Review Article

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Technological developments of amphibious aircraft designs: Research milestone and current achievement

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Abstract: This study aims to examine the development of research on seaplanes and determine the innovations that have been achieved or researched. To better serve the demands of real aircraft designers, this research presented a new process for creating seaplane designs. Combining historical seaplane data with current ship and aircraft design data resulted in a new preliminary seaplane concept design. Another benefit of this design approach is transforming an existing landplane into a seaplane by adding a floating device that satisfies seaplane conversion standards. Enhancing hydrodynamic performance was the addition of a trimaran design. A retractable float device was employed to add drag reduction during flying. The trimaran idea provided superior hydrostatic stability and increased water speed, while the floats' retractable design decreased aerodynamic drag for improved flying performance. A computational design framework is also created to assess the efficacy and performance of hydrofoils for amphibious aircraft, with a particular emphasis on water take-off performance. For validation, a comparison is made between the numerical simulations and the experiment results. The results of this study show that seaplane research over the past decade has produced several innovations, from general to detailed designs. Seaplane also has the potential to be developed in the coming years.

Keywords: amphibious aircraft, trimaran hydrofoils, take-off and landing performance, computational fluid dynamics, optimization

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1 Introduction

The Wright brothers' successful invention of the first airplane in 1903 marked the beginning of a twentieth-century trend marked by constant advancement and discovery in aeronautics. To create the most excellent airplane feasible, designers must balance several competing demands and limits, considering both market demands and preexisting designs. The development of airplane design made it possible to examine effective transportation strategies, such as multipurpose vehicles, from a wider angle. Amphibian aircraft was one design of such adaptable vehicles that had been around for decades. Since Henry Fabre's 1910-powered seaplane flight, much study has been conducted on seaplane flight. However, with better aircraft design and the building of appropriate land-based infrastructure, the use and operation of seaplanes drastically decreased. The designs of these cars are antiquated, and no progress is being made on their upgrades. These days, seaplanes are primarily used as water bombers in firefighting operations. In the private sector, where most seaplanes are little landplanes modified with floats, they are also extensively utilized.

A novel and enhanced conceptual design approach has been devised to tackle the deficiency of the sophisticated seaplane design. The design process is competitive in the short and long term and satisfies the requirements of the existing aviation market programs. The information obtained from studying boat and aviation technologies must be combined to create a seaplane. It must have adequate hydrostatic stability, decent lift requirements, appropriate water take-off and landing characteristics, structural support for air and water capabilities, and good aerodynamic qualities that might impact flight performance. The original goal of this study was to develop a different approach to conceptual design that would result in a cutting-edge seaplane design. The new conceptual design approach combined modern amphibious aircraft design procedures with seaplane design notions gathered during the early phases of the seaplane dream. The availability of big motorboats and the absence of appropriate land aircraft infrastructure gave rise to the seaplane concept. French engineer Henry Fabre achieved the first flight of a motorized seaplane in 1910. This aircraft was entitled "Le canard." Seaplane aviation has been extensively studied since then. Early development was carried out in the United States by Glenn Curtis, who collaborated with Alexander Graham Bell at the Aerial Experiment Association. On January 26, 1911, he launched his first Hydroaeroplane off San Diego Bay. Another Curtiss model, dubbed "The Flying Fish," was launched in 1912. The suction caused take-off issues for this prototype's maiden flight. Curtiss decided to add the step, separating the front part from the tail section and making it the first seaplane to show off the step's benefits.

The seaplane remained latent until the idea was brought back to life in the mid-1980s as part of the advanced amphibious vehicle (AAV) concept. The AAV itself was introduced as a type of transport vehicle that capable to operate on both land and sea. To swiftly move land troops from an amphibious assault ship, the United States military developed AAVs. These military uses reinvigorated the concept of designs that may be utilized for civilian transportation. Sports and leisure travel once again bolstered the seaplane market. Among the many things that helped the seaplane business thrive was the idea of wing-in-ground (WIG) effect vehicles. One such vehicle is the Russian Ekranoplan. Its design aimed to make the most efficient use of aerodynamic lift forces while minimizing aerodynamic drag. Even today, these vehicles significantly impact how boats and ships are designed for fast sailing and cruising. Seaplanes are also the subject of similar research, which aims to enhance their performance in extreme weather and high-wave situations.

A floatplane is a seaplane that floats under the fuselage and functions like a boat, allowing it to take-off and land on the water's surface. The dynamic performance of a floatplane is generally the same as that of a plane boat running on the surface of seawater. As the floatplane moves forward, the longitudinal center of gravity moves aft, increasing the water pressure at the bottom of the hull. During take-off, the speed of a seaplane undergoes three stages: displacement, plowing, and planting. The displacement phase is a state in which the buoyancy force supports the total weight of the seaplane in the same position as the rest of the seaplane. The planning phase is a condition in which the hydrodynamic lift and the buoyancy force together support the weight of the seaplane, providing the highest resistance. In a planning situation, the floatplane's whole weight is sustained by the floater's hydrodynamic lift and the wing's aerodynamic lift. The planning phase usually takes place before the take-off of high-speed seaplanes. The goal is to reduce resistance force as much as possible so that the floating aircraft can take off rapidly with less engine power, thus saving fuel. Early in the floater's design process, the flare, trim angle, deadrise angle, transverse step, and primary dimensions can be chosen to reduce the resistance force. The early research mainly concentrated on floater trim angle optimization to lower the overall resistance. When flying over water, the floater, a crucial component of the seaplane's structure, significantly impacts how well the aircraft performs. It is feasible to obtain a thorough grasp of the traits and behavior of seaplane floaters in the framework of this journal review because the study is concentrated more on the hull or floater aspect than other components like wings. This is predicated on the idea that a seaplane spends most of its operational time in the water, traveling in shallow waters or stopping at a pier. The seaplane's capacity to float steadily is crucial before it can move on to the flight phase. Hence, it is essential to focus on the floater before other components. In addition to offering a deeper comprehension of the floater's technical aspects, the analysis will pave the way for future investigations into hydrodynamics, material selection for floater construction, and the dynamic behavior of seaplanes about water media. Therefore, this research is anticipated to significantly impact developing and comprehending more sophisticated and effective seaplane technology. Recognizing a seaplane requires understanding its unique movements, particularly in water.

Like ships, seaplanes must be able to float, which is facilitated by a floater or hull with buoyancy. This ability to float enables the seaplane to initiate the next dynamic movement, landing or taking off. Landing is the phase in which the seaplane transitions from flying to landing on water. Seaplanes rely on floaters for safe landings since they cannot use wheels. During take-off, the seaplane leaves the water to become airborne. In contrast to conventional aircraft, seaplanes generate lift not only through their wings but also with the assistance of the floaters. During take-off and landing, the floater maintains the seaplane's smooth movement and prevents porpoising. Good performance during these critical phases can result in benefits such as increased durability of the floater material, improved fuel efficiency, and time savings. Furthermore, these benefits have a direct impact on passenger comfort and safety. Given the significance of the floater function in seaplanes and its impact on hydrodynamic performance, it is crucial to advance research on seaplane hydrodynamics and motion. Experts are working to identify various hydrodynamic phenomena, including the forces acting on the floater. The Von-Karman equation is the foundation for seaplane hydrodynamic research, allowing for investigating the load forces acting on the floater. In addition, equations used in this field typically involve lift, resistance, and load forces. Due to the complexity of problems that are difficult to solve manually, computer technology and numerical simulation-based research have become the solution. The latest software can quickly and accurately perform hydrodynamic analysis, making it a reliable trend in research methods in recent years. Simulation methods can visualize how the seaplane will behave, making it easier to understand case studies. In addition to computer simulation, many researchers use simulation on test facilities designed to suit their needs. Tests are generally conducted in towing tanks that attempt to recognize the straight-line motion of the vehicle, such as taxiing, landing, and take-off (although take-off is very difficult to replicate). This direct testing method provides results that closely resemble actual conditions and offers insight into phenomena that computers may not be able to replicate. Because a seaplane floater is an amphibious vehicle that needs to function well in two different media, choosing the suitable material presents some intricate technical considerations. Given the various densities of various materials, one of the main requirements is that the material produces the appropriate lift. Overly heavy materials can cause floaters to function less, and overly light materials can compromise operational stability and safety. In addition, corrosion resistance is essential when choosing materials for seaplane operations, primarily carried out in a water environment. The seaplane floater also needs to support both dynamic and static loads. For instance, loads from the aircraft structure and buoyancy from the water are considered static loads. In contrast, stresses from the vessel's motion in the water, such as slamming occurrences, are considered dynamic loads. As a result, preserving the structural integrity of seaplane floaters depends heavily on the strength and durability of the materials. From the use of wood and metal to more modern research that led to the creation of composite materials that promise improved performance in the face of operational constraints, the history of material development for seaplane floaters shows the growth of technology. The last 10 years have seen a notable upsurge in seaplane research, indicating a return to the exploration and application of this technology. It is thought that there is a tight connection between this occurrence and the world's increasingly varied transportation needs.

Recent hydrodynamics and structural engineering advances have led to significant gains in the seaplane design. These developments have opened up new possibilities for enhancing industry performance, including emergency response, transportation, and tourism. We hope these advancements will be included in future designs, emphasizing float design, aircraft–water interactions, and water dynamics. To guarantee the general adoption and modernization of seaplanes, this review seeks to direct future research and offer helpful designer ideas for producing seaplanes that satisfy aviation and marine performance standards.

2 Seaplane utilization

Seaplanes, also known as amphibious aircraft, have been integral to both military and leisure sectors for decades. Their unique ability to take-off and land on water provides them with a versatility that sets them apart from traditional fixed-wing aircraft [1]. However, there is a difference between seaplanes and amphibious aircraft. Amphibious aircraft can take-off from a runway on land and land on water (sea/lake/river) or vice versa. This type of aircraft has a float and landing gear. On the other hand, a seaplane is an aircraft that can only take-off and land on the water's surface because it has no landing gear. Seaplanes are crafted to function seamlessly in challenging environments, such as unprepared airstrips and sizable water bodies, eliminating the necessity for specialized surfaces, docks, or handling infrastructure [2]. Their prime era of usage primarily occurred in the period between the two World Wars. During this time, the limited availability of extensive, paved runways rendered seaplanes highly advantageous for commercial and military purposes.

2.1 Versatility of seaplane

Seaplanes are highly efficient transportation to and from isolated and underdeveloped regions. They also serve as a vital link between the islands and the mainland. The hull bottom is designed to withstand water loads and provides extra protection in case of forced landings on unprepared fields. This safety feature was precious in the past when engine reliability was lower than it is today [3]. However, operating safely on rough terrain and water remains an asset. Bush operators and sport pilots use seaplanes. Despite the perceived additional safety of operating on the water, about half of all seaplane accidents occur during these operations, and they are inherently riskier than operations on land. The versatility of seaplanes, though advantageous, does entail inevitable trade-offs. Unlike conventional aircraft designs, where achieving optimal performance involves intricate compromises, seaplanes face additional complexities due to specific water-handling needs [4]. Generally, a seaplane's initial expenses and weight are higher than a land-based aircraft with equivalent capacity. This is primarily attributable to the rigid hull and a larger power plant, which is necessary to counteract water suction during take-off and ensure sufficient climbing performance. Seaplanes are also used to fight fires, and they have been adapted as water bombers to carry up to 12,000 liters of fluid, such as the Beriev Be-200 to combat forest fires. This is the case in the United States, Canada, and Greece. Portugal and Russia are among the countries that rely on water bombers for firefighting. However, the seaplane market in Europe is less well developed than in North America. Most seaplanes are privately owned, and seaplane airlines are few. They compete with other transport modes such as ferries and trains [5].

