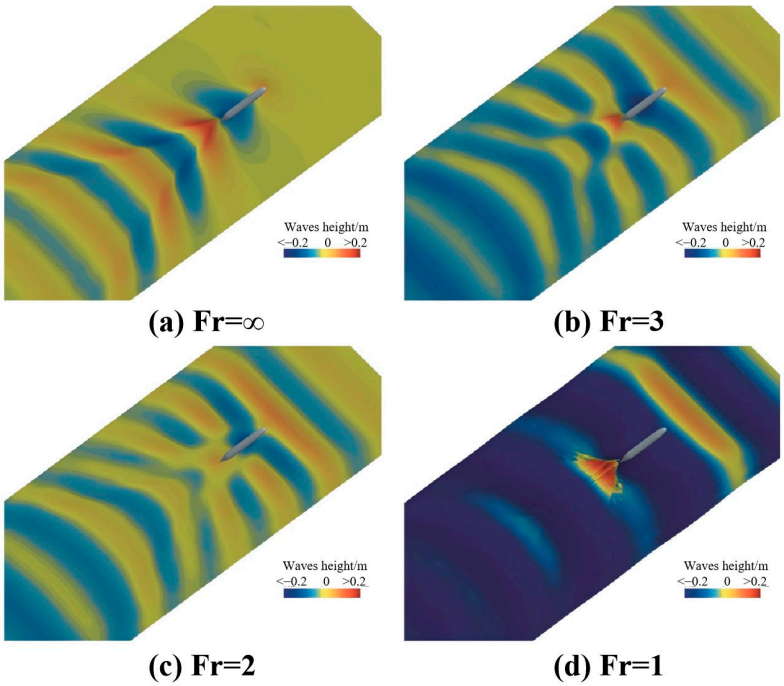


Figure 10. Free surface wave signatures induced by the submarine at different internal Froude numbers (Fr here still refers to the internal Froude number. The smaller the Fr, the stronger the density stratification) [105].

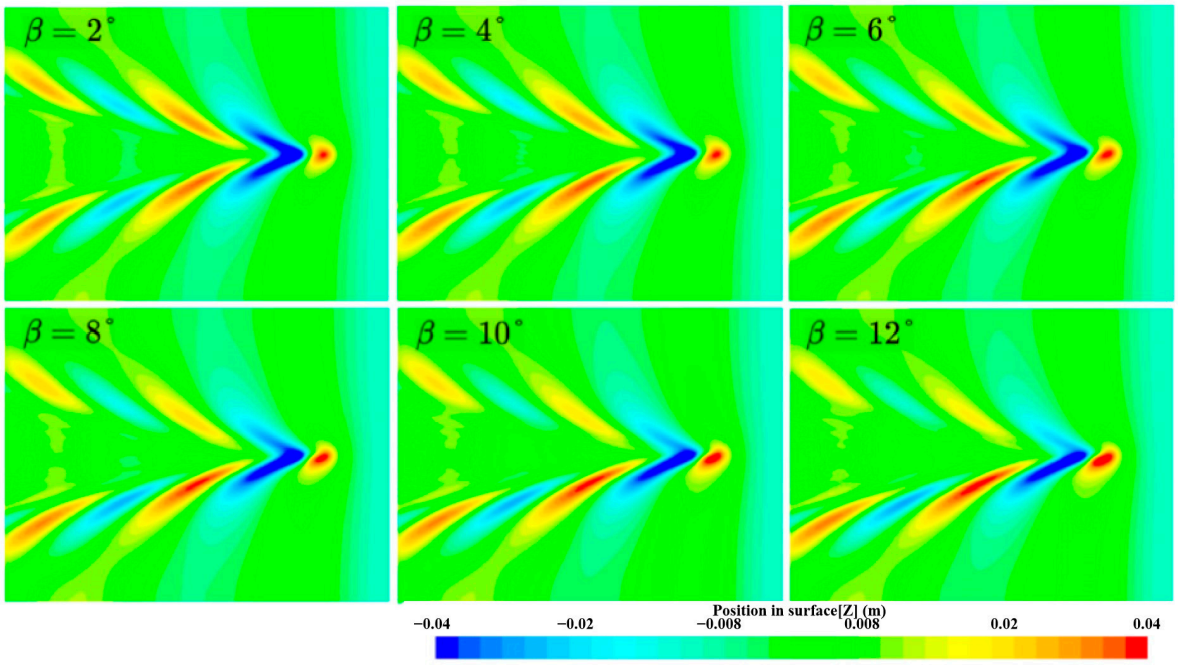


Figure 11. A free surface wave's wake at different drift angles [132].

While wake phenomena generated by canonical geometries (spheres [133], cylinders, ellipsoids, and disks) in density stratified fluids have been systematically investigated, yielding well-characterized evolutionary patterns of wake structures and surface wave signatures, significant challenges persist in realistic oceanic conditions. The complex geometries of operational underwater vehicles and their associated multiscale turbulent dynamics create wake persistence mechanisms that fundamentally differ from idealized cases. Critical research imperatives include: (1) developing predictive models for wake concealment through the strategic utilization of density stratification, and (2) mitigating

free surface disturbance through optimized vehicle hydrodynamics. Addressing these challenges will advance signature suppression capabilities in marine platforms through the improved understanding of stratified flow–vehicle and morphology–physical oceanography coupling.

