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Resistance of Autonomous Underwater Vehicles (AUVs) Operating Near Free Surface: A Review

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ABSTRACT

An autonomous underwater vehicle demonstrates complex resistance dynamics as it maneuvers close to the free surface of the water. The boundary region characterizes special features in situations containing surface waves, air and water interaction, as well as changes in pressure conditions, all of which contribute to significant challenges by augmenting resistance levels and inducing changes in the behavior of the surrounding fluid. This paper addresses the effect of resistance on the design, motion, and energy consumption of a vehicle, quantified according to shape, operating depth, speed, and propulsion means. This detailed review of CFD simulations and experimental methodologies is anticipated to contribute to the ongoing advancements in both aspects, as well as shed light on the existing constraints of the approach. Such findings can play a crucial role in the enhancement and development of more efficient, capable, and high-performing AUVs designed for operations near the free surface.

1. Introduction.

Operating near the water surface presents challenges for Autonomous Underwater Vehicles (AUVs) due to the distinctive hydrodynamic characteristics of the water-air interface, impacting resistance and overall performance (Hong et al., 2021; Mitra et al., 2020). The water-air interface forms a boundary layer with distinctive hydrodynamic characteristics that can greatly affect the resistance of an AUV (Chen et al., 2019). Understanding this resistance is crucial, as it directly affects the vehicle's energy consumption, operational efficiency, stability, and overall performance. In environments where surface phenomena such as waves, wind, and air-water interactions come into play, the hydrodynamic behavior of AUVs can change dramatically, making predictable and efficient operations more challenging (Hwang et al., 2019; Newaz et al., 2021). The vertical displacement and pitch angle of the AUV are large due to the small size of the AUV, impacting the control stability of the AUV near the free surface.

AUVs come with applications over a broad spectrum of marine geoscience research and are being applied in scientific, military, and commercial operations (Panda et al., 2021). These highly versatile vehicles are essential in a wide range of activities including academic research, geological surveying, and military applications (Nguyen et al., 2016). Their ability to operate autonomously in diverse underwater environments has made them invaluable tools for tasks ranging from detailed mapping of the ocean floor to the inspection of undersea infrastructure and beyond (Watanabe, 2020; Kasaya et al., 2020). These vehicles are deployed through ships and submarines for various tasks. Figure 1 demonstrates the deployment of an AUV from a surface ship.

Operating near the water surface presents challenges for

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AUVs due to the distinctive hydrodynamic characteristics of the water-air interface, impacting resistance and overall performance(Hong et al., 2021; Mitra et al., 2020). The water-air interface forms a boundary layer with distinctive hydrodynamic characteristics that can greatly affect the resistance of an AUV(Chen et al., 2019). Understanding this resistance is crucial, as it directly affects the vehicle's energy consumption, operational efficiency, stability, and overall performance. In environments where surface phenomena such as waves, wind, and air-water interactions come into play, the hydrodynamic behavior of AUVs can change dramatically, making predictable and efficient operation more challenging (Hwang et al., 2019; Newaz et al., 2021). The vertical displacement and pitch angle of the AUV are large due to the small size of the AUV, impacting the control stability of the AUV near the free surface.

Figure 1: Deployment of an AUV from surface ship.

Source: Kasaya et al., 2020.

In this paper, the objective is to provide an insight into the difficulties faced by AUVs near the free surface. The study goes into great depth, describing hydrodynamic design requirements, near-surface issues, and how these considerations impact the operation and design of AUVs. The objective of the present article is to help the reader in clarifying the scientific understanding of the diverse range of problems that relate to the interactions between AUVs and the water surface, and the current methodological and technological advances in this area, by reviewing the state of the art of research conducted in this field. Ultimately, we will enable further development of AUVs for improved performance and a specific emphasis on operation in turbulent and dynamic near-surface environments.

2. Overview of Resistance.

To develop effective systems, having a thorough understanding of the basic concepts of resistance, or hydrodynamic drag, is very important for underwater vehicles. The resistance encountered by submarines while cruising through water can be divided into various types which are described as follows:

2.1. Frictional Resistance.

It is a form of resistance caused by the friction of the vehicle moving through the water. This is the main average contribution that impacts vehicle dynamics (Faltinsen, 1993). Factors like the roughness of the hull, vehicle shape, and speed change the frictional resistance(Molland et al., 2011). According to ITTC guidelines, (2017), the Frictional resistance coefficient C_F can estimated empirically using equation (1), based on experimental data.

$$C_F = \frac{0.075}{(log_{10}Re - 2)^2} \tag{1}$$

where R_e is the Reynolds number. The friction resistance R_F can then be calculated by using equation (2)

$$R_F = \frac{1}{2}\rho S V^2 C_F \tag{2}$$

where ρ is the water density, S is the wetted surface area, and V is the vehicle's velocity through water.