2.2 Seaplane utilization in military

Seaplanes have played a crucial role in military operations, providing strategic advantages in various scenarios. Their ability to operate from water surfaces expands the range of potential deployment locations, making them valuable assets for maritime surveillance, search and rescue missions, and antisubmarine warfare [6]. Flying boats were used to recover downed airmen and operated as a scouting boat. They successfully sank submarines and located enemy ships. Many warships are equipped with catapult-launched seaplanes, with some carrying as many as four. These aircraft identify targets on the horizon for the ship's main artillery or countering enemy reconnaissance aircraft. Seaplanes also excel in operating in rough sea conditions, a capability that can be challenging for traditional aircraft. This makes them valuable for maritime patrol and reconnaissance in harsh weather conditions when other aircraft have limited operational capacity. In addition, their versatility allows for swift deployment and repositioning, making them ideal for rapid response missions and disaster relief operations. The ability to operate from both water and land runways expands the range of possible missions where they can be deployed [7].

2.2.1 The consolidated PBY Catalina

The Blohm und Voss BV-238 was the largest flying boat of World War II (WWII), with a take-off weight of 100 tons, and was also the heaviest aircraft to fly during the period. Meanwhile, the Consolidated PBY Catalina, one of the most successful and widely used flying boats, was operated by countries such as the United States, the United Kingdom, Russia, and Canada. Japan, Germany, and Italy also used similar aircraft. Consolidated's (Model 28) XP3Y-1, two-step hull design, was similar to the P2Y, which still featured the high parasol wing, but the external bracing and wires were gone. The wing was mounted on a tower above the fuselage and incorporated integral fuel tanks. Table 1 presents the specification of The Consolidated PBY Catalina (in 1943).

Few large flying boats are currently in operation. They are primarily used for specialized roles, such as water-bombing for aerial firefights [2]. Creating a place where they can quickly reload large amounts of water is a significant advantage. Some surplus WW II seaplanes are still used for this purpose although the most effective firefighting aircraft to date is the Bombardier 415.

2.2.2 The Bombardier 415

The Bombardier 415 is a Canadian amphibious aircraft purpose-built as a water bomber. It was designed and built specifically for aerial firefighting. On June 20, 2016, the Bombardier 415 type certificate was obtained from Bombardier by Viking Air. This aircraft allows operators

Table 1: Specification of the consolidated PBY Catalina (in 1943) [8]

Dimensions	
Wing span	31.70 m
Length	19.47 m
Height	6.50 m
Weights	
Empty	9,845 kg
Max. take-off	16,066 kg
Performance	
Max. speed	288 km/h
Cruise	188 km/h
Range	4,096 km

Table 2: Specification of the Bombardier 415 [9]

Dimensions	
Wing span	28.60 m
Length	19.82 m
Height	8.90 m
Weights	
Empty	12,880 kg
Max. take-off	19,890 kg
Performance	
Max. speed	359 km/h
Cruise	333 km/h
Range	2,443 km

to access sites in remote locations, use unprepared runways, facilitate on-water or on-land, and perform short take-off and landing (STOL capabilities), and Table 2 shows the specifications of Bombardier 415.

The Chinese Harbin SH-5, launched in 1986; the Russian Beriev 200, jet-propelled and launched in 2003; and the Japanese ShinMaywa US-2, launched in 2007, are the only three large-size flying boats of the new generation. They are designed to perform a wide range of duties, including aerial firefighting, antisubmarine warfare, and air–sea rescue, which are the primary uses of these aircraft. Although new engines and the latest generation avionics have been adopted, their overall design has not significantly evolved from the flying boats of WW II. The ability to float and rise again from the water caused excessive drag and added considerable weight to the aircraft. In military aircraft, these trade-offs reduce payload, speed, and range; in commercial aircraft, they increase cost. Competing with new civilian jet aircraft such as the de Havilland Comet and Boeing 707 is impossible. Very few commercial airliners continued to operate flying boats, but only to reach destinations still inaccessible to land-based aircraft. Seaplanes also excel at operating in rough sea conditions, which can be challenging for traditional aircraft. This makes them an invaluable asset for maritime patrol and reconnaissance missions in harsh weather conditions when other aircraft may be limited in their ability to operate. Their versatility makes them ideal for rapid response and disaster relief missions, as they can be rapidly deployed and repositioned. Their ability to operate from water and land runways expands their range of missions [10]. Despite their advantages, seaplanes also have some disadvantages for military use. Their effectiveness in specific missions can be limited by their relatively lower speed and payload capacity than traditional land-based aircraft. In addition, the specialized maintenance and support infrastructure required for seaplanes can add complexity and cost to military operations [11]. In recent years, there has been a trend toward developing advanced seaplanes with enhanced capabilities, such as longer endurance, improved surveillance and reconnaissance systems, and increased cargo capacity. These developments aim to overcome some of the limitations of traditional seaplanes and to increase their utility in military operations. Integrating stealth features, allowing seaplanes to operate covertly in hostile environments, is one of the most notable advances in seaplane technology. This enhancement has proven beneficial for intelligence gathering and special operations missions. Unmanned aerial systems in amphibious aircraft designs are another trend in the use of seaplanes. This integration has enabled militaries to conduct long-endurance missions without risking the lives of personnel. UAS-equipped seaplanes have proven invaluable for persistent surveillance, remote reconnaissance, and maritime activity monitoring [12]. In conclusion, the evolution of seaplane technology has paved the way for their increased relevance in modern military operations. With ongoing developments to overcome traditional limitations and enhance their capabilities, seaplanes remain valuable for militaries worldwide.

2.3 Seaplane utilization in leisure

Seaplanes have become popular in the leisure and tourism industry, providing a unique and exciting mode of transportation for enthusiasts and tourists. Seaplanes have become increasingly popular for leisure activities in recent years. They offer a unique and exciting way to explore remote locations that are otherwise difficult to reach. Seaplanes can land on water and offer endless possibilities for sightseeing, watersports, camping, fishing, photography, dining, and transportation [13]. Seaplanes offer several advantages for leisure activities. First, seaplanes allow travelers to explore unspoiled natural landscapes by providing access to remote locations that are difficult or impossible to reach by road or conventional aircraft. Second, seaplanes offer a unique perspective of the surrounding landscape and landmarks, providing spectacular aerial views. In addition, seaplanes offer endless possibilities for exploration and adventure due to their flexibility in landing and taking off, providing access to a wide range of water bodies, including lakes, rivers, and coastal areas. Seaplanes also provide a platform for various leisure activities such as scenic tours, island-hopping adventures, wildlife viewing, and lake flights. Seaplanes provide endless opportunities for memorable leisure experiences, from water sports such as water skiing and wakeboarding to seaplane camping, fishing, hunting, photography and filming, and dining and events. Seaplanes also allow travelers to explore destinations that are otherwise difficult to reach. With the ability to land on both water and land, seaplanes can access remote islands, secluded lakes, and hidden coastal areas inaccessible by other transport modes. Whether camping on a remote island or flying over breathtaking scenery, seaplanes offer travelers a unique opportunity to experience the beauty of these remote locations from a different perspective. Seaplane take-off and landing flexibility means they can easily navigate narrow waterways or land on small, unmarked airstrips. Not only does this add to the excitement of the trip but it also gives travelers access to remote places that still need to be touched by mass tourism. Seaplanes open a world of possibilities for leisure travelers seeking unforgettable experiences off the beaten track. However, there are still many modern civil aircraft on the market. These are typically used for light transport to lakes and other remote areas. Most are offered as third-party modifications.

2.4 The de Havilland Beaver

The de Havilland Beaver and Otter models were initially designed to have a supplemental type certificate for aircraft such as the Cessna Caravan and Skywagon. This may be possible. They needed to be reconfigured. The most well-known utility floatplanes in service are no longer in production. Approximately 2,000 units were delivered, and the specification is shown in Table 3.

However, small amphibious flying boats are almost extinct, except for a few homebuilt or uncertified prototypes. The Lake Buccaneer and its derived versions, the Renegade and Sea Fury, are the last single-engine amphibious hull planes still in production. Currently, Lake Amphibian is on the verge of ceasing business. In 2009, the American Dornier Seaplanes Company, owned by the grandson of Claude Dornier, the German pioneer of amphibious aircraft, announced its intention to begin producing the Seastar, which is an all-composite, twin-engined, 14-engined aircraft, and multirole amphibious flying boat will be produced. Except for remote areas of the Alaskan and Canadian wilderness, where residents typically operate civilian seaplanes for personal use, there are many seaplane operators in Seattle, Vancouver, and Sidney, as well as in the Caribbean Sea, connecting island groups. In addition, Greece also utilizes seaplanes. Since 2007, the Scottish-based commercial operator Loch Lomond Seaplanes has been using seaplanes to connect the many islands to the mainland. Currently, it is the only European city-based seaplane service. The market for seaplanes is a small part of the aviation industry that deals with the manufacture, use, and demand for these specialized aircraft that travel on water. It combines aspects of aviation and marine technology to meet specific commercial and leisure needs. There has been a steady increase in the demand for seaplanes in the leisure and tourism industry over the last few years. This growth can be attributed to several factors. One factor is seaplanes' unique experience in leisure and tourism activities. Seaplanes provide an exciting and scenic way to explore coastal areas, islands, and other remote destinations that are not accessible by traditional means of land transport. The increasing popularity of luxury travel experiences is another factor driving demand for seaplanes in leisure and tourism. The demand for seaplane charters is driven by travelers searching for personalized and memorable experiences and leisure activities such as sightseeing tours. This has led to significant developments in the operation of seaplanes, suggesting considerable potential for growth in the leisure air transport sector.

Seaplanes are an environmental friendly option for access to remote areas as they do not need runways or airports. This makes them a sustainable choice for tourism and minimizes the impact on the natural environment. In addition, seaplane tours offer a unique perspective of coastal landscapes and islands, allowing tourists to explore destinations off the beaten track. On the other hand, seaplanes' operation depends on weather conditions, which can inconvenience travelers due to potential disruptions and cancellations. In addition, when considering seaplanes in certain areas, noise and potential disturbance to wildlife in sensitive ecosystems are essential factors to consider. Seaplanes in the leisure market have been criticized for their noise pollution and potential impact on wildlife

Table 3: Specification of the de Havilland Beaver [14]

Dimensions	
Wing span	14.63 m
Length	9.14 m
Height	2.74 m
Weights	
Empty	1360.77 kg
Max. take-off	2721.55 kg
Performance	
Max. speed	283.35 km/h
Cruise	246.31 km/h
Range	550 km

habitats. Some people worry that seaplane charters damage the natural environment and disturb local wildlife. This has raised concerns about long-term ecological damage. Safety issues relating to take-offs and landings on the water have also raised doubts about the suitability of seaplanes for activities such as sightseeing tours. However, proponents say that technological advancements and stricter regulations address those concerns. Compared to other modes of transportation like cars, buses, and trains, air travel has expanded more quickly. With seaplanes, this is different, however. Seaplanes cannot be considered an essential means of transportation despite the importance of aviation. Regulations governing aviation differ for land-based and seaplanes. In addition, when operating on water, seaplanes must adhere to water regulations. Several of these laws must be well established in Europe, especially in the United Kingdom. Convincing the authorities that there should be no strict regulations for safe seaplane operations is the most significant obstacle for novice seaplane operators, according to an experienced seaplane pilot. It is crucial to steer clear of strict guidelines regarding precise landing and maneuvering zones. Most issues that seaplanes face today are social, legal, operational, and infrastructure issues rather than technological ones. It is important to note that there have been no significant technological advances in seaplanes recently. If seaplanes are unsafe and have both water and air capabilities, the market and the authorities will not be convinced that seaplanes are as safe and efficient as a boat on the water or an aircraft in the air [3]. Despite these challenges, seaplanes have the potential to enhance the tourism experience and provide access to unparalleled natural beauty. Careful planning and considering environmental and logistical factors are essential to ensure the responsible and sustainable use of seaplanes for leisure and tourism.