5. Influences of Oceanic Internal Waves

In the previous chapter, we mentioned that density stratification occurs in the actual marine environment. When external disturbances destabilize this stratified structure, internal waves may be generated. In the ocean, the amplitude of internal waves is generally much larger than that of surface waves, up to a few hundred meters. It carries enormous energy during propagation and travels over long distances at high speeds, with wavelengths up to several hundred or even several thousand meters. Since the maximum amplitude of internal waves occurs below the sea surface, they are extremely stealthy and often leave the underwater vehicle unguarded. The propagation of internal waves leads to sudden strong currents and significant convergence and divergence during propagation, causing the fluid above and below the pycnocline to flow in opposite directions and to form shear currents below the sea surface. [134–138]. Its destructive power is sufficient to tear apart marine structures or underwater vehicles. These unique properties of internal waves make them a great threat to the safety of navigation. When a submarine suddenly encounters an internal wave, its sailing attitude will change drastically, and the submarine may be thrown out of the water or pressed into the seabed, which may cause damage to the hull or ancillary structures or may cause the destruction of the submarine and the death of the people. In 1963, the US nuclear submarine "Thresher" sank in a sudden accident in the Atlantic Ocean and was pulled to the bottom of the sea. It was later speculated that the cause of the accident might be that the submarine encountered strong internal waves in the ocean. In April 2021, the Indonesian submarine KRI Nanggala crashed near the Dragon's Eye Strait. The submarine broke into three parts. NASA claimed that the cause of the accident was the submarine's encounter with internal waves. As there have been dozens of serious accidents caused by internal waves in real situations [139,140], scholars have carried out many studies on the model of internal waves and the interaction between internal waves and underwater vehicles. Figure 12 shows numerical simulation results depicting the "falling deep" experienced by a vehicle encountering internal waves.

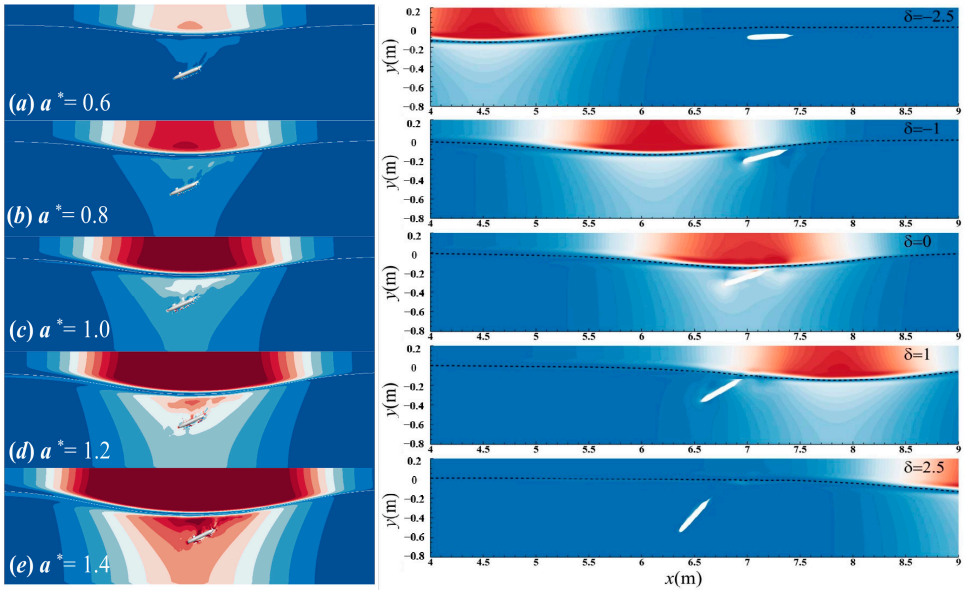


Figure 12. The "falling deep" experienced by a vehicle encountering internal waves [141].

5.1. Internal Wave Theory

The theoretical study of internal solitary waves has always been a hot issue of great concern in the field of ocean engineering. Since the Scottish scientist Russell first observed and described internal solitary waves in 1834 [142], scholars have carried out a great deal of research on the theory of internal solitary waves. Stokes and Raleigh demonstrated that internal waves are fluctuations that occur within a density-stabilized stratified ocean. In 1895, Korteweg and G. de.Vries [143] derived the famous KdV equation under the assumption of small amplitude and weak nonlinearity, which describes the evolution of waves under the combined influence of weak nonlinearity and weak dispersion. It can take into account both nonlinear and dispersion effects, and the form is simple, which is widely used in the study of internal solitary waves. However, the assumption of weak nonlinearity of the KdV equation limits its applicability, and scholars have conducted a lot of research on the scope of application of the KdV equation. In 1981, Koop and Butler [144] verified the applicability of the weakly nonlinear model by means of physical experiments and found that the KdV model agrees poorly with experimental results under deepwater conditions. Later, Segur and Hammack [145] conducted validation experiments using stratified saline water and obtained the same conclusion. Based on this model, Benjamin [146] and Ono [147] proposed a theory of internal solitary waves in deep water applicable to lower water depths that tend to be infinite. With the gradual deepening of the research, scholars found that when the ratio of the wave amplitude to the total water depth is greater than 0.1, the theoretical solution of KdV deviates a lot from the measured value, and it is difficult to accurately characterize the internal solitary waves.