2.2. Form Resistance.

Form resistance is another component of the total resistance that an underwater vehicle experiences when moving through water. The reason for this phenomenon is the pressure differential between the front and back of the vehicle, which is determined by its shape or form (Ranmuthugala & Leong, 2016). A vehicle that has a large or irregular shape will create more form resistance, as water must flow around more blockages and generate more vortices. A vehicle that has a streamlined shape, such as a torpedo or a fish, will create less form resistance, as water can flow smoothly along the surface and separate with minimal turbulence(Ma et al., 2018). Therefore, designing a streamlined shape for an underwater vehicle can significantly reduce the form resistance and enhance its hydrodynamic efficiency.

2.3. Wave-Making Resistance.

The wave-making resistance is one of the components of the underwater vehicle resistance created when the vehicle operates close to the free surface. This is the resistance developed through the energy transferred by an AUV to water for the movement to be created in the surface waves. The waves themselves can be broken into two parts: the bow wave, created due to the pressure difference between the front and rear part of the vehicle, and the stern wave, again created due to the difference in the same pressure but in the opposite direction (Shakeri et al., 2006). The bow wave and the stern wave act together, depending on the phase between them, which is a function of the length and speed of the vehicle, respectively (Kwag, 2000). The interaction is such that either it is constructive or destructive, hence forming either a big wave or a small wave. Accordingly, a big wave will imply more energy lost by the vehicle, while a small wave will mean less energy lost. Thus, the wave-making resistance is directly proportional to the wave size it creates. Wave-making resistance is significant for underwater vehicles operating near the surface, where the waves are more noticeable and affect the performance of the AUV more (Lambert et al., 2023). As the underwater vehicle moves faster, the wavelength of the waves increases, and the resulting wave becomes more extensive due to constructive interference. This means that the wave-making resistance increases as the AUV moves at high speed. Also, as the AUV moves closer to the surface water, the wave height increases and wave-making resistance increases (Haven & Terray, 2015). Accordingly, when speed is increased, wave-making resistance grows, while the closer the surface is, the higher this resistance becomes, hence the more significant at higher speeds.

2.4. Viscous Pressure Resistance.

It is a component of total resistance opposing an underwater vehicle's movement in water, which is due to the pressure differential of the forward and backward dimensions (Basic & Blagojevic, 2015). As the vehicle moves, it creates a boundary layer of water that adheres to its surface. The boundary layer can detach from the surface at some cross-section, giving rise to vortices and turbulence in the AUV wake or draft, thereby reducing the pressure at the rear of the AUV and increasing the pressure at the vehicle's front so that a net drag force is exerted to oppose the vehicle's motion (Leonard & Krishnaprasad, 1994). It is in the proportion of the square of the vehicle's speed. It is influenced by the Reynolds number: a dimensionless parameter measuring the ratio of the inertial and viscous forces affecting the flow (Kaneda et al., 2021). A streamlined shape for the vehicle can be designed so that viscous pressure resistance is minimized and, correspondingly, boundary layer separation and wake formation are also minimized.

2.5. Appendage Resistance.

Appendage resistance affects underwater vehicles, such as submarines and AUVs, when they have devices or structures that protrude from the hull, such as propellers, rudders, fins, sensors, sail and other equipment. These appendages increase the wetted surface area and the form drag of the vehicle and create interference effects with the hull and the wake. Appendage resistance can be reduced by reducing the number of appendages and optimizing their size, shape, and location (Sulisetyono & Rinaldi, 2022; Wang et al., 2019). Typically, empirical formulas or coefficients derived from computational fluid dynamics (CFD) simulations or experimental data are used to determine appendage resistance. Underwater vehicles' hydrodynamic performance and energy efficiency can be greatly influenced by appendage resistance, particularly in small and fast-moving vehicles.

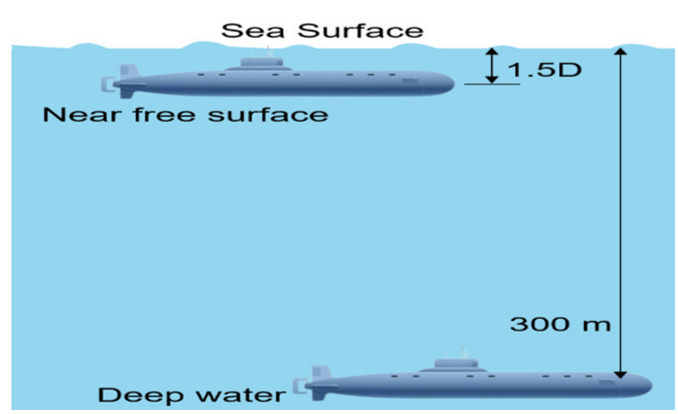
3. Challenges Near the Free Surface.