2.5 Seaplane utilization for transportation and logistics

Indonesian aircraft manufacturer PT Dirgantara Indonesia (PTDI) is on track to have the amphibious version of its indigenous N219 twin-engine aircraft in series production by 2024. Indonesia is developing the 19-seat N219A amphibious aircraft as part of a national priority research program. The program aims to develop the domestic aircraft industry and support remote tourism and logistics delivery [15]. PTDI's director of technology and development, Gita Amperiawan, confirmed this. She also confirmed that Indonesia's transport minister had requested an update on the project. PTDI has developed the standard take-off and landing version of the N219 aircraft and has recently received type certification, which would allow PTDI to begin commercial production of the aircraft. However, the technology for the N219 amphibious aircraft is still being developed. The N219 commercial aircraft offers hope for Indonesia's fast-growing aerospace industry and is currently being developed into an amphibious aircraft. The N219A aircraft is well suited to Indonesia's archipelagic characteristics and can support the development of land and sea connectivity in the country [16]. N219A aircraft specification is presented in Table 4.

Due to the country's archipelagic nature, Indonesia is keen to use amphibious aircraft to reduce its reliance on airport infrastructure and provide easy access to islands and tourist destinations inaccessible by air. The N219A is highly versatile, capable of flying over lakes, large rivers, bays, and oceans, and allows for more accessible construction of airports compared to traditional airports. Several areas in Indonesia are already served with seaplanes, including Pulau Bawah (Riau Islands) and Sumbawa (West Nusa Tenggara), and there are several operators of this type of aircraft in Indonesia, including AIRFAST Indonesia and Trivia-Air.

3 Seaplane industry

Early in the twentieth century, technological advances and the innovative work of aviation visionaries such as Glenn Curtiss and the Wright brothers marked a transformative period for the seaplane industry. A turning point was reached in 1911 with the introduction of the Curtiss Model E. With its central float and outrigger floats, this unique biplane showed significant developments in seaplane technology. This era's central character, Glenn Curtiss, was instrumental in expanding the capabilities of amphibious flying.

Table 4: Specification of the N219A aircraft [17]

Dimensions	
Wing span	19.80 m
Length	15.77 m
Height	5.94 m
Weights	
Empty	5,670 kg
Max. take-off	5,579 kg
Capacity	
Crew	2
Seat capacity	19

3.1 The overview of industrial seaplanes in the early 20s

The Curtiss Model E demonstrated that water take-offs and landings were possible and established the foundation for later advancements in seaplane engineering. Beyond the specific aircraft, seaplane technology evolved due to Curtiss' unwavering experimentation and dedication to perfection, impacting both military and commercial applications. Seaplanes became an essential asset during the First World War due to their unparalleled adaptability. They offered unparalleled versatility for maritime operations essential for coastal defense, antisubmarine patrols, and surveillance. Seaplanes' unique ability to take-off and land on water gave military strategists a powerful tool to extend their reach over vast ocean areas where conventional aircraft or ships were limited. The immense potential of seaplanes for long-distance travel was demonstrated by the successful completion of the first transatlantic flight in 1919 by the NC-4, a Curtiss NC flying boat. In addition to their military applications, seaplanes also spurred innovation in aviation infrastructure, leading to the development of seaplane bases and landing facilities along coastlines and waterways worldwide. These facilities opened new frontiers in international travel and trade by facilitating the integration of seaplanes into global transport networks. In addition, the development of seaplane technology has catalyzed advances in aircraft design and engineering, paving the way for the development of amphibious aircraft capable of operating seamlessly in both air and water environments. This aircraft hybridization has expanded seaplanes' operational capabilities, enabling them to perform various roles, from military surveillance to civil air travel.

As flying boats were used to establish long-distance air routes, British carrier Imperial Airways became prominent in commercial aviation. Flying boats such as the Short Empire and Sunderland became iconic icons of luxury travel during this era, connecting various parts of the British Empire. Flying boats were popular among affluent travelers looking for upscale and picturesque vacation experiences because of their unique design, which featured a boat-like hull and wing-mounted struts. These developments in the early twentieth century created new opportunities for floating transportation and marine surveillance, which had a long-lasting effect on aviation. During this time, the seaplane industry made a lasting contribution to aviation history by influencing amphibious flight in the future and laying the groundwork for further technological advancements. Nevertheless, despite their early success, seaplanes lost commercial significance as land planes were more widely used, helped by better runway infrastructure. With the increased efficiency and comfort of landplanes, seaplane use gradually declined after WWII. However, seaplanes have had specialized uses since the early twentieth century, including search and rescue, maritime surveillance, and tourism in areas with many waterways. Since aviation engineers and enthusiasts are building upon the foundations left by the visionaries of the early twentieth century, the inventive spirit and technological insights obtained during this period continue to influence present amphibious and seaplane technology. The modern seaplane sector is evidence of aviation's adaptability and tenacity in navigating.

3.2 Seaplane development in the last decade

Seaplanes have played an essential role in the development of aircraft worldwide. They have had extensive commercial and military applications since the early years of modern aviation. However, the problem is that the aviation industry has been significantly impacted by the lockdowns imposed in major countries worldwide, resulting in halted production and delayed deliveries of amphibious aircraft. There was a 60% drop in passenger traffic in 2020 compared to 2019, according to the International Civil Aviation Organization. In addition, significant supply chain disruptions, economic slowdowns, low production rates, and other factors are expected to affect market growth. The General Aviation Manufacturers Association report for 2020 shows that deliveries of ICON A5 aircraft fell from 41 in 2019 to 26 in 2020. Similarly, DAHER delivered 20 Kodiak 100 models in 2019 but only 8 in 2020. The impact of COVID-19 on the market is evident in the reduced aircraft deliveries in 2020. Aviation technology has progressed significantly in recent years, particularly in developing seaplanes. Seaplanes are no longer solely for military purposes; they serve commercial and research needs. Due to their reliability in both air and water, they can be developed into multipurpose vehicles. Seaplane technology development focuses on design, manufacturing, and unmanned systems.

3.2.1 AKOYA seaplane

Seaplane manufacturers primarily focus on introducing the latest technologies to reduce aircraft weight. Lisa Airplanes, a French company, has developed a lightweight seaplane named AKOYA. Unlike other aircraft, the new seaplane AKOYA has a unique design with no hull or step and no break lines or joints in its aerodynamic fuselage. The company has used sea foil technology to neutralize the effects of crashing waves, giving aircraft comfort and high stability. This allows it to take-off in a broader range of sea conditions than other seaplanes fitted with standard hulls or floats. These advancements are expected to benefit the growth of the global amphibious aircraft market during the forecast period.

The aircraft's two underwater fins enable it to lift its fuselage out of the water quickly and provide additional stability during take-off acceleration and water landings. This amphibious aircraft provides access to unexpected destinations, from private airstrips and white sandy beaches to Scandinavian fjords and ski resorts. It is the only light aircraft equipped with skis fixed on the retractable landing gear, making it highly versatile. The skis are an essential component of the landing gear. They fit inside the fuselage during flight and can be easily removed during summer. These skis enable the airplane to take-off and land on snow surfaces. They are located midway up the wheels, and the skis-in design allows the light sport aircraft to transition from snow to a dry surface without any changes to the landing gear. The specification is presented in Table 5.

3.2.2 Unmanned seaplane

However, in the last decade, with the development of unmanned aerial systems, unmanned seaplanes have appeared as a new type of vehicle, such as Sea Scout, Gull 2, and Flying Fish [18]. Unmanned seaplanes can achieve autonomous take-off and landing on water. Although they lack the inherent directional constraints of an arrow runway, cameras are widely used in various circumstances, including surveillance and inspection, sea-borne medical assistance, environmental monitoring, and more. Aquatic UAVs have recently become a hot topic for surveillance, environmental monitoring, and other maritime missions. For the first time, in 2002, NASA fielded an amphibious UAV. The program successfully built an unmanned seaplane and autonomous take-off, waypoint following, and landing from land and water environments. A seaplane with autonomous capabilities could incorporate a landing site as a strategic waypoint in a longer unattended mission profile. The flexibility to continue the mission beyond flight also allows onboard resources that would otherwise be dedicated to flight activities to be reallocated to further mission objectives. The landed UAS can direct most of its computing, power, and storage resources to data collection, processing tasks, and flight and mission planning. In addition, a seaplane UAS equipped with energy harvesting technologies, such as solar or wave energy collection, could effectively self-refresh before landing on a new mission objective. They proposed a comprehensive set of system and environmental models that can be used to assess and optimize the performance of an energy-harvesting unmanned seaplane in 2011. Then, I designed and built an autonomous unmanned seaplane for persistent ocean surveillance equipped with a solar power system and an autonomous control and guidance system. Then, an autonomous control system for an unmanned seaplane has emerged in recent years – a fuselage for an amphibious UAV in 2016. Examples of unmanned seaplanes are the phase I Flying Fish and the phase II Flying Fish. Phase I of the Flying Fish project was completed in just 8 months. Two air vehicles were developed and field-tested during the project, demonstrating robust, self-managed, autonomous take-off, flight, and landing from open ocean and inland lakes. During live field tests, the Phase II Flying Fish demonstrated solar-energy recovery, autonomous charging, and sequential self-initiated autonomous flight operations.

However, there are some unavoidable problems, especially when unmanned seaplanes launch. An unstable coupling between the heave and pitch degrees of freedom characterizes the motion known as porpoising. This type of motion can cause damage to the aircraft's equipment and fuselage structure. This can lead to the overturning of these seaplanes. In addition, it remains an intractable problem to deal with hydrodynamic interactions with the water surface and unpredictable random waves in high sea states. Because unmanned seaplanes often travel at higher speeds than conventional watercraft, they are more susceptible to rough sea waves, resulting in peculiar and violent motions such as jumping off the crests of waves and falling to the wave's surface. The inability of unmanned seaplanes to operate in severe weather conditions has hindered their development and deployment. In high sea states, unmanned

Table 5: Specification of the Lisa Akoya

Dimensions	
Wing span	11.00 m
Length	6.90 m
Height	2.35 m
Weights	
Empty	400 kg
Max. take-off	650 kg
Performance	
Stall speed	64 km/h
Cruise	210 km/h
Range	1,250 km

seaplanes encounter prominent sea wave influences and complex hydrodynamic impacts. As a result, it is tough to implement an autonomous take-off or landing where stability can be guaranteed only by adjusting the geometric parameters. To improve the seakeeping capability of unmanned seaplanes, the controllers need to ensure safety margins in common wave conditions and survivability in extreme wave conditions.