In order to better describe the internal solitary waves' waveforms under different conditions and to make the KdV equation more widely applicable, Helfrich and Melville [148] modified the KdV equation in 1986 by adding a third-order nonlinear term to obtain the eKdV equation. They compared the numerical solution of the eKdV equation with experimental results for internal solitary waves of larger amplitude and found a good agreement [149]. This model can be used to describe the phenomenon of internal solitary waves with flattened and broadened waveforms actually observed in the ocean and is wider than the KdV equations in terms of amplitude applicability [150]. However, it is important to note that when the amplitude of internal solitary waves is close to or equal to the limiting amplitude of its theoretical solution, the wavelength increases rapidly, i.e., the waveform broadens at a very fast rate. At this point the eKdV theory no longer applies, either. The reason is that the quadratic nonlinear coefficient in the KdV equation is equal to zero at this critical depth when the upper and lower fluid thicknesses are close to each other. To overcome this deficiency, Michallet and Barthelemy [151] proposed the mKdV equation, which can be used in this case. Under the same conditions, the characteristic wavelength of the mKdV theory is much larger than that of the eKdV theory.

However, the eKdV and mKdV theories are still based on weakly nonlinear and weakly dispersive conditions and are applicable to weakly and moderately nonlinear internal solitary waves, not to strongly nonlinear large-amplitude internal solitary waves. Choi and Camassa [152] developed a two-layer Green-Nahdi model with strong nonlinearity and weak dispersion based on the completely nonlinear Euler equation. The model makes only long-wave assumptions and does not constrain the nonlinearity of internal solitary waves, which is the same as the theory of large-amplitude internal solitary waves proposed by Miyata [153,154] under stationary conditions, and is therefore known as the MCC theory [150]. Camassa et al. [155] compared the theoretical solution of MCC at different density ratios and thickness ratios with the fully nonlinear numerical solution based on Euler's equation as well as the experimental results to investigate the applicability of the

MCC model, which proved that the MCC theory is in good agreement with the numerical solution and the experimental results.

In order to determine the scope of application of the above theories, scholars have conducted numerous studies by numerical simulations and physical experiments. Huang [156] explored the applicability conditions of the KdV, eKdV, mKdV, and MCC theories by using modeling tests in a stratified flume. Conditions for the combination of nonlinear and dispersion parameters available for each theory are given quantitatively. Cui et al. [157] provided and verified the quantitative applicability of the KdV, MCC, eKdV, and mKdV theories through extensive numerical simulations and theoretical calculations. Figure 13 shows the comparison of the waveforms of the numerical and theoretical solutions of different internal wave models with the experimental results. From this we can clearly see the difference between the models and the range of applicability.

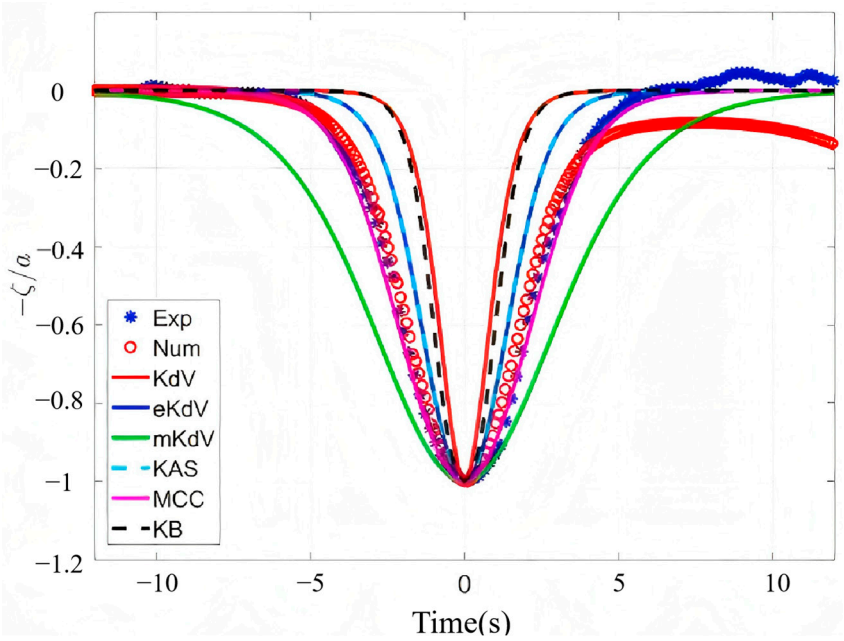


Figure 13. Comparison of waveforms between numerical and theoretical solutions of the isolated wave model and experimental results [157].