The free surface environment is the region where water contacts air to form the boundary layer, separating the two different fluid domains. This region poses some additional challenges during the design and operation of AUVs because these vehicles have to deal with the complex and non-linear phenomena that occur at the air-water interface(Battista et al., 2018). The free-surface environment is highly variable and uncertain because it is the consequence of atmospheric and oceanic conditions such as wind, waves, currents, and density gradients, all of which can influence the pressure distribution and wave dynamics on the surface and the interaction forces and moments between the air and water domains. Such impacts can be significant for the hydrodynamic performance and stability of the underwater vehicle, along with its sensing and communication capabilities(Lambert & Brizzolara, 2020). Free surface is described in Figure 2 for submarine. Its suitable operating depth is 300m. There is no effect of surface waves at that depth, however when it comes near to surface i.e 1.5 times of its maximum diameter, free surface effect increases exponentially.

3.1. Influence of Surface Waves and Turbulence.

Underwater Vehicles operating near the free surface must deal with the complex and nonlinear phenomena that occur at the air-water interface. One of the main factors that affect the flow around the underwater vehicle is due to the surface wave field, which in turn is generated by the wind, the weather, or other surface activities such as ships or swimmers (Lambert & Brizzolara, 2020). Free surface waves of this kind probably generate an environment that has highly turbulent and unsteady features characterized by varying pressure and velocity, conditions, and interaction effects between both air and water domains (Kawamura, 2000). The turbulence involved may give rise to irregular and fluctuating forces and moments acting on a vehicle, affecting its behavior, stability, maneuverability, and control. For AUVs operating near the free surface, these waves give rise to additional motion and resistance, particularly during the transition between the submerging and surfacing of the vehicle or when it is operating in the wave-breaking zone (Dimas, 2007). Their unpredictability entails turbulence, which makes maintaining a steady course and speed difficult, which highly influences the operational efficiency and energy consumption when the vehicle is moving (Haven & Terray, 2015). Understanding and modelling the influence of surface waves and turbulence on the hydrodynamic performance and behavior of underwater vehicles is quite significant.

Figure 2: Description of Free Surface.



Source: Authors.

3.2. Air-Water Interface Effects on Resistance.

In the region where air interacts with water: an air-water interface is established, thereby forming a boundary layer that isolates two fluid domains with dissimilar characteristics (Cheung & Street, 1988). This domain presents some specific issues for the design and operational functioning of the AUVs that must cope with complex and non-linear phenomena occurring at this air-water interface. The effect of AUV resistance mainly lies in the existence of air and how water density and pressure would change at this boundary layer. These factors can change the flow patterns around the vehicle, which may increase drag and, therefore, the efficiency of the propulsion system. Such effects are mostly pronounced in wave-making resistance.

3.3. Impact of Vehicle Design and Operation.

3.3.1. Role of AUV Shape and Size.

The shape and dimensions of an AUV have a significant impact on its hydrodynamic efficiency when operating near the water's surface. Streamlined designs resembling torpedoes experience reduced drag and wave-making resistance, while larger AUVs may encounter more wave-making resistance due to their greater displacement of water. Smaller AUVs, on the other hand, can move at high speed, but they are also more vulnerable to turbulence and waves (Alam et al., 2014). The performance of vertical tunnel thrusters on AUVs near the free surface is also influenced by a decrease in thrust generated (Ayers & Johari, 2018). Free surface turbulence can further decrease pressure as well as skin friction and affect drag and lift coefficients on the AUV hull (Mitra et al., 2020; Furlong et al., 2012). Mitra et al. (2019) investigated the impact of shallow waters on AUV resistance by comparing hull drag between restricted depth and infinite-depth water conditions. Hong et al., (2021) examined the hydrodynamic coefficients of AUVs moving close to the free surface with consideration for boundary layer transition from laminar to turbulent flow.

Streamlined designs are usually favored for minimizing resistance(Sousa et al., 2018). Streamlined, torpedo-like AUVs experience less drag and wave resistance than bulkier designs. The actual size of the AUV also matters because a bigger AUV might result in more wave-making resistance due to a more significant displacement of water. In contrast, smaller AUVs could be more agile but perhaps more prone to turbulence and wave encounters (Salari & Rava, 2017).

3.3.2. Influence of Propulsion Systems.

The choice of propulsion system significantly affects the performance of an AUV near the free surface. Traditional propeller - driven systems may be less effective in turbulent waters, where a little bit of air interference may come by, thus leading to the loss of efficiency in the process (Grlj et al., 2022). Other innovative propulsion mechanisms include jet propulsion or perhaps a hybrid system that may adapt to different operational depths, which can offer more stability and efficiency in surface-near operations (Georgescu et al., 2017). Moreover, the positions of propulsion systems can be suitably located to have the least effects from surface waves and turbulence.