3.3 The obstacle of the seaplane industry

Over its historical course, the seaplane industry has faced numerous technological, economic, environmental, and regulatory obstacles. Seaplanes faced distinct technological challenges due to their intricate design, which necessitated a careful balancing act between hydrodynamics and aerodynamics. The limited engine efficiency of early seaplanes required developments to create engines that could meet the various requirements of air and water navigation. These technical nuances added to the early complexity of the operational and manufacturing issues. The infrastructure presented a significant obstacle because seaplanes needed specialized facilities like bases and water runways. The lack of infrastructure of this kind caused the restricted accessibility of seaplanes to areas with abundant water resources. Seaplanes' reliance on bodies of water for take-off and landing further limited their use and created barriers in areas where building water runways was not feasible. Operating costs were challenges for the seaplane business from an economic standpoint. The total cost-effectiveness of seaplane operations was impacted by maintenance, training, and infrastructure costs, as well as comparatively lower passenger capacities compared to land-based aircraft. The economic challenges were especially acute for short-distance lines, where high passenger volumes are essential for financial viability. Environmental and regulatory considerations played a pivotal role in shaping the trajectory of the seaplane industry. The environmental impact, including noise pollution issues and potential disturbances to marine ecosystems, prompted a need for sustainable practices and heightened regulatory scrutiny. Crafting regulatory frameworks that addressed the unique characteristics of water-based operations, ensured safety standards, and mitigated environmental concerns required a delicate balance. Seaplanes also faced fierce competition from developing and spreading adequate land-based transportation, such as air and road travel. The relative benefits of seaplanes, especially over shorter distances, decreased as airports and road networks expanded and were replaced by quicker and more convenient options. In addition, seaplanes showed a weather sensitivity that presented operational difficulties. Strong winds, waves, and storms are examples of unfavorable weather that can interfere with timetables and jeopardize the dependability of seaplane services, affecting efficiency and safety. The seaplane sector has survived these complex challenges by carving out specializations in tourism, specialized transportation, and niche uses where the benefits of operating on the water outweigh the drawbacks. The seaplane industry's future trajectory will be shaped by its ability to overcome hurdles and manage environmental and regulatory concerns through proactive measures, innovative infrastructure expansion, and ongoing technological innovation.

4 Seaplane operation and management

The seaplane possesses the qualities of both a ship and an aircraft, such as its ability to carry a large load, fly quickly, and hover over the water's surface. The seaplane has advanced considerably in recent years. However, because seaplane safety management combines two departments – maritime and aviation – safety management still needs a clear definition, and research on this topic is still in its early phases. In addition, there is a dearth of research that corresponds to the various stages of navigation safety in risk identification. Ultimately, a thorough examination of the seaplane's general concept revealed the necessity for improved safety management and the suggestion of other research avenues.

4.1 Strength, weakness, opportunity, and threat (SWOT)

This SWOT analysis aims to pinpoint the most critical external and internal elements that affect a seaplane's ability to operate. The next step is to separate the SWOT analysis into the two primary areas listed below:

(a) Internal factors: advantages and disadvantages of the specific mode of transportation.
(b) External factors: the chances and dangers that the outside world of seaplane operations presents.

The publication "European Aeronautics: A Vision for 2020" presents the idea of sustainability and positions it as the cornerstone of aviation's future, which is taken into consideration while analyzing the benefits and drawbacks of seaplane operations. EU Vision 2020 is a deliberate contemplation of what Europe must accomplish soon to emerge as a global leader in aviation rather than a strict timeline. Air travel must fulfill Vision 2020's ever-growing requirements for reduced prices, improved service quality, the highest levels of safety and environmental protection, and a system seamlessly connected with other transportation networks [6].

4.1.1 Strength

The opposition of environmental authorities to the alleged impact of seaplanes is one of the primary challenges facing the seaplane industry presently. The noise made by seaplanes landing, taxiing, and taking off noises, recognized as more significant than ambient noise, is the primary source of complaints. Animals are also believed to be impacted by the noise produced during takeoff, landing, and collision. One recent example is the ongoing conflict between the Trossachs National Park and Loch Lomond Sea Planes. Furthermore, as was already said, the resistance of environmental authorities is seen to be the most global barrier to seaplanes. This remark was likewise endorsed by 20% of European operators [19]. Worldwide, not much research has been done to evaluate the effects of seaplanes on the environment. The research conducted by Harbour Air Ireland by the US Army Corps of Engineers and Cronin Millar Consulting Engineers is likely the most thorough and objective one [20]. The findings of this study were as follows: no effect on wildlife, fisheries, soil, water, air, or hydrology. The carbon emissions from a seaplane are more significant than those from a boat. Nonetheless, this must be observed because significantly more boats than seaplanes fly through a particular location. Furthermore, it is vital to remember that the upcoming generation of propulsion systems – currently undergoing testing – will produce far less noise and carbon emissions. It should be highlighted that, in contrast to boats, seaplanes do not utilize hazardous antifouling coatings or release sewage or greasy bilge water. The explosive and volatile component MBTE (methyl tertiary butyl ether), which is found in boats, is not present in the gasoline now used in seaplanes, and the exhaust from these aircraft is released into the air, high above the water, having little effect on the water. In addition, because aircraft propellers are submerged, they do not harm marine life or sediments and generate very little waste from chemical toilets and effluent. Additional research has shown that seaplanes only produce a 3-inch wake and have little impact on the coastline's erosion. In addition, seaplanes have a negligible effect on noise pollution. Most noise is produced during take-off, when the seaplane needs to use a lot of engine power to become airborne.

4.1.2 Weakness

Seaplanes are currently considered an "endangered species," despite their undeniable potential that is prevented from being realized due to several issues. These issues are diverse and relate to several elements of the seaplane environment. Seaplane development is hindered greatly by the design aspect, which is connected to several other domains. The number of seaplanes in operation has decreased; there have been no new, cutting-edge designs; and the majority of seaplanes are nearing the end of their useful lives at the same time as more effective commercial aircraft designs have been unveiled. Because of this, the market now needs more contemporary and reasonably priced seaplanes. Seaplanes will have to operate under visual flight rules (VFR) due to the requirement for more creative designs and the application of modern technologies. They will render them inappropriate for bad weather or choppy waves. Moreover, some environmental concerns could soon alter the existing situation. As previously stated, Vision 2020 aims to reduce nitrogen oxide (NOx) emissions by 80% and carbon dioxide (CO_2) by 50%. Improved aerodynamic performance, along with new-generation engines and alternative fuels, must be considered to keep these values as low as feasible and reach the 2020 objectives. Finally, perhaps most significantly, the seaplane industry is constrained by the dearth of standard infrastructural equipment and the small number of seaplane bases. This implies that frequent maintenance and refilling need to be given careful thought.

4.1.3 Opportunity

Enhancing the operational efficiency of seaplanes is a major task, and the seaplane industry has several prospects. Suppose the sector can provide a distinct service to the huge commercial carriers by convenience, innovation, or economies of scale. In that case, it is logical to predict that demand will arise. However, a nascent industry lacks access to comprehensive market research and an awareness of current trends, which makes demand projection challenging.

The subsequent enumeration comprises many pivotal attributes that may be taken into account to furnish dependable novel prospects for seaplanes:

(a) Simple application in regions with a high concentration of islands and/or water resources.

(b) Faster service than ferries for connecting island or mainland locations, as well as the capacity to depart precisely from sizable inland cities, benefit specific commuter groups on their frequent journeys.
(c) An unusual transportation experience, particularly for visitors. Transport with prompt dispatch.
(d) Travel times can be reduced by avoiding the use of several modes of transportation or by realizing significant time savings when traveling by any land-based mode of transportation takes a long time.
(e) Bigger seaplanes less susceptible to weather and water conditions have more seats and a more excellent range.

4.1.4 Threat

A few challenges must be resolved before seaplanes may truly take flight. This section will highlight the main risks to seaplane operations today and the essential problems that need to be solved.
(a) Difficult airport access (car and rail transport substitution is complex due to challenging airport access).
(b) The adoption of seaplane transportation may be impacted by the public's opinion of light aircraft safety. It should be mentioned, nonetheless, that the air accidents investigation branch reports that there has not been a single accident reported in the United Kingdom. This is partially due to the historically low number of seaplane operations in the United Kingdom.
(c) Acceptance by the public and environment.
(d) Time constraints for flights. Certain rules need to be loosened to better support seaplane operations and make them more financially viable without sacrificing safety requirements.

Table 6 summarizes the aforementioned analysis of strengths, weaknesses, opportunities, and threats.

4.2 Seaplane safety management

The primary uses for seaplanes are the military, maritime patrol, forest firefighting, rescue, and other uses. Seaplanes have been on the global market for more than 80 years. They are in style in the Maldives, Australia, Canada, and the United States. The seaplane belongs to private persons. Greater privatization is occurring in the United States [20]. Seaplanes are utilized for inter-Maldivian island transportation. In Canada and Australia, seaplanes have been utilized for fixed-route passenger transportation. A seaplane is controlled similarly to a ship operating in mooring and navigation waters. In the air, nevertheless, it is operated similarly to an airplane. China's civil seaplane market is just getting started. However, two departments, maritime and aviation, related to the overseeing functional cross of the Maritime Organization [21] and Civil Aviation Organization, are involved in the safety management of seaplanes. The Hainan Maritime Bureau, which researches seaplane maritime safety management, was also in charge of the maritime supervision of seaplanes. It is situated in

Table 6: SWOT analysis of managing and operating seaplanes

Strength	Weakness	Opportunities	Threats
(a) Can reach challenging places (b) Flexible and versatile type of transportation (c) Links from point to point (d) Very few occurrences involving take-off, landing, or boat crashes (e) No infrastructure is required for runways, landing strips are "unprepared," and landing fees are less than for landplanes	(a) Seaplane design has not experienced any notable advances compared to contemporary commercial aircraft (b) There is a dearth of affordable, contemporary seaplanes (c) Because seaplanes must operate under VFR, they are inappropriate in inclement weather or choppy waters (d) Upcoming environmental restrictions, such as those limiting CO_2 and NOx emissions	(a) Simple use in areas with a large number of islands and abundant water resources (b) Unusual transportation experience, particularly for visitors (c) Transport with prompt dispatch (d) Bigger seaplanes are less susceptible to weather and water conditions, have more seats, and have a longer range (e) Air freight services: Due to increased competition, air transport cargo	(a) Potentially challenging airport accessibility (it is complicated to replace cars and trains as modes of transportation in this situation due to the challenging airport accessibility) (b) Approval from environmental and population activists (c) Fly time restrictions (d) The procedure for new seaplane certification (e) Resistance to corrosion (f) Seaplanes continue to rely too heavily on the weather

Sanya City, Hainan province. There are several scholarly studies on the safety management of seaplanes, with a focus on simulation modeling of diverse port traffic between ships and seaplanes and collision risk variables.