The KdV, eKdV, mKdV, and MCC internal solitary waves theories are all based on a simplification of the ocean model as two layers of homogeneous fluid with different densities that are not mixed with each other. However, the actual ocean environment is with pycnocline thickness, so in order to further characterize the real properties of internal solitary waves, in recent years, the theory has been gradually developed and improved from a two-layer model to a continuous layering model. D. Fructus and J. Grue [158] derived a method to compute fully nonlinear internal solitary waves in a density-continuous stratified fluid, with the stratification determined by a constant Brunt–Väisälä frequency. Stastna [159] and Lamb [160] proposed the DJL (Dubreil-Jacotin–Long) equation, which makes no assumptions about nonlinearity and is equivalent to the complete set of Euler equations in steady stratification. Therefore, the obtained solutions are exact internal solitary wave solutions under inviscid conditions and are suitable for fully nonlinear large magnitude internal solitary waves [161]. Wang [162] viewed the ocean as a system of three fluids with stable density stratification. They developed new strong and weak nonlinear models based on spinless flow and used MITgcm to solve the original equations, confirming the existence and stability of two-mode internal waves in the deep ocean.

Scholars have a long history of research on internal waves. The current research on internal wave theory has been more mature, with many results and a quantitative

distinction between the scope of application of different internal wave models, so that researchers can choose a more appropriate theoretical model according to their needs. We summarize the range of applicability and the flow field environment of the internal wave model as shown in Table 2.

Table 2. Applicability of internal wave models.

Model Name	Creator	Fluid Type	Range of Application
KdV	Korteweg G. de.Vries	two-layer fluid	weak nonlinearity shallow
eKdV	Helfrich Melville	two-layer fluid	medium nonlinear shallow
mKdV	Michallet Barthelemy	two-layer fluid	medium nonlinear shallow
MCC	Miyata Choi Camassa	two-layer fluid three-layer fluid	strongly nonlinear deepwater
DJL	Dubreil Jacotin Long	continuously stratified fluid	strongly nonlinear shallow/deepwater

5.2. Experiments

Experimental research is a very important means in fluid mechanics research, and tank experiments can objectively recognize the generation and propagation of internal solitary waves and observe the flow field characteristics of their interaction with the underwater vehicle. Therefore, in the study of internal waves affecting the underwater vehicle, physical experiments are one of the focuses of scholars at home and abroad.

Stratified fluid tanks are the basis of internal wave experiments, and the current stratified fluid tanks can be broadly categorized into shallow tanks, deep tanks, long straight tanks, and circulating tanks according to the scale and shape of the tanks. In experimental studies, the "two-tube method" and the "two-barrel method" are widely used to simulate fluid stratification environments. In terms of wave generation, a variety of experimental methods have been developed that can generate stably propagating internal solitary waves, such as using the gravity collapse method, the pumping plate method, and the pushing plate method. Walker [163] generated internal solitary waves by disturbing the interface separating the upper and lower fluids with a wave-making paddle in a stratified tank. Huang [164] and Chen [165] qualitatively described the generation process of internal solitary waves by using the double-pusher plate wave-making method and gravity collapse method to generate waves, respectively. Wei et al. [166] improved the conventional gravity collapse wave-making device and applied it to the engineering practice. Du [167] explored the whole process of wave generating by the gravity collapse method, based on which he determined the conditions for the generation of stable internal solitary waves in a stratified tank.

On this basis, scholars have carried out a large number of experimental studies on the interaction between internal solitary waves and underwater vehicles under laboratory conditions. Scholars firstly conducted a systematic study on the loads on the underwater vehicle under internal waves. In the first studies, the underwater vehicles were mostly set up as fixed bodies, and the loads on the underwater vehicles were obtained by force balances. E.V. Ermanyuk et al. [168] carried out flume experiments on the interaction of internal solitary waves with a transverse cylinder and demonstrated that the change in the thickness of the pycnocline does not have a significant effect on the horizontal force. Xu et al. [169] explored the wave resistance in the environment of internal solitary waves

and firstly obtained the relationship between the horizontal resistance and the fluctuating elements, simplifying the underwater vehicle into a horizontal piling. The experimental results show that when the characteristic frequency of the internal wave is kept constant, the drag force of the horizontal piling increases with the increase in the amplitude, and its value is related to the layer thickness ratio of the internal wave. Xu et al. [170] focused on the loading effect of periodic internal waves on the submarine model through model tests and found that the period of the internal wave and the incident wave amplitude both have a significant effect on the submarine's force, in addition to the submergence depth which has an effect on the loading. Wei [166,171] conducted experiments on the generation and evolution of internal waves. Through modeling experiments, they completed quantitative measurements and analyses of the loads applied to a slender submerged body under the action of internal solitary waves and obtained the rules of the change in the loads applied to the body. All of the above studies were conducted under the condition that the internal wave meets the underwater vehicle in a forward direction; however, when the underwater vehicle encounters the internal wave in the actual ocean, its attitude is not certain, and it is likely to meet the internal wave in an oblique direction. Different angles of incidence have a significant effect on the wave loading characteristics on slender bodies, especially the internal solitary waves in the transverse direction of action, which have a more severe effect on slender bodies [172]. Considering this situation, Wang et al. [173] investigated the force of oblique internal solitary waves on the underwater vehicle through model experiments, as shown in Figure 14 below, revealing the force characteristics of the propagation direction and wave amplitude of inclined internal solitary waves on the submerged body at different dive depths. From the above studies, it can be seen that the force on the underwater vehicle is greatly influenced by the amplitude of the internal wave and the diving depth. Horizontal and vertical wave forces increase as the amplitude increases. Underwater vehicles at different dive depths are subjected to horizontal forces of different magnitudes and directions and will maximize the vertical forces in the wave packet. And when the wave direction angle $\theta < 45^\circ$, the inclined internal wave makes the vertical action more significant, while when $\theta > 45^\circ$, the horizontal action is more significant. An increase in the wave angle θ causes a large increase in the horizontal force and a bimodal shape in the vertical force.