3.3.3. Effects of Speed and Diving Depth.

The operating speed and diving depth of an underwater vehicle are two important factors that affect its resistance, which is the drag force that opposes its motion. The relative contribution of each component to the total resistance varies with the speed and depth of the vehicle. At high speeds close to the surface, the wave-making resistance is significant and can raise the total resistance substantially (Goutham & Vijayakumar, 2022). Frictional resistance is dominant and can lower the total resistance at low speeds. Still, the low speeds may result in longer duration and higher susceptibility to surface conditions—mainly wind, waves, and currents. The optimal diving depth of the underwater vehicle depends on its mission profile in terms of required speed, range, and data collection (Kamal et al., 2020). Thus, maintaining depth under the zone affected by waves is often a judicious choice to keep the wave-making resistance at a minimum yet near the surface.

4. Computational and Experimental Methods.

4.1. Overview of CFD methods.

Computational Fluid Dynamics (CFD) is a compelling tool that models and analyzes, through numerical processes, the behavior of fluids in motion. CFD has vast applications in problems related to fluid flow, e.g., in aerodynamics, heat transfer, combustion, and multiphase flows. CFD helps in shaping and configuring AUVs for minimum resistance performance and AUV efficiency (Podgorska, 2019). CFD can also help predict and control AUV dynamics in various flow conditions: steady and unsteady, laminar and turbulent, and flows of a complex nature. CFD has made it possible to show the details of aeration, including the velocity, pressure, temperature, and turbulence distributions in the flow field surrounding the AUV. CFD can also compute the hydrodynamic coefficients of the AUV, including a drag coefficient, lift coefficient, and moment coefficient, which are used to describe the forces and moments acting on the AUV(Mansoorzadeh & Javanmard, 2014).

One of the principal challenges in AUV design for near-free surface operation is that the drag resistance must be minimized to conserve speed, endurance, and maneuverability. Aryawan et al.[41] performed the CFD analysis on the resistance characteristics of remotely controlled vehicles when submerged in water and sailing on the surface, using ANSYS CFX with k-ω SST turbulence model. They found that the ROV has less resistance when it is sailing at the surface compared to when it is submerged. The resistance increases as the Froude number increases and the submergence depth decreases. Sulisetyono and Wardhana [22] did the CFD simulation with ANSYS Fluent to reduce the resistance coefficient with the increase of the Reynolds number and the angle of attack. Some other CFD studies and challenges are described in Table 1.

4.1.1. Simulating Fluid Flow.

CFD is a numerical method for simulating and examining the flow of fluids around an AUV. The CFD can be used to predict and optimize the AUV resistance. It may also help understand the effects of some impacting factors, such as speed, depth, shape, and surface waves, on the resistance of an AUV

Table 1: CFD Studies on the hydrodynamics of underwater vehicles.

Author	Findings	Challenges
Mitra et al. (2021)	Effects of rotational flow fields on drag, skin friction, and pressure coefficients of the AUV	Hydrodynamic analysis of AUVs in rotating flow fields for shallow-water cruising
Dong et al. (2023)	UAUV hydrodynamics are influenced by initial velocity, pitch angle, thickness ratio	Motion characteristics during water-entry process
Yılmaz & Yılmaz (2022)	UUV drag, lift forces, coefficients across depths, velocities	Depth and velocity effects
Liu et al. (2022)	Self-propelled UUV characteristics	UUV maneuverability near seabed; Reynolds number impact
Castillo-Zamora et al. (2021)	Mini-AUV hydrodynamic parameter identification, controller design	Hydrodynamic parameter identification via CFD
De Sousa et al. (2019)	Study of AUV flow, drag, pressure, velocity, streamlines distribution	Depth impact, rudders' hydrodynamics
Min et al. (2020)	Identification for multi-propeller AUV maneuvering characteristics, controller design	Accurate multi-propeller AUV hydrodynamic model, algorithm convergence improvement.
Liu et al. (2019)	AUV dynamic behavior	Propeller-thrust coupling, mixed meshing strategy implementation
Javanmard & Mansoorzadeh (2019)	Effects of struts on the drag coefficient of an AUV	Accuracy of the CFD model
Stryczniewicz & Drężek (2019)	Underwater glider lift, drag, dynamic motion modeling	Accurate CFD modeling of glider lift, drag; dynamic motion integration
Webster et al. (2018)	Steady-state dive prediction for AUV using RANS	Accurate Prediction of AUV dive trajectory,
Du et al. (2018)	Effect of Submarine flow on AUV hydrodynamic coefficients, angle sensitivity	Submarine flow interference during AUV recovery
Nedelcu et al. (2018)	Hydrodynamic modeling of ROV	Lack of extensive hydrodynamic test facilities
Bustos et al. (2018)	Glider hydrodynamic forces, moments	Low-cost AUV design, hydrodynamic forces, dynamic modeling integration
Zheng et al. (2017)	AUV hydrodynamic coefficients	Complex fluid dynamics around AUVs, accurate hydrodynamic coefficient calculation
Liu et al. (2017)	Hydrodynamic modeling for small-scale UUV, coefficient calculation	Accurate hydrodynamic modelling
Zhu et al. (2016)	AUV dynamic behaviors in lateral flow	Lateral flow impact, tail fin layouts
Safari et al. (2022)	Drag, lift, moment coefficients, control surface effects	Modeling AUV maneuvering, and predicting hydrodynamic forces using CFD.
Guo et al. (2022)	Flow field around UV near the seabed	Influence of topography and flow velocity at the seabed
Nematollahi et al. (2015)	Hydrodynamic characteristics of an AUV	Interaction with the free surface
Shariati & Mousavizadegan (2017)	Impact of appendages on the resistance of the DARPPA Suboff	Free surface modeling