4.2.1 The generic seaplane

The International Maritime Organization (IMO) has approved a generic ship model for ship safety management that was created following the IMO's Interim Guidelines [22]. The pertinent UK MCA study on high-speed passenger craft and the ongoing research on high-speed ships, cruise ships, and containers offer valuable insights for creating a general framework for controlling ship safety. Creating a generic seaplane model that considers how they land, take-off, and navigate in seas resembling ships. They also incorporate the IMO's expertise in ship safety management. The general seaplane comprises all the operational, technological, engineering, and environmental networks that interact with one another while being transported; it is not a particular kind of watercraft. Thus, the generic seaplane can take the form shown in Figure 1. This generic model can be broken down into its component levels. While other generics will be the subject of additional discussion, these primary generic components – takeoff/landing, mooring stability, construction, and aircraft function – will be addressed in more detail.

Seaplane ports and terminals are unlike container and bulk terminals in terms of basic arrangement and structure. Container ports can load and discharge at the same time. However, in terms of passenger capacity and on-site amenities, seaplane ports and passenger terminals are comparable. A seaplane's chance of taking off or landing on the water increases when it gets closer to hydraulic facilities like terminals, channels, moorings, and bridges. In addition, there is a higher chance of collisions close to streams with intricate traffic patterns or erratic water activity.

The larger area set aside for seaplane take-off and landing has to be clear of other vessels during these operations. Control of the landing and take-off waters and on-site warning are essential. Because of their unique nature, seaplane activities require approval from the Air Force towers and airport control. Seaplane operations heavily rely on the Departments of Civil Aviation and Marine Administration. During taxiing, take-off, and landing, unclear water markings and regions can significantly impact seaplane navigation and localization.

Because a seaplane combines aspects of a ship and an aircraft, its pilots must possess a certain level of flight and navigational knowledge and expertise. This covers understanding the 1972 International Regulations for Preventing Collisions at Sea, fundamental water traffic safety information, and marine pollution control techniques. Pilots operating seaplanes must also possess certification for driving on land and in the water. Pilots must prioritize aircraft security, skill, and working circumstances to guarantee safe navigation.

In contrast to managing marine ports, managing seaplane terminals involves staff participating in passenger boarding and docking operations. Management staff will need to supervise communications and monitoring in the heliport area to guarantee the safety of seaplanes. One kind of vehicle that can land on water is the seaplane. It may be used in the field of marine supervision. Seaplane management should be increased by civil aviation departments and competent maritime authorities to guarantee safe operation. Improving management laws and clearly defining whose entity is in charge of seaplane safety

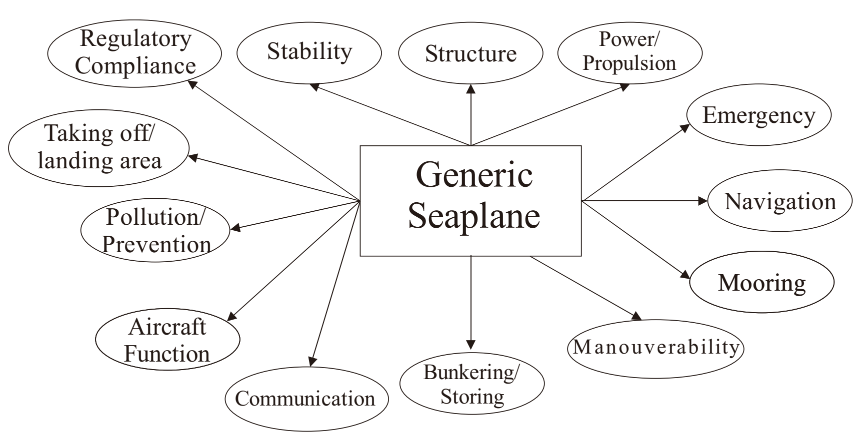


Figure 1: Generic seaplane components (redrawn based on data in Guo *et al.* [23]).

management is crucial. Furthermore, safety guidelines and standards for the operation of seaplanes in aquatic situations must be clarified, and research on seaplanes in water still has to be enhanced.

4.3 Seaplane traffic and operations

The global economy has grown significantly in recent years. There have been significant national economies engaged. Transport vehicles, computer technology, and telecommunications have all increased. In this instance, transportation, particularly that of airplanes, has been crucial to the growth of the world economy. People can travel to farther locations more swiftly and safely if they depend more on air transportation [24]. Air travel is growing faster than both rail and motorized land vehicles combined. Seaplanes, though, operate differently. From an economic perspective as opposed to a technical one, a few variables have led to the decrease in the use of seaplanes. Seaplanes must abide by both aviation and water rules when operating on water. Some of these rules must be established more firmly in Europe, particularly in the United Kingdom. Another drawback to seaplane operation is moving between the air and the water. The most significant obstacle for a novice seaplane operator, according to an experienced pilot, is persuading the authorities that lax restrictions prohibiting seaplane operation are unnecessary, particularly concerning the exact landing and maneuvering zones required for safe seaplane operations. To increase traffic and operations, it is necessary to have seaplane facilities that are sophisticated, modern, and convenient. Funding for appropriate seaports will come from public or private sources. Still, as seaplanes are not a top priority in the transportation industry, there is a lack of trust in investing [25]. Seaplanes can supplement large airlines, but they cannot compete with them. They may provide more pathways to isolated locations unreachable by land. A project named Future Seaplane Traffic (FUSETRA) has been established in Europe to examine and resolve the issues that modern amphibians and seaplanes confront. An online survey was developed and distributed to them globally to determine what common interests that seaplane operators have. It was determined that the following subjects would be interesting:

(a) Overview of Seaplane Operators
(b) Operational Concerns
(c) Pilots, Rules, and Certification
(d) Aircraft and Infrastructure
(e) Broad concerns and remarks on the seaplane transport system's potential growth.

In North America, seaplane travel is quite common, particularly in Canada, because of the region's many bodies of water and the isolation of many significant locations. Seaplane facilities do not have to be elaborate buildings that cost money. Simple jetties, floating docks, little beach ramps, and mooring buoys and boats might all be used to satisfy the criteria for a seaplane operation facility. To name a few issues, there are now operational, regulatory, social, infrastructural, and operational hurdles. In conclusion, the following are a few reasons why seaplane use has decreased:

(a) During WWII, landings on water runways became less spectacular than landings on land-based runways, which increased in quantity and length.
(b) Unused land planes and concrete runways on defunct military bases were left behind after WWII. Thus, future carriers may acquire these landplanes from the military at a reduced cost.
(c) Engine performance and design improvements allowed land-based aircraft to go farther and faster.

5 Floater design

Seaplane design necessitates an understanding of both boat and aircraft technologies. It has to have enough structural support for both air and water performance, good aerodynamic qualities that might impact flight performance, strong water take-off and landing characteristics, and acceptable hydrostatic stability. This study aimed to provide a different conceptual approach to developing cutting-edge seaplanes. The novel approach blends traditional amphibious aircraft design techniques with vintage seaplane design principles from the early phases of seaplane development. Modern amphibious aircraft design codes produce the geometry and performance data of the aircraft from a set of necessary inputs. The code gives the designer the most freedom in choosing the aircraft's configuration. This study suggests using contemporary empirical methods based on conventional empirical equations to enhance the performance of this sophisticated seaplane design.

5.1 Water operation design

Because of their exceptional capacity to take off and land on water, seaplanes, also known as amphibious aircraft, have been used for military and recreational purposes for many years. Their adaptability distinguishes them from

conventional fixed-wing aircraft. Customary seaplanes have the following disadvantages:
(a) The vast, wet surface area generates hydrodynamic drag during planing.
(b) Limitations on the weight and size of floating gears may cause stability problems.
(c) Water spray can cause obstructions. Hence, forms that are specifically made to deflect it are needed.
(d) Poor performance in solid gusts and waves makes sailing smoothly in adverse circumstances difficult.
(e) In places with limited space, the ability to move in the water might sometimes be a deciding issue.

The majority of the points mentioned earlier concern seaplane water handling. The way the seaplane manages water must be thoroughly investigated for the design. It is essential to make improvements without sacrificing other requirements. The study examined the benefits and drawbacks of the earlier designs. The benefits of the previous designs are included in the current one, and recommendations to mitigate the drawbacks were explored until an appropriate resolution was discovered. It is essential to remember that naval architecture terminology is the main focus of the study of water operation design for seaplanes. This contains the following terms: trim angle, keel angle, stern post angle, forebody, after body, and beam. A brief definition of these concepts will be given in this text.

5.2 Hydrodynamic shape characteristics

Similar form features between floats and airplane hulls influence aerodynamic and hydrodynamic design. Consequently, buoyancy is achieved by making sure the hull's volume shifts enough water to sustain the aircraft's weight. The designer must guarantee that the CG's interaction with the hull's metacentric height creates a moment of restoration [26]. Figure 2 displays a few factors that primarily influence the seaplane's hydrodynamic properties. The normal and parallel contact hull dimensions simplify the hydrodynamic forces. Furthermore, supplementary force elements, such as propeller thrust, generate forward ship forces and are influenced by the trim angle.

Seaplane hulls and floats are crucial parts of the aircraft. They offer stability and buoyancy for activities on the water. As shown in Figure 3, the beam is the most extensive part of the float as a floater width mark. The beam is frequently regarded as the primary design reference parameter and plays a critical role in establishing these floating structures' overall performance and characteristics. According to the literature review, the beam is frequently utilized as the design reference parameter for seaplane hulls and flotation devices.

The buoyancy requirement dictates the beam's breadth and cargo-holding capacity. Hull loading is measured using the beam load coefficient, which is based on the beam as a characteristic dimension and affects performance in the following ways.

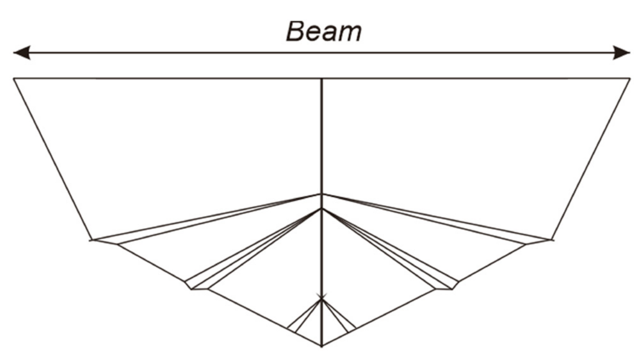


Figure 3: A beam of the conventional boat.

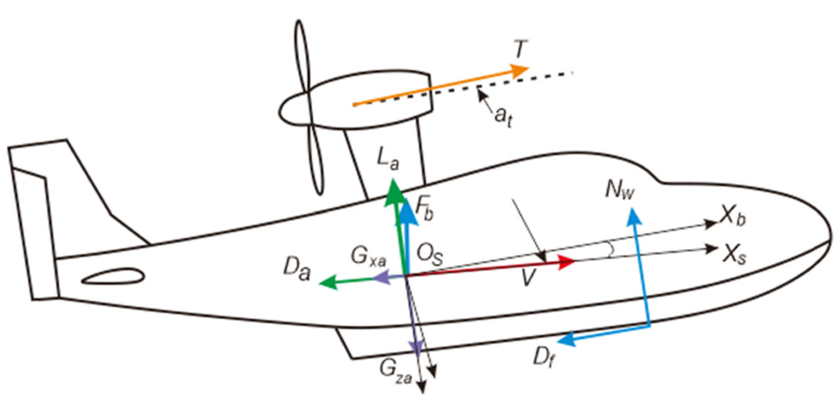


Figure 2: Hydrodynamic forces acting on a seaplane (redrawn based on data in Du *et al.* [27]).