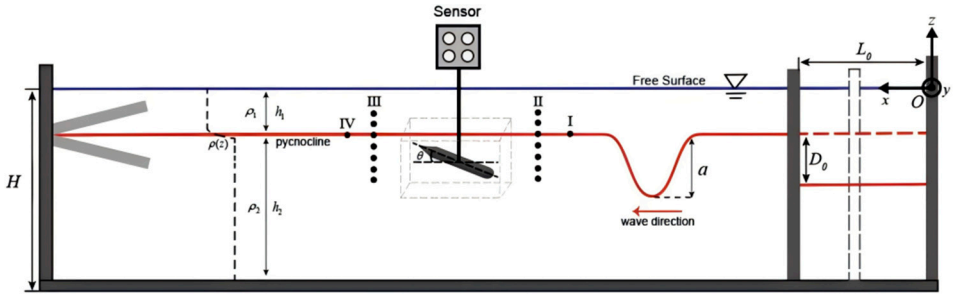


Figure 14. Experiments on the interaction of oblique internal solitary waves with a submerged body [173].

With the advancement of physical experimental techniques [174,175], scholars have gradually turned to the experimental study of the interaction of internal waves with moving underwater vehicles. Chen et al. [176] conducted experiments in a towed internal wave tank and established the theory of the resistance of ellipsoids with different length-to-diameter ratios when moving at different Froude numbers. In order to investigate the influence of internal waves on the body in more degrees of freedom, Du et al. [177] completed an experimental study on the influence of internal solitary waves on the kinematic characteristics of vehicles in a large-scale stratified tank, and Figure 15 is a schematic of the experimental

system. They obtained the kinematic laws of the vertical and longitudinal swing, transverse and longitudinal rocking, as well as its center of mass trajectory. An important finding is that the submarine's center of gravity trajectory is an irregular elliptic line. You [178] investigated the interaction between internal waves and semi-submersible platforms, and the experimental results were similar to those described by Xu [170], in that the internal wave period would have an important effect on the motion response of platforms.

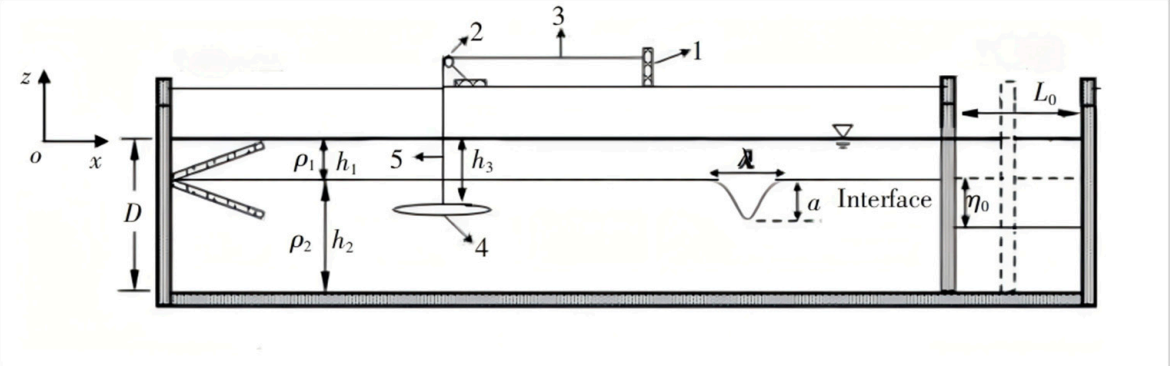


Figure 15. Force measuring device for internal wave experiments [177].

Different schemes have been proposed by scholars on how to measure the internal wave loads on the model in laboratory conditions. Wang et al. [179] designed an experimental system for studying the interaction between internal solitary waves and underwater vehicles, which records the forces on the vehicle model and the corresponding directions on the connecting rods during the propagation of internal solitary waves by means of pressure sensors in the X, Y, and Z directions. He et al. [180] proposed a force measurement system based on a double-rod connection, and the double-rod design can satisfy the experiments under a variety of working conditions, such as fixed, suspended, horizontal, and inclined of the underwater vehicle. Wang et al. [181] proposed an embedded force measurement method, in which force sensors are embedded inside the structural object model, which can record the 3D force data of the model during the passage of internal solitary waves.

In most of the current experiments, scholars tend to simplify the underwater vehicle into simple geometries, such as cylinders and ellipsoids, which are different from the shape of the actual underwater vehicle, but have a strong reference value for the overall loading and the surrounding flow field under the internal wave environment. On the other hand, due to the limitations of the scale of the flume, the size of the model, and the measurement technique, the current research mainly focuses on the force analysis of the fixed body and the towed body under the action of internal waves and lacks the experimental research on the motion response of the floating body or the self-propelled body after encountering the internal waves, after which further research work is still needed.