Source: Authors.

(Zheng et al., 2017). A study by Xu et al. (2024) have demonstrated that CFD can accurately model fluid-solid interactions, including the damping effects caused by fluid viscosity and resistance on AUVs during motion.

4.1.2. Optimization.

CFD can be used to model different design configurations of the underwater vehicle, such as the hull shape, the appendages, the propulsion system, and the control surfaces, and to evaluate their impact on the resistance and other performance criteria, such as stability, maneuverability, and control (Bao et al., 2023). CFD can also be integrated with optimization methods, such as genetic algorithms, gradient-based methods, or surrogate models, to find suitable design parameters that satisfy the design objectives and constraints. In this situation, CFD can complement experimental and analytical methods in designing and operating underwater vehicles (Han et al., 2020).

4.1.3. Variability Analysis.

Sources of the variability and the uncertainty of resistance can be different: model parameters, boundary conditions, numerical methods, as well as measurement errors. CFD can also support the sensitivity analysis, uncertainty quantification, and reliability analysis of resistance using tools like Monte Carlo simulations, Polynomial Chaos Expansion, and the Probabilistic Collocation Method (Gu & Sarris, 2015). CFD plays a crucial role in precisely evaluating and improving resistance by employing innovative techniques such as robust design, multi-objective optimization, and surrogate modeling (Serafino et al., 2020). These techniques guarantee that the solutions obtained are not just efficient but also flexible in response to variations in conditions and uncertainties. The purpose of robust design is to develop designs that consistently demonstrate high performance across diverse scenarios (Wu et al., 2018). Multi-objective optimization involves the simultaneous consideration of multiple performance criteria to attain the most favorable outcome for all objectives. Surrogate modeling simplifies intricate systems, facilitating expedited and more effective analysis.

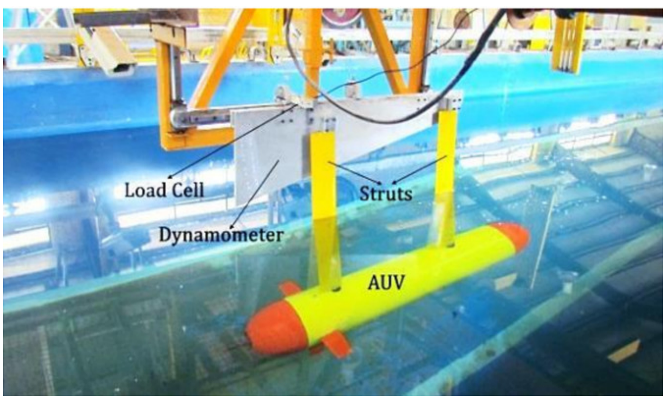
4.2. Advancements in Experimental Methods.

The recent development of experimental techniques has confirmed the accuracy of CFD simulations, thus allowing a more authentic and intricate understanding of the resistance of AUVs. The following are some methods to perform experiments.

4.2.1. Scaled Model Testing.

Scaled model testing involves scaled-down models of underwater vehicles to measure and estimate their flow resistance. Testing means facilities like wind/water tunnels and towing tanks where the flow and wave conditions can be controlled (Sulisetyono & Rinaldi, 2022). The scaling techniques to be adopted in the scaled model testing, however, need to be more advanced to apply the account for the effects of Reynolds number, Froude number, and Mach number on the flow and wave characteristics, as well as resistances of the underwater vehicle. These parameters depend on the size, speed, and shape of the underwater vehicle, as well as on the fluid properties, such as density and viscosity. Therefore, scaling the model of the underwater vehicle requires scaling the flow and wave parameters accordingly, to ensure the similarity and the accuracy of the results. Scaling techniques can be based on empirical formulas, charts, or numerical methods, and can vary depending on the type and the purpose of the test (Zheku et al., 2023). Figure 3 shows an example of a scaled model test of an AUV in a towing tank (Javanmard & Mansoorzadeh, 2019).