(a) Stability's upper and lower trim limits are raised.
(b) Spray rises and maneuverability falls.

The breadth of a seaplane's beam influences its stability in static and dynamic flight conditions. A broader beam makes the seaplane more resistant to pitching or rolling movements, which usually leads to improved initial stability. On the other hand, an overly broad beam may make the ship less maneuverable and more vulnerable to lateral pressures like wind and waves.

An aircraft's hull or float's length-to-beam ratio affects its drag and resistance. A thin hull offers benefits in drag and structural weight since it can sustain more weight with the same resistance as a shorter or broader hull. A thin hull offers benefits in drag and structural weight since it can sustain more weight with the same resistance as a shorter or broader hull. Thus, optimal performance is required when choosing a hull with a balanced length-to-beam ratio. Thin hulls, with a more excellent length-to-beam ratio, provide several advantages for aerodynamics and structural elements. The foremost benefit lies in reduced drag, as a slender hull generates less resistance through the air and water. This feature is handy for flying boats since their streamlined hulls increase overall speed and fuel economy [28]. A slimmer hull also facilitates effective weight distribution, which increases cargo capacity without degrading performance. This also has a favorable effect on the aircraft's structural weight since a longer, narrower hull requires less material to give the required strength than a shorter, wider hull. This factor is essential for maximizing the weight-to-lift ratio of the aircraft as a whole, which enhances fuel economy and operational adaptability. However, the aerodynamic drag increases together with the hull's beam width.

The angle of a boat's hull bottom in a cross section is known as deadrise. Boats with flatter hulls have lower deadrise angles, whereas boats with greater deadrise angles have more V-hulls. The deadrise angle impacts a boat's performance in many ways. Steeper deadrise angles are often linked to improved handling in stormy water because they enable the boat to cut through waves and lessen the effect of rough seas [29].
(a) There is minimal impact on humping resistance when deadrise is increased between 15 and 30 degrees.
(b) The resistance rises when the speed surpasses the hump speed.
(c) At design speed, the joyful trim moment increases.
(d) The stability's lower trim limit rises as the deadrise angle does.
(e) Effect loading is much diminished.

The angle formed by the boat's hull bottom and a horizontal plane is called the deadrise angle (Figure 4), and it significantly impacts hydrodynamic efficiency. A V-shaped hull, typically the consequence of a sharper deadrise angle, reduces drag, increases fuel economy, and speeds the boat through waves more effectively. In harsh seas when wave action is expected, a greater deadrise angle typically results in a V-shaped hull, which allows the boat to cut through waves more effectively, lowering resistance and drag and improving fuel economy and faster speeds [30].

According to research, landing stability will be enhanced by raising the deadrise from 20 to 25 degrees. Subsequent research validates that the impact loads are the primary factor the deadrise angle influences. As the deadrise angle increases, impact loads drop. But when the deadrise angle rises, the hull's bottom stops being a functional design element. The hull will encounter more significant frictional drag and ride more profoundly in the water. The planning area is where this influence is most noticeable.

Seaworthiness and take-off speed are invariably compromised when choosing an aircraft's bottom design. In calmer waters, a flat bottom enables a quicker take-off, but in rougher seas, wave slamming can create significant buffeting, which can slow down the aircraft's take-off compared to a sharp-bottom design that rides the waves instead of cutting through them. An amphibious aircraft that has a flat-bottomed hull is not suited for littoral operations since it will smash into turbulent water. The double concave design is preferred because it combines the benefits of the blunt and sharp "V" shapes. It offers a straight edge for effective water entrance and wave cutting and a level surface for planning. In addition to reducing stress and the possibility that spray may reach the engines, the double concave directs water down and away from the fuselage and wings. The double concave bottom is the best of both worlds since it offers all the advantages of the double concave plus more it accelerates and begins to plane, for example. Water resistance decreases with the increasing speed as it emerges from the water and is sustained on progressively lower scallops [31]. The hull's twin-scalloped bottoms are positioned in the front and back,

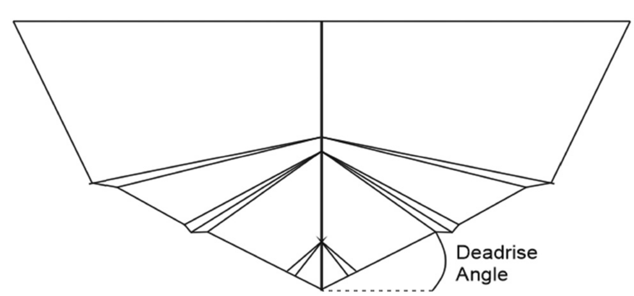


Figure 4: Deadrise angle.

respectively, with the former chosen for its capacity to cut through the water and minimize drag and spray. A variety of boat V-hull bottom types are displayed in Figure 5. The surface of an unflared hull bottom is flatter and more superficial, whereas points form the surface of a flared hull bottom.

5.3 Hydrodynamic characteristics of prismatic planning surfaces

Researching the hydrodynamic properties of planning surfaces before seaplane design is necessary. Planning commences when the fuselage's center of gravity is elevated above the average height, and it is still floating. The dynamic response of the hull to the water will determine how a planning surface is designed. A WIG boat is subject to two distinct forms of compressive pressures on its hull. The hydrostatic (buoyancy) force is the first. The weight of the water that the body has displaced is equal to the hydrostatic force operating on it, whether it is partially or entirely submerged in water, according to Archimedes' principle. For seaplanes, total hydrodynamic pressure drag comes in two varieties. The first is pressure drag, caused by the water pressure working against the fuselage's tilt. The second is the viscous drag, which is caused by the friction in the liquid and operates at a tangent to the hull's bottom. The second force is the hydrodynamic force, which is related to the square of the speed and is dependent on the fluid flow around the hull. Various operating modes for seaplanes are available based on their position and speed. The following explanation applies to the operational modes:

(a) The seaplane can be regarded as a displacement hull (movement through the water by the displacement of the water) with low Froude numbers $Fn < 0.4$. The vessel is impacted by hydrostatic and hydrodynamic forces in this range. This area's hydrostatic (restoring) force is greater than the hydrodynamic forces (added mass and damping).
(b) The seaplane enters the gliding phase, in which it starts to rise and glide on the upper portion of the water's surface at a higher Froude number ($0.4 < Fn < 1.0$). Both hydrodynamic and hydrostatic forces are acting on the vessel in this instance, with the hydrostatic force being less strong. Furthermore, aerodynamic forces will also exert an impact on the boat.
(c) The seaplane emerges from the water and is entirely in the air, only affected by aerodynamic forces when the Froude number $Fn > 1.0$.

Figure 6 depicts the center of hydrostatic pressure for the buoyancy force and the center of hydrodynamic pressure for the dynamic forces. The buoyancy and dynamic pressure are the compressive forces acting on the hull's surface when the seaplane is hydroplaning. Every force on the hull has a different center of pressure dependent on things like mass, weight, force arm, *etc.*

5.4 Hull model

Most seaplane designs are created as twin floats or boat hulls with wing tip stabilizers to operate on the water [32]. Due to the wide fore and aft hull body, boat hull seaplanes are less likely than twin floats to experience longitudinal stability problems. Lateral stability problems are also less common in boat hull seaplanes. Because of its placement beneath the center of gravity, the metacenter occasionally experiences a drop in height. Floats at the tips of the wings

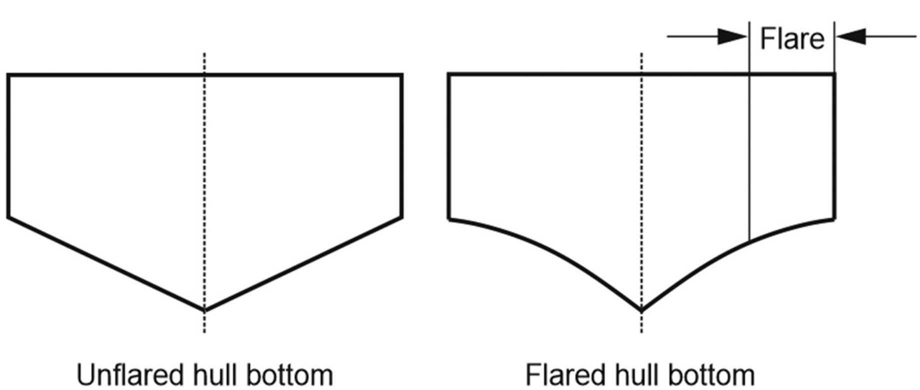


Figure 5: Different kinds of boat hull bottoms (redrawn based on data in Gudmundsson [26]).

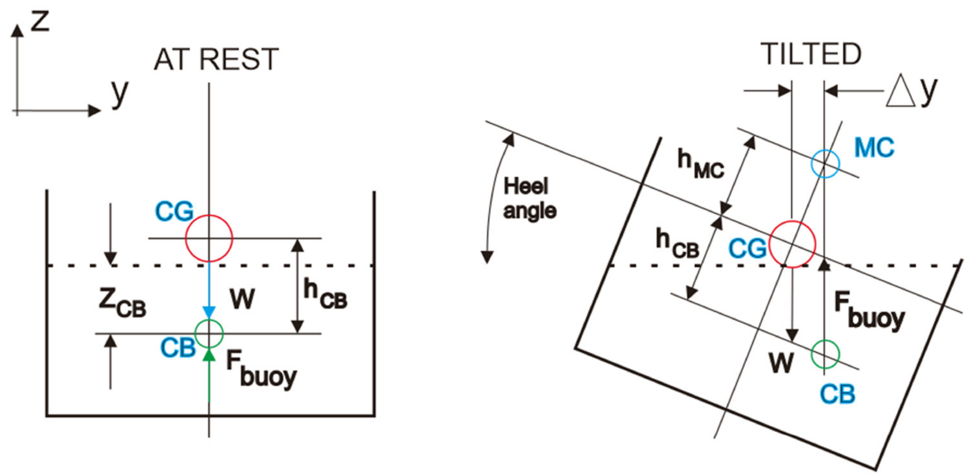


Figure 6: Centre of hydrodynamic and hydrostatic pressures (redrawn based on data in Gudmundsson [26]).

may balance the ship and counteract heel turns. As weight increases, the aircraft's center of gravity moves downward concerning the metacenter. Because of this, the seaplane has sufficient stability. Boat hulls' uneven shape is a significant disadvantage since it increases aerodynamic drag. An attempt to reduce this drag has involved examining the effects of altering the length-to-width ratio of the hull. The hydrodynamics of the hull did not alter, with wind tunnel tests showing that a drop of 29% in the lowest drag coefficient was obtained when the beam ratio was raised from 6 to 15. Other tests substituted a retractable planing flap for a fixed step on a hull or a float. The step is the sudden break in the lower line between the fore and aft hulls. Stepping the water away from the hull causes the drag to decrease and helps with planning and improving longitudinal control. When the retractable step depth was changed during and after take-off, performance benefits of 8% in water resistance and 2–3% in total drag were seen. The impact of waves on the fuselage's resistance to take-off has been the subject of additional testing [33]. The more significant drag resulting from the longer wetted length of the beam may be connected to factors that enhance the seaplane's resistance during take-off. Essentially, to have adequate water performance, the seaplane hull needs to fulfill the following requirements:

(a) Has to float.
(b) Achieve both dynamic and static stability.
(c) The suction force between the water and the hull must be fought to provide hydrodynamic lift through the water.
(d) Planning and taxiing-related hydrodynamic resistances need to be avoided or reduced.