5.3. Numerical Simulation

Due to the limitations of laboratory space, equipment, and other conditions, it is very difficult to carry out internal solitary waves experiments in real-scale or complex environments. With the rapid development of computer technology and the maturity of computational fluid dynamics (CFD) technology, numerical simulation has gradually become an important means for scholars to carry out research on the generation, propagation, and evolution of internal solitary waves and their interactions with underwater vehicles.

In order to investigate the effect of internal solitary waves on the load and motion of a submerged body, scholars have firstly worked on the load characteristics of fixed submerged bodies under the action of internal solitary waves. Huang et al. [182] established

a numerical simulation method for the interaction between internal solitary waves and underwater vehicles based on the RANS method and the KdV theory and found that the action of waves would make the flow field around the vehicle become abnormally complex, which would generate abrupt hydrodynamic changes. Figure 16 shows the movement process of the free-moving submarine in the internal wave. Under the action of the internal wave, the underwater vehicle moves backward in the horizontal direction along the direction of the wave and moves vertically upward, accompanied by large pitch motion. Chen et al. [183] simulated the interaction between internal solitary waves and a moving submarine based on the KdV-mKdV theoretical solution of internal solitary waves by replacing the submarine speed with a constant flow and obtained the loading characteristics suffered by a submarine with speed, which opens up a new path for the future study of the interaction between internal waves and moving submarines. Xie et al. [184] investigated the interaction of large-amplitude, strongly nonlinear internal solitary waves with small-scale cylinders in a two-layer fluid using a solution of the MCC theory. In the study, they used Morison's formula to calculate the forces and moments, which is a commonly used method in current research to more accurately obtain the forces on underwater vehicles. In addition to the common concave type of internal solitary waves, when the thickness of the upper layer is greater than the thickness of the lower layer, the waveform is convex. Li [185] simulated different types of (convex and concave) internal solitary waves in a numerical tank to comparatively analyze the differences in wave forces in the submerged body under the action of different types of internal solitary waves. Guan et al. [186] conducted a similar study to obtain the flow field form and force characteristics of an underwater vehicle encountering convex and concave internal solitary waves in the ocean. In addition to the effect that the internal wave shape can have on the loading of the underwater vehicle, differences in the position and attitude of the submerged body can also affect its loading characteristics. Yang [187] studied the interaction between oceanic internal solitary waves and submersibles in a three-dimensional situation and found that the change rule of the load of the submersibles was related to the depth of the dive, the wave amplitude, the ratio of the thickness of the upper and lower layers, and the morphology of the waves. Wu et al. investigated the effects of amplitude and dive depth on the loading of a teardrop-shaped rotary body under horizontal transverse and head-on wave conditions, respectively. Gu [188] conducted a similar study, but they added the effect of ridges to the background environment, which produces changes in shape as the internal wave passes over the ridges.

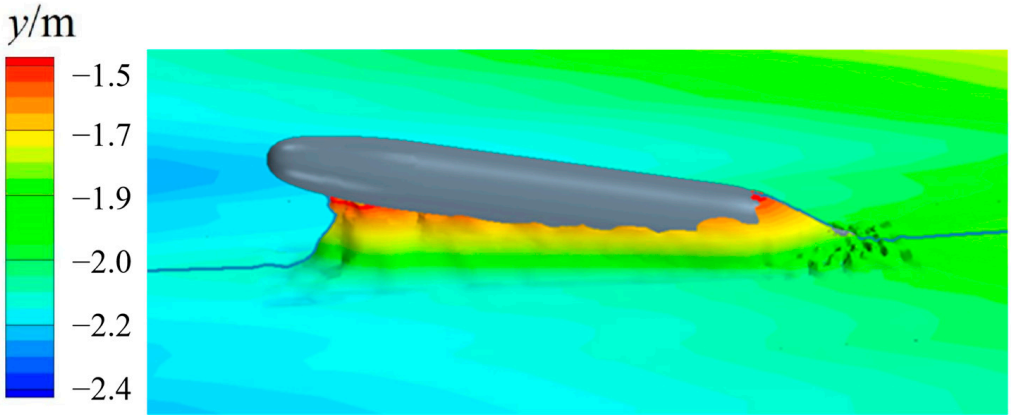


Figure 16. Vehicle crossing internal waves [182].

Most of the above studies have been modeled based on the condition of intra-interfacial waves, where the flow field is viewed as two layers of fluid with different densities and

unmixed with each other. This is the simplest approximation, but the density of the actual ocean environment varies continuously, so there is also a continuous pycnocline at the actual internal wave interface, meaning there are still some limitations to these studies. However, these results can provide a qualitative reference for subsequent studies because in the real ocean, the size of the underwater vehicle is very small compared to the thickness of the pycnocline, and within this small range, the variation in density is also very small.

The continuously stratified ocean model is a model that is closer to the actual ocean environment and has been emphasized by more and more scholars in recent years. Li et al. [189] used a fully nonlinear model based on the DJL equation to obtain the initial field of internal solitary waves and establish a numerical model of internal solitary waves in continuously stratified fluid. Wei et al. [166] established a similar criterion for full-size and model-scale submersibles in fluids with continuous stratification. This result provides a theoretical basis for modeling tests. Yao et al. [190] investigated the effect of depth on the wave force and moment of an elongated cylinder under the action of internal solitary waves in a continuously stratified fluid and compared it with the data obtained from experiments. You et al. [191] investigated the load mechanism of internal solitary waves acting on a truncated cylindrical float in linear continuous stratification and the motion response of the float when subjected to internal solitary waves.