Figure 3: AUV model testing in Towing Tank.



Source: Javanmard & Mansoorzadeh, 2019.

4.2.2. *Advanced Water Tunnels and Wave Tanks.*

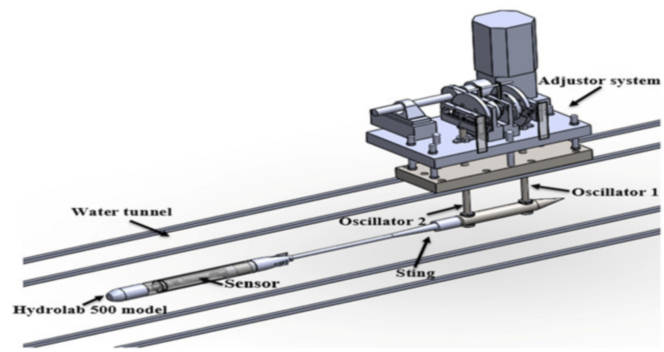
The use of facilities, such as water tunnels and wave tanks, is also common to undertake experiments under controlled conditions. Facilities of this kind have been developed further in the recent past so that much more precision in controlling the parameters, e.g., wave height and frequency, can be achieved and the water turbulence more accurately simulated. For instance, some facilities can produce irregular waves with different spectra and different directions of action, concomitantly with wind and current effects, to simulate the diversity of the free surface expanse. Some facilities can also produce high-speed flows with low levels of turbulence to simulate the laminar and transitioning regimes of the flow around the underwater vehicle (Aldhaheri et al., 2022). These facilities can provide helpful information on the hydrodynamic performance and behavior of the given underwater vehicle under varied conditions, such as pressure distribution, wake structure, stability characteristics, control characteristics, and the necessary drag coefficient. This would allow the model to be tuned and further refined in numerical simulations or analytical models to optimize the design and operation of underwater vehicles. Figure 4 is an example of an experimental setup at Wave Tank, Edinburgh. Many researchers have used testing facilities to perform hydrodynamic analysis on AUVs, as detailed in Table 2.

The water tunnel testing facility utilized by Nouri et al., (2016) to ascertain an AUV's hydrodynamic coefficients is depicted in Figure 5. It uses the concept of planar motion mechanism to perform velocity and acceleration-dependent tests.

Figure 4: FloWave Ocean Energy Research Facility at Edinburgh.

Source: Authors.

Figure 5: Model setup in water tunnel.



Source: Nouri et al. 2016.

5. Mitigation Strategies and Future Directions.

The reduction of resistance is an essential aim in the design and operation of AUVs. Especially in this last decade, several mitigation strategies and future directions have been proposed and explored, significant resistance can be referred to as the AUV operating close to the free surface. Some of these strategies and directions are described below.

5.1. *Technological Advancements to Reduce Resistance*

Several technological advancements are being explored to reduce the resistance of AUVs operating near the free surface:

5.1.1. *Advanced Materials*

Biomimetic materials and superhydrophobic polymers that can improve drag performance and being used as modern coatings and materials created for this purpose (Wu et al., 2020). Superhydrophobic materials are able.

5.1.2. *Advanced Materials.*

Biomimetic materials and superhydrophobic polymers that can improve drag performance and being used as modern coatings and materials created for this purpose (Wu et al., 2020). Superhydrophobic materials can deflect water droplets away from their surface and create an air barrier to keep the water

Table 2: Experimental Studies on Hydrodynamics of Underwater Vehicles.

Authors	Findings	Challenges
Nouri et al., (2016)	Estimates AUV hydrodynamic derivatives under controlled conditions	Test time constraints, surface wave effects
Parunov et al., (2023)	Hover, transition, cruise; thrust, aerodynamics compared	Mitigating free surface effects
Javanmard et al., (2020)	Determination of drag and lift hydrodynamic coefficients	Accuracy of the results and sensitivity of sensors
Kim et al., (2015)	Identification of force, and moment coefficients crucial for AUV control system algorithm development	Accurate measurement of hydrodynamics coefficient of AUV during the lateral and angular maneuver
Shankar & Vijayakumar, (2022)	Experimental Determination of Hydrodynamic Coefficients	Precise settings for estimation in lift, and drag estimation via varied speeds, angles, load cell.
Moonesun et al., (2013)	Towing tank tests with scaled Reynolds numbers, depth considerations	Accurate scaling of the submarine model with unequal Reynolds number
Rus et al., n.d.)	Drag coefficients for three submersible hulls via the method of forces.	Addressing similarity considerations and size ratios in wind tunnel testing
Mahalatkar et al., (2006)	Variable-angle-of-attack hydrofoil cavitation	Complex assembly, Balancing simplicity, stability, movement, regulation, cost, and tightness