The features of a boat hull are often shared by a float design. The longitudinal stability is one way that a float and a boat hull vary from one another. When the nose of the float is inclined downward at around one-third of its take-off speed, floats tend to lose their longitudinal stability. Suction over the longitudinal stability is shown by the area of most significant curvature, often seen around the front of the float. Porpoising oscillations might still occur from instability brought on by inadequate damping, even if the float could be rendered longitudinally stable by restoring the moment [34]. A seaplane may experience porpoising, a dynamic instability, as it takes off or lands and travels over the water on the step. It happens when the angle formed by the seaplane's float or fuselage and the water's surface is greater than or equal to the upper or lower bound of the angle formed by the aircraft's bank. Two kinds of porpoising exist. One way to fight the first kind is to impart a constant load on the horizontal tail. As a result, the airplane will swiftly alter its trim angle to "pass" the porpoise. The only way to counterbalance the second is to provide alternating upward and downward loads to the tailplane, which would not offset the surfaces. Even yet, this only works occasionally. Numerous concepts were put forth and examined in search of potential technological fixes. The goal was to lower the expenses of research, manufacturing, and operation for the advanced seaplane design. Retractable floats, inflatable floats, hydrofoils, water engines, foldable wings, advanced composites, reverse engines, multiple hulls, and more were among the concepts considered. One benefit of inflatable floats is that they will lessen drag. On the other hand, controlling and stabilizing the seaplane while it is in the water is the main issue with inflatable floats. When taxiing in the port, water thrusters can help the aircraft move in the water. However, once the aircraft is airborne, water thrusters become ineffective and can add weight to the payload. When flying a seaplane on the water, its wings can be folded back. This lessens the environmental impact and improves accessibility to maintenance facilities and seaports. A seaplane can operate in a variety of weather situations with the use of navigational aids. A hydrofoil is a foil that works on water. It is a piece of equipment attached to the side or bottom of a boat's hull that looks like wings. Its purpose is to reduce the water resistance of the hull and elevate the boat out of the water. A boat can use a hydrofoil to generate lift beneath the water's surface, whereas an airplane can use an airfoil. Hydrofoils' primary benefit is their ability to reduce hydrodynamic drag. A watercraft fitted with a hydrofoil rises above the water as it accelerates. It "flies" across the surface, to put it simply. This idea differs from hydroplanes, which create lift at high speeds by forcing water downward through a specially built-hull [35]. The hydrofoils and part of the propulsion system stay in the water when the boat is moving quickly. The hydrodynamic drag is massively reduced because most boats are no longer in the water. In fluid mechanics, this is known as "reducing the wetted surface area." When it comes to watercraft, the idea is obvious. Hydrofoils can achieve greater speeds than traditional hull boats by lowering the water's drag.

5.4.1 Trimaran

Multihull boats have become a popular alternative to traditional boat designs because of their great carrying capacity, stability, speed, and resistance to strong waves. Furthermore, in the case of multihulls, the resistance also depends on the waves' interaction. Compared to hulls with infinite spacing, there is a 20% increase in drag [36]. A trimaran is a multihull boat consisting of a primary hull joined to two smaller outer hulls by means of lateral struts. In a trimaran, 90–95% of the boat's buoyancy comes from the middle hull. The hull is thin and long. Next, the so-called amas, or outer hulls, offer stability. The hull design may be pretty flexible with this configuration. Due to the significant distance between the hulls, the trimaran can be kept stable with only a modest amount of buoyancy in the amas (refer to Figure 7). For this reason, the amas of many trimarans are rarely seen in the water. Due to the significant distance between the hulls, the trimaran can be kept stable with only a modest amount of buoyancy in the amas. For this reason, the amas of many trimarans are rarely seen in the water. Trimarans have the following benefits:

(a) Its narrow ship hulls provide little wave resistance at high speeds.
(b) Better stability can be attributed to the proper arrangement of the side floats. In times of high sea, a trimaran can sustain a fast speed.
(c) The main hull and outrigger wave interference can provide a positive wave interference that maximizes the connection between necessary engine power and speed. Even if the outriggers or the hull sustains significant damage in an emergency, the all-float construction stays afloat.

The stability of trimarans is higher. This is due to how the hulls are arranged, which balances the boat by giving each center of buoyancy a righting moment around the center of gravity. As a result, both the boat and the seaplane perform better on the water in large waves and have more stability when rolling and docking. Another benefit is the cross-deck layout connecting the main hull and the amas. This transverse deck fills up a sizable vacant space on a catamaran. The Trimaran stability beam model is shown in Figure 8. Engineers oppose significant gaps in the design since they make it harder to use and necessitate the incorporation of more essential elements. More substantial structures add weight and cost. However, the trimaran's transverse deck is much smaller. Because longitudinal bending does not extend the boat's length, it necessitates a smaller space between the hulls and poses less of an issue for the transverse deck.

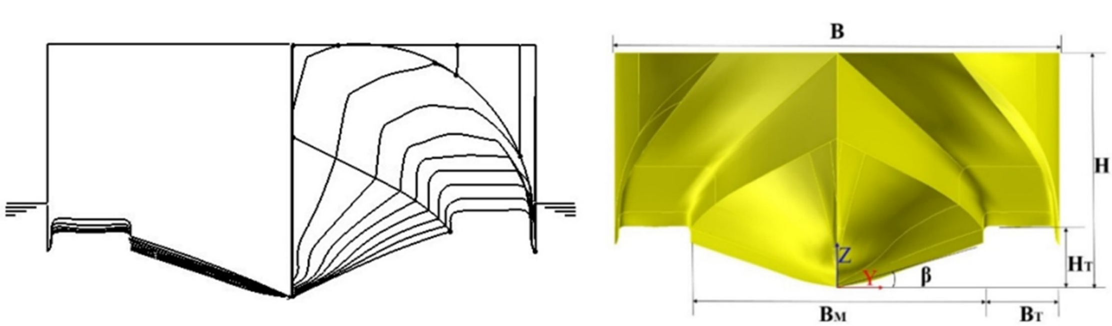


Figure 7: Trimaran hull design [37].

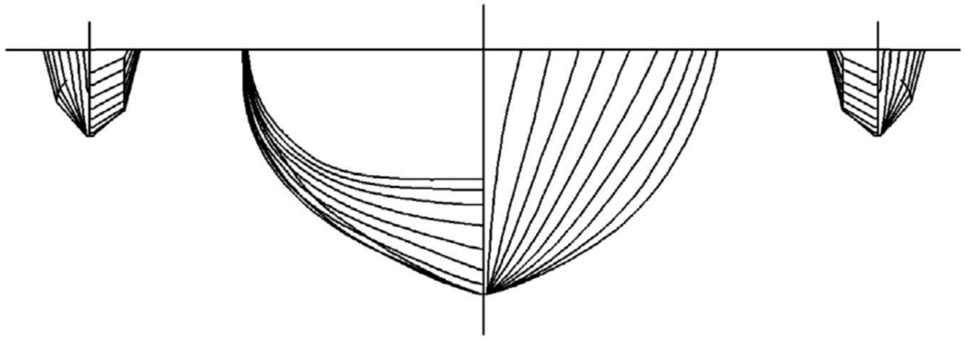


Figure 8: Trimaran stability beam model [38].

Wave performance is an additional crucial factor that has to be examined. The performance of a seaplane needs to be maintained in all kinds of weather and water situations. In a traditional float, a wave travels through the bow and creates lift, which pulls the stern down. The center of buoyancy of the float moves with the wave as it travels through its body. The lifting force pushes the bow down when the wave strikes the stern. A dangerous pitch effect in choppy conditions at high speeds might sink the bow and cause a serious capsize. Outriggers may work in a wider variety of rough sea conditions than typical floats because their lack of buoyancy minimizes the lifting force that causes the wave's crest to tilt toward the stern. As shown in Figure 9, earlier research on trimarans has demonstrated that their wave resistance is far less than that of a comparable catamaran. Compared to the monohull and catamaran, the red line represents a trimaran with the slightest resistance to the Froude number ratio. The trimaran should theoretically perform better in this situation in terms of seakeeping.

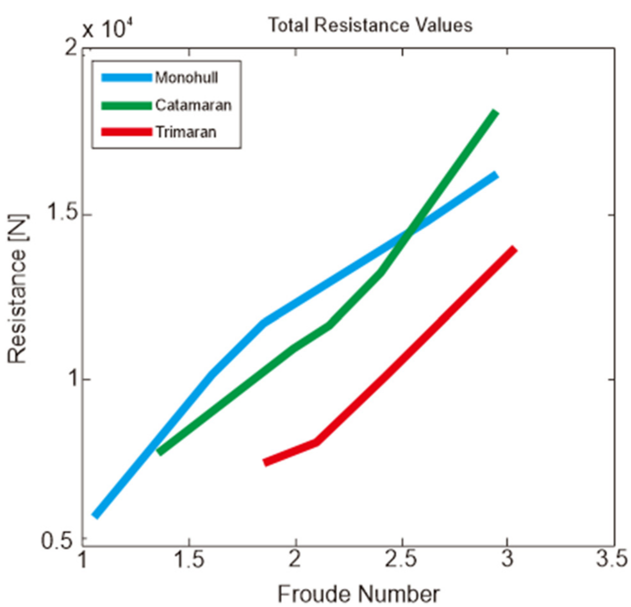


Figure 9: Resistance comparison curves (redrawn based on Bertorello *et al.*'s data [39]).

5.4.2 Outrigger design

The trimaran's overall drag can be reduced by the arrangement and design of the outriggers, as shown in Figure 10. A perfectly designed trimaran has an outrigger that is half the length and has 4% of the displacement of the main hull. The positions of the outriggers about the main hull are quantified in terms of the stagger, or the lateral displacement of the outrigger about the main hull, and the clearance, or the longitudinal displacement of the outrigger's centerline from the hull's centerline [40].

The results show that a small value of outrigger transverse spacing often produces a small heave amplitude RAO when traveling in head sea waves. In addition, if the outriggers are placed at the bow part of the main hull when Fn = 0.4, it will often result in a smaller amplitude of motion. This article provides an optimization method for trimaran outrigger layout by combining the 2.5D method with NSGA-II. The results verify that no specific layout allows minimum motion at forward speed trimarans. The results show that determining the optimal trimaran outrigger layout depends typically on the sailing speed and the incident waves. For regular wave conditions, when a trimaran is traveling in head-sea waves, for Fn = 0.4, the recommended outrigger layout is a/L = 0.640, p/L = 0.067; for Fn = 0.5, the recommended outrigger layout is a/L = 0.199, p/L = 0.087. Alternatively for a trimaran traveling in oblique waves (wave heading α = 135°), for Fn = 0.4, the recommended outrigger layout is a/L = 0.639, p/L = 0.141. For Fn = 0.5, the recommended outrigger layout is a/L = 0.619, p/L = 0.067. For irregular wave conditions, when Fn = 0.4, the recommended outrigger layout is

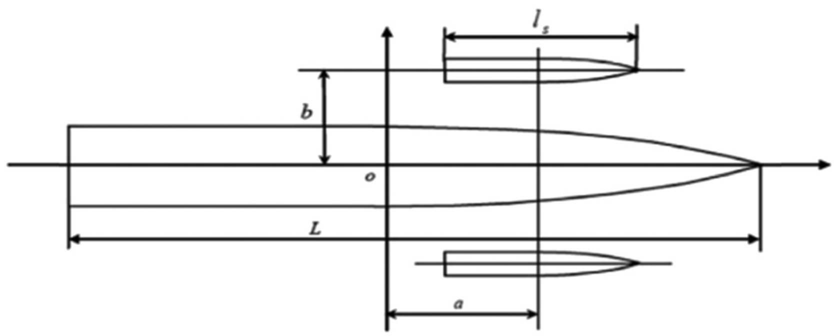


Figure 10: Trimaran tagger and clearance [41].

a/L = 0.5864, p/L = 0.0675; for Fn = 0.5, the recommended outrigger layout is a/L = 0.5625, p/L = 0.0715 [42].