In previous studies, most of the numerical simulation studies assumed that the underwater vehicle is in a stationary state. In order to obtain simulations closer to the real situation, scholars have carried out some numerical simulation work on the interaction between internal waves and suspended or moving vehicles, as well as the motion response of vehicles after encountering internal waves. The work of Gao et al. [192,193] provides some reference for this study. For the dynamic response characteristics of a suspended submarine under the action of internal solitary waves, the waves' amplitude greatly affects the vertical oscillation characteristics, while the longitudinal oscillation characteristics of the submarine are affected by the distance between the submarine and the pycnocline [194]. Liu et al. [195] simulated the motions of the suboff scaling model at three different dive depths under the action of internal solitary waves and analyzed the motion response laws of the model at different dive depths in detail. Wang [196] carried out simulations of the interaction between internal solitary waves and suspended and speed-carrying submerged bodies under strongly stratified and continuously stratified layers and investigated the effects of three key parameters (submergence depth, wave amplitude, and speed) on the response of the submerged body's motion and its loading characteristics. Similar studies by Cheng [197] and Wang [198] revealed the reason for the "falling deep" phenomenon of the underwater vehicle under the influence of internal waves. Summarizing the above studies, it was found that for a floating body under the pycnocline, its trajectory is similar to the streamlines in the region. Its maximum horizontal displacement is about 60% of its length, and its vertical displacement can be up to four times the diameter of the submerged body, as shown in Figure 17. Stationary underwater vehicles experience greater vertical forces and pitching moments in internal waves compared to moving underwater vehicles. It is interesting to note that when the wave amplitude is small (2 and 3 times the diameter), the submersible will eventually "falling deep" under the action of the internal waves. However, when the amplitude is large (four times the diameter), the submersible will be dragged back to its initial position. These conclusions inform the control approach for underwater vehicles that experience internal waves in the real ocean.

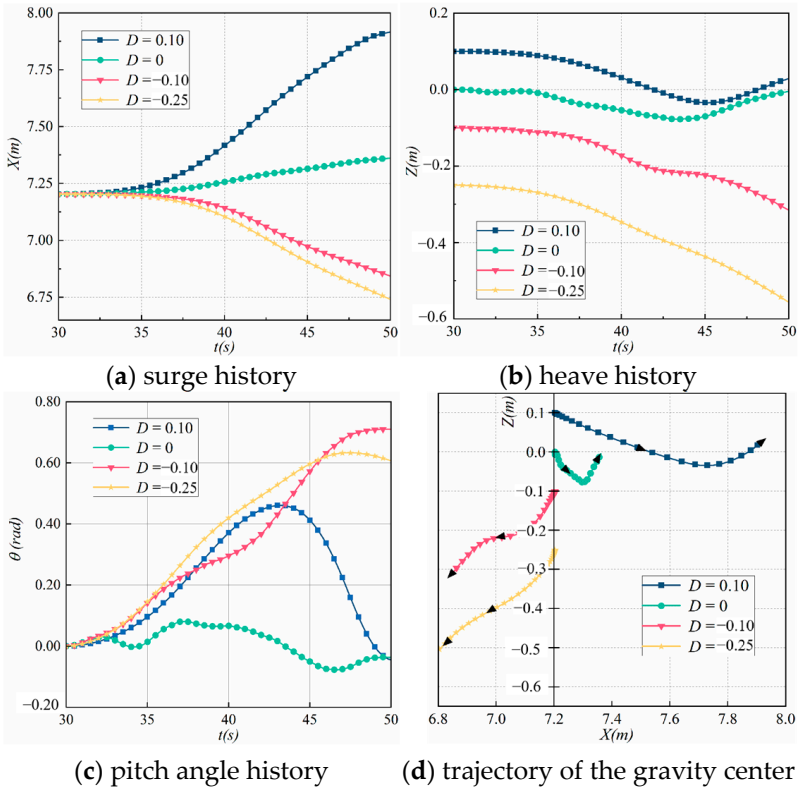


Figure 17. Motion response of a floating body at different submerged positions in an internal wave environment [196].

In order to avoid the influences of internal waves on the underwater vehicle, Zhang et al. [199,200] conducted a series of studies for the prediction of internal isolated waves; in their study, a machine learning method was introduced, which can provide a reference for the underwater vehicle to predict the internal waves in the actual ocean. However, when the underwater vehicle encounters internal waves, how to control it from falling deep is the key to ensuring safety. The PD control method proposed by Cheng et al. [141,201] can effectively alleviate the "falling deep" of the vehicle, which is worthy of further attention by scholars.

Most of the underwater vehicles in the current study are simplified as simple geometries or light bodies, while the propeller and rudder structures, as the propulsion and steering devices of the underwater vehicles, have a crucial influence on the motion state of the vehicles. However, little research has been performed on the effects of internal waves on underwater vehicle attachment. Zou et al. [202] investigated the interaction of internal solitary waves with hydrofoils based on the spectral proper orthogonal decomposition (SPOD) by experimental methods. For the first time, the authors introduced the SPOD method to study internal wave action. This method provides flow field information in the frequency domain. They obtained data on the flow field and force of an airfoil structure evolving with time under the action of internal waves by means of a particle image velocimetry technique and a force sensor.