Source: Authors.

at a distance from the body. Additionally, these advanced coatings can enhance durability and performance in various applications. This minimizes frictional drag and improves resistance to fouling. Drag-reducing polymers can be applied to modify flow structure in water or on surfaces, thereby reducing turbulence and minimizing drag within the boundary layer (Chen et al., 2023). Biomimetic materials imitate surface characteristics found in marine animals such as shark skin, dolphin skin, or lotus leaf by creating micro or nano-scale structures that alter flow behavior and decrease water adhesion (Fish, 2020). These advanced materials significantly lower resistance for underwater vehicles like AUVs operating near free surfaces where complex phenomena like wave breaking, spray, and cavitation occur due to highly unsteady nonlinear flows at the air-water interface.

5.1.3. Active Flow Control Systems.

Active flow control systems are those systems that can achieve these changes with the aid of the application of external energy, that is, actuation to the fluid by blowing or suction, plasma actuators, synthetic jets, etc., or piezoelectric actuators (Yang et al., 2021). The active flow control systems can be designed to offer more flexibility and adaptability compared with passive flow control features, such as geometric modifications or coatings, since they can also be operated on and off or adjusted to the flow condition and mission requirements (Talarczyk, 2023). Active flow control systems have the capability of dramatically reducing the resistance of underwater vehicles, especially the free flow of AUVs, where the unsteadiness and nonlinearity of the flow and its aeration phenomena create, due to the air-water interface, very complex phenomena, including wave-breaking, spray, and cavitation.

5.1.4. Hybrid Propulsion Systems.

Hybrid propulsion systems can reduce the induced resistance by integrating traditional and innovative propulsion methods, such as propellers, jets, vortices, or ions, in performance across varied operating conditions at different speeds, depths, and mission profiles. Hybrid propulsion systems may offer more flexibility and adaptability over conventional propulsion systems since they entail switching or combining different propulsion modes or changing power and thrust output by flow conditions and mission requirements (Anand et al., 2024; Kadiyam & Mohan, 2019). Hybrid propulsion systems, especially those of underwater vehicles, remarkably reduce the resistance of AUVs, which work at a close distance to the free surface, in highly nonlinear and unsteady flow.

5.2. Innovative Design Concepts for AUVs.

Innovative designs are crucial in addressing the unique challenges posed by the AUV in near near-free surface environment. These are needed to overcome these challenges and optimize the hydrodynamic characteristics of AUVs. Some of the possible design concepts are:

5.2.1. Modular and Flexible Design.

AUVs can undergo structural, and functionality changes based on a demand or situation due to several innovative design attributes like modularity and flexibility. In this design, an AUV can have different modules quickly mounted/dismounted for configuration adjustments in mass, adding/subtracting buoyancies, and adding/ subtracting resistance (Zhou et al., 2023). This design concept may be adapted in such a way that it enhances viability and scalability for AUVs, potentially configurable for different missions and payloads such as formation control, long-range surveillance, or multi-purpose operations (Wang et al., 2021; Wang et al., 2023). Additionally, during the

AUV design process, improvement of the reliability and maintainability of the vehicle increases because these sections are easily repaired or replaced in case some damage occurs (Cruz et al., 2013). Therefore, the significant advantage of the modular and flexible design for AUVs operating near the free surface is that such vehicles can be designed and built to face several environmental challenges and operational constraints.

5.2.2. Bio-inspired Designs.

Bio-inspired designs reflect another innovative concept in creating AUVs: they copy the form, function, and behavior of aquatic organisms. With biomimetic attributes and movements of fish, dolphins, whales, or whatever, this mimicking will give AUVs better hydrodynamic performance, such as a reduction in drag and an increase in efficiency and agility (Costa et al., 2018). These include soft robotic AUVs inspired to use flexible and deformable structures to fit the fluid environment, morphing AUVs to alter their shape and configuration to achieve optimal combination for hydrodynamic performance, and the bio-inspired sensors and controllers used to mimic the sensing and perception mechanisms of aquatic animals (Triantafyllou et al., 2020).

5.2.3. Surface Adaptive AUVs.

Surface adaptive AUVs are one of the innovative design concepts that aim at the reduction of resistance and improved stability of AUVs in the aggressive free surface environment (Ehlers, 2020). Giant waves, surface reflections, and air interaction are the three major problems in the free surface environment that a normal AUV has to face. Surface adaptive AUVs will, therefore, be free to use mechanisms that affect variations in buoyancy or shape, creating adjustments appropriate to the varying wave conditions. For instance, surface-adaptive AUVs can use variable ballast systems to control depth and trim. Another feature may be morphing structures that change the cross-sectional area and the drag coefficient. Adapting to surface environments, the surface-adaptive AUV can assure improvement in performance, efficiency, and survivability(S. Wang et al., 2018).

5.3. Future Research Directions and Potential Areas of Study.

Future research in the following areas could further optimize AUV resistance of AUVs:

5.3.1. Enhanced CFD Modeling.

The CFD method is an essential tool for hydrodynamic performance investigation and optimization in AUVs under various flow scenarios. However, there still exist some inherent difficulties in the CFD models concerning accounting for multiphase phenomena or integrating structural dynamics (Kieckhefen et al., 2020). Some potential signaling points in making the simulation of CFD better for AUV involve: devising more accurate and efficient CFD methods and tools; researching the effects of diverse design parameters and environmental factors on AUV resistance and stability; expanding the CFD models so that motion and control in 6-DOF through complex flow fields can be captured for dynamically behaving AUVs; and comparing and validating CFD results with experimental data from sea trials and full-scale model testing.

5.3.2. Machine Learning and AI.

Machine learning and artificial intelligence (ML/AI) techniques can improve the design and control of AUVs concerning resistance performance near the free surface. Deriving from ML/AI, many data-driven optimizations, adaptive navigation, cooperative coordination functions, and others can be generated for AUVs. Some recent studies by Okereke et al., (2023), and Sands (2020) demonstrated the advantages and feasibility of using ML/AI techniques for AUVs. Future work may, therefore, be directed along the paths of development of novel ML/AI algorithms and architectures capable of dealing with complex and highly uncertain underwater environments, fusion of ML/AI with physics-based models and sensors, learning from heterogeneous sources of data; and transfer of knowledge across domains and tasks to improve accuracy and reliability in AUVs. Artificial intelligence and machine learning techniques for AUV design and operating strategies shall be optimized for performance improvements.

5.3.3. Energy Harvesting Technologies.

Energy-harvesting technologies harness the energy available in the environment, such as ocean currents or waves, and power AUVs cleanly and sustainably. This minimizes the use of batteries and increases endurance and the AUV's range. Some recent works by Zeng & Wang, (2023); Maheen, (2023), Yang & Martinez, (2023) and Li et al., (2022) considered and assessed various energy harvesting technologies for AUVs. Future research directions may be the development and optimization of low-power components, converters, and storage systems; the exploration of various forms of ocean energy; allowing self-repair and reconfiguration of energy harvesters; and reduction in the environmental impact and ecological footprint of energy harvesting devices.

5.3.4. Autonomous Adaptation.

In addition, Autonomous adaptation can also improve the performance and efficiency of AUVs close to the free surface with adaptability to the dynamic environment conditions and mission requirements, such as resistance, uncertainties, disturbances, etc. Some recent research by Lu et al., (2023) and Xu et al., (2023) has proved that it is possible and beneficial to use mechanisms of autonomous adaptation by the AUV, including emergent behavior, self-organization, learning, and evolution, among others. Future work might include designing new algorithms and architectures for ADAPT to handle the complexity and uncertainty of the underwater world, integrating autonomous adaptation with physics-based models and sensors to bring about better accuracy and reliability in AUVs, and allowing ADAPT to optimize resistance management through the adaptation of AUV operation parameters according to real-time environmental information, ensuring safety and ethics in the autonomous adaptation for AUVs.

5.3.5. Eco-Friendly Solutions.

Eco-friendly solutions can reduce the resistance and the environmental impact of AUV operations near the free surface by adopting natural-inspired designs, biodegradable materials, and minimal disturbance approaches. Future research directions may include enhancing the sustainability and resilience of AUVs by using renewable energy sources, promoting the biodiversity and conservation of the marine ecosystem by using low-cost and low-impact AUVs, and collaborating with stakeholders and communities to ensure the ethical and responsible use of AUVs. Furthermore, through the integration of these strategies and continuous research in these areas, the AUVs should be developed so that they will not only be more efficient to cope with the complexities of the free surface environment but also more sustainable and adaptable to varying oceanographic conditions.

Conclusions.

This review has identified several gaps in research that need addressing to take the field of AUV resistance analysis one step further. Advanced materials and surface coatings that can further cut down resistance are topics within the gaps, as well as the role of marine growth and biofouling in affecting the AUVs. Another line of development about the real-time adaptive control systems is that their design should adjust itself to the changing resistance conditions to optimize AUV operation. However, the more extended parameters dealing with experimental studies to validate CFD models in actual sea conditions and the new testing facilities to develop that can simulate realistic free surface environments, are required to study the effects of near-surface operations in the long run on the structural integrity and maintenance needs of AUVs. The investigation of resistance for AUVs operating close to the free surface is both a dynamic and critical domain. Developments in this area hold great promises for revolutionizing the design and operation of AUVs, making them more effective, efficient, and environmentally friendly in different ocean environments.

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