With the gradual deepening of the study, we can roughly summarize the influence of internal waves on the motion of the body:

(1) The motion response of a submarine located above and at the pycnocline is more affected under the action of internal solitary waves. The effect on the loading characteristics of the submarine increases as it moves closer to the pycnocline.
(2) The speed of response of the submerged body motion and the peak size of the load applied are mainly affected by the amplitude of the wave. The larger the amplitude

of the internal solitary waves, the faster the response of the submerged body motion and the larger the peak value of the load applied.

(3) Under the influence of internal solitary waves, a self-propelled body is more susceptible to runaway phenomena and force surge compared to a suspended body. Additionally, the peak load on the submerged body increases at higher speeds.

Overall, numerical simulation studies on the interaction between internal waves and underwater vehicles have achieved systematization, comprehensiveness, and depth compared to experimental studies. Scholars have summarized the influence of internal waves on the hydrodynamic performance and motion state of underwater vehicles. However, there is still relatively little research on the attitude control of underwater vehicles encountering internal waves. Further research can be conducted on the control strategy and attitude regulation of underwater vehicles encountering internal waves in the future. The majority of current studies concentrate solely on the underwater vehicle, neglecting the interaction between internal waves and the appendages of the underwater vehicle. Attachments such as propellers and rudders play a vital role in the maneuvering of underwater vehicles, and the action of internal waves on the attachments will have a critical influence on the state of the vehicle itself. Therefore, further research in this area is necessary. In addition, to reduce the influence of internal waves, it is firstly necessary to improve the monitoring and prediction of internal waves. The work in this area is very scarce in current studies, and deep learning can provide very significant help in this area. This is a research direction that future scholars need to focus on.

6. Conclusions

This review focuses on the impact of four complex marine environments—waves, currents, density stratification, and internal waves on the hydrodynamic characteristics, motion response, wake evolution, path planning, and other aspects of underwater vehicle performance. It provides a comprehensive overview of current research on the effects of these environments on vehicles, including theoretical studies, algorithm optimization, physical experiments, and numerical simulations. The review concludes with reflections on future research directions:

(1) The effects of waves on underwater vehicles cover near-surface stabilization, out-of-water motion, and in-water motion. Wave forces, drift effects, and attitude perturbations together affect the stability of near-surface vehicles. Waves change the shape of the evacuation, the vehicle trajectory, and the variables at the entry point, which increase the complexity and risk of exiting the water; in the presence of waves, the entry process will be accompanied by complex flow phenomena, such as the evolution of the cavitation, splashing, and vortex distribution, which leads to increased difficulty in entering the water. The current research mainly focuses on the principle of the influence of waves, the load and motion characteristics of the underwater vehicle, and the evolution of the flow field, and there are fewer studies on how to reduce the influence of waves, the control strategy in the waves, and the rapid selection of suitable exit and entry positions, which can be further researched in the future.

(2) The presence of currents mainly affects parameters such as course direction, speed, pressure distribution, and hydrodynamic characteristics of the underwater vehicle, which can interfere with positioning and navigation performance, and ultimately reduce the accuracy of its path planning. At present, scholars have established a complete motion model of the underwater vehicle in the sea current environment, on the basis of which they have summarized the influence law of the sea current on the operation state, and improved the existing path planning algorithms and put forward some path planning methods which are applicable to the ocean current environment.

With the rapid development of artificial intelligence in recent years, the integration of multiple algorithms and the introduction of deep learning and other technologies can significantly improve the path planning ability; therefore, the development of a multi-algorithm collaborative model based on machine learning is the main direction for the development of the path planning problem.

(3) Density stratification can lead to the phenomenon of "sea cliffs", which can have a serious impact on the loads on the vehicles, as well as cause anomalies in the wake of the vehicle and affect the shape of the free surface, which greatly increases the risk of exposure for the vehicle. After more than a century of research, scholars now have a clear understanding of the influence law of density stratification on the loading of the vehicle and the evolution process of the wake field. However, current research focuses on simplified or ideal environments and models. Further research and development of numerical, computational, and experimental methods are needed in the future to study the actual density jump layer and complex vehicles.

(4) At present, the research on the influence of internal waves on underwater vehicles is relatively systematic, and scholars have conducted deep research in theoretical studies, physical experiments, and numerical simulations. Using experimental and CFD methods, the mechanism of internal wave effects on the underwater vehicle is revealed based on various internal wave models, such as KdV, MCC, DJL, etc. The influence of various parameters is explored. However, there are still some aspects that deserve further exploration. In terms of internal wave experiments, it is now possible to generate stably propagating internal waves in the laboratory based on a variety of methods, and to conduct some experiments on the interaction of internal waves with simple structural objects. Due to the limitations of scale, equipment, and other conditions, there is a lack of experimental studies on the interaction of internal waves with complex structures or self-propelled bodies, and further research work is still needed. In terms of numerical simulation studies, most of the studies are carried out on the underwater vehicle itself, and there are few studies on the interaction between internal waves and the attachments, which deserves the attention of scholars.

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