5.5 Types of hydrofoils

Hydrofoil boats come in various configurations, as shown in Figure 11. Designs can be divided into two main categories – surface piercing and fully submerged. Surface piercing designs, with their U-shaped foils, have the advantage of built-in stability when pitching and rolling. If a surface-piercing hydrofoil pitches to the right, for instance, the increased submerged area will produce a more significant lift, which will cause the boat's pitch to shift back to the left. In contrast, in fully submerged hydrofoil designs, it is always below the water surface. These designs rely on automatic systems to actively control the angle of attack of the hydrofoil to maintain stability. However, as a bonus, with the foils fully submerged, these designs are the least likely to be affected by choppy conditions on the surface.

The number of hydrofoils on an aircraft is a significant factor when determining its weight and stability in an early design. Because the hydrofoils provide lift throughout the water take-off and reduce the wetted fuselage area, the LISA Akoya's configuration appears to eliminate the complicated fuselage design considerations of stepped and planing configurations. Instead, more aerodynamic fuselages can be designed. We determine a number of performance-enhancing factors to help choose an appropriate hydrofoil profile. These requirements include a high lift-to-drag ratio across the speed range when hull resistance predominates, and a low coefficient of hydrofoil drag over the whole takeoff speed range. As shown in Figure 12, a hydrofoil with a higher lift coefficient is preferred since the hydrofoil area will decrease. The hydrofoil moment coefficient's rate of change concerning the angle of attack must be kept within the range of the hull trim angle to guarantee stability. Furthermore, it is crucial to consider the center of gravity and its separation from the hydrofoil.

The effectiveness of hydrofoils concerning their application in amphibious aircraft is evaluated in this section. First, we evaluate the aircraft's performance during water takeoff with and without hydrofoils. Figure 13 compares the impact on hull drag. It displays notable reductions in viscous resistance and minor decreases in fuselage wave resistance. These findings are consistent with the hydrofoil's ability to decrease submerged volume and wetted area by supporting the hull above the water's surface. When the hull achieves takeoff speed, the hydrofoils can

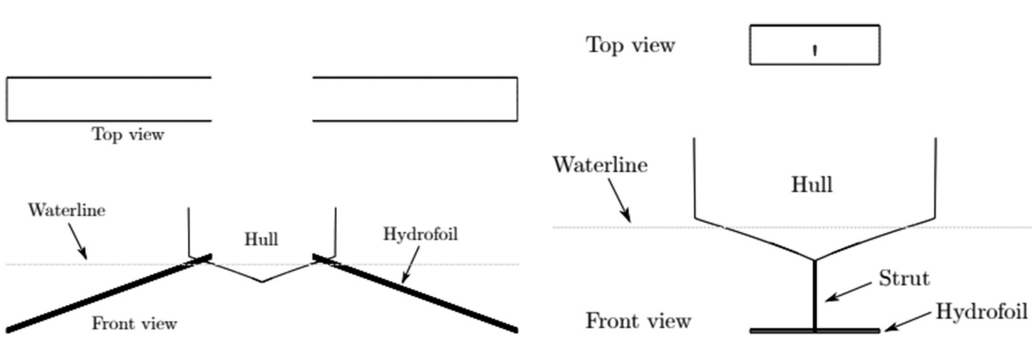


Figure 11: Hydrofoil configuration [43].

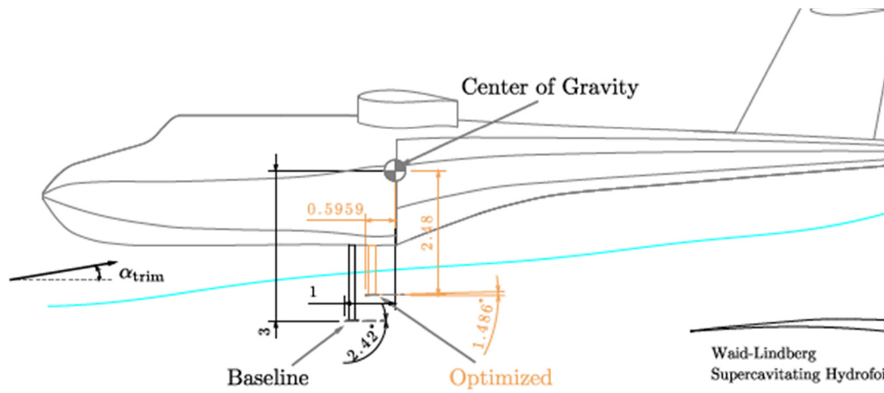


Figure 12: Hydrofoil drawing with baseline [43].

help raise it ultimately before this speed, but the arrangement with no hydrofoils shows that the hull is still partially submerged due to viscous drag. Figure 14 illustrates how the hydrofoil's lift decreases as the wing's lift increases when the aircraft travels slower than the necessary take-off speed. Despite a decline in hydrofoil lift toward the conclusion, the overall lift results for lift forces increased over time. In the meantime, the overall drag forces rose till the peak and then somewhat decreased toward the finish.

According to the outcomes of the water-take-off operation, the hydrofoil successfully reduced hull drag and buoyancy load, which were the specified objectives. This case study proved that the hydrofoil successfully enhanced the efficiency and performance of amphibious aircraft during water takeoff by reducing the water takeoff distance. Nevertheless, our findings demonstrated that, with the proper tuning, the addition of hydrofoils might provide a performance boost. This finding further demonstrated the necessity for creating an all-encompassing design framework for amphibious aircraft and the advantages of including optimization in design studies. According to the optimization findings, the minimum water take-off distance was nondifferentiable and multimodal concerning the span and angle of incidence as design variables. These factors depend on the hydrofoil profile. Even though it was not as complicated as other design problems, minimizing stabilizer forces was nevertheless crucial. Regarding amphibious aircraft operations, namely, water landings, our study is the first to assess hydrofoil performance thoroughly. Thanks to its modular architecture, the framework may be easily upgraded to incorporate more accurate aerodynamic, hydrodynamic, and propulsion models.

5.6 Retractable float system

The fact that the floats will be exposed when in flight is one issue with using a trimaran. The aerodynamic drag can

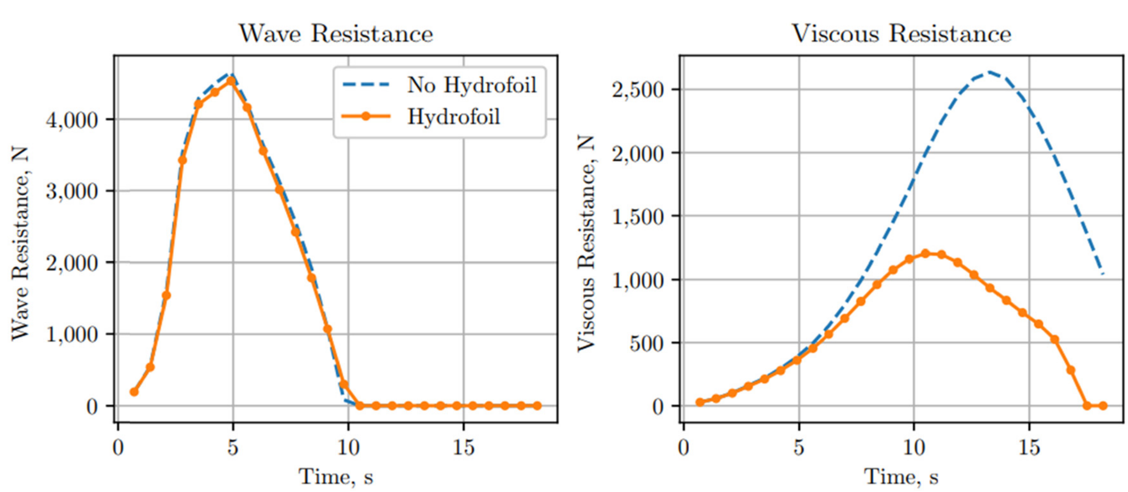


Figure 13: Hull resistance comparisons with and without the hydrofoil [43].

theoretically be decreased by retracting the floats or mounting them within the hull or fuselage. Tigerfish Aviation is the company behind retractable amphibious pontoon technology, which involves the utilization of retractable pontoons. The pontoons may be retracted to create a single component linked to the hull and fuselage in an adaption of the same design idea. This will lower the aerodynamic drag by reducing the drag caused by the interference factor that the floats and boat hull add. But if the floats are pulled back to this position, the floats' aerodynamic drag will be partially eliminated. Putting the floats within the hull is a last resort. Retraction of the floats into the hull occurs in the same manner as that of the landing gear [44]. The need for extra structural support is the sole drawback. This indicates that the struts' weight has increased. Retaining the seaplane's stability was another benefit of the retractable float system for this design. It is possible to automate the retract mechanism. This allows the seaplane to be controlled during unexpected heel turns. The automatic retraction mechanism is set up to keep the seaplane in the water where one float goes up toward the waterline and the other float drops down if the aircraft leans to one side. The two floats stay at the water's edge. If the seaplane flips over, the automatic retraction mechanism is set up to keep the craft in the water, with one float moving up near the waterline and the other moving down. At the waterline, both floats stay still. The analysis of all the concepts put forth resulted in a reduction in the number of technological solutions needed to fulfill the specifications of this future seaplane concept due to its complexity and high cost. The seaplane's trimaran hull and retractable floats were determined to perform well.

6 Hydrodynamics research

The capacity to travel through air and water has become a crucial aspect of transportation, particularly with the increasing necessity to access remote areas. Seaplanes are considered a highly relevant and effective means of transportation. Hydrodynamics, which encompasses lift, drag, and stability, is significant in designing an efficient and reliable seaplane. Seaplane hydrodynamics also includes various ocean components in its analysis. These include wind, waves, currents, and multiresource ocean energy devices [45]. Hydrodynamic analysis also extends to small seaplane properties such as bailers, which can have a significant effect [46]. However, this review will focus on developing hydrodynamics, particularly in seaplane hulls. Analyzing seaplane hydrodynamics is vital for optimizing operational efficiency, flight safety, and sustainability. Optimizing lifting force enhances flight performance and fuel efficiency while minimizing drag, contributing to environmental friendliness. Improved efficiency during take-off and landing reduces fuel consumption and environmental impact. Stability is crucial for balanced flight and landing operations, positively impacting operational ease and passenger experience. Seaplane designs considering lifting, drag, and stability directly contribute to minimizing carbon emissions and enhancing resource efficiency. Figure 15 is an example of hydrodynamics research with a simulation method. This approach minimizes human mistakes while providing flexibility in scenario setup and efficiency in research expenditures. The model, the setting, the dominant style, and the domain are typically included in the visualization outcome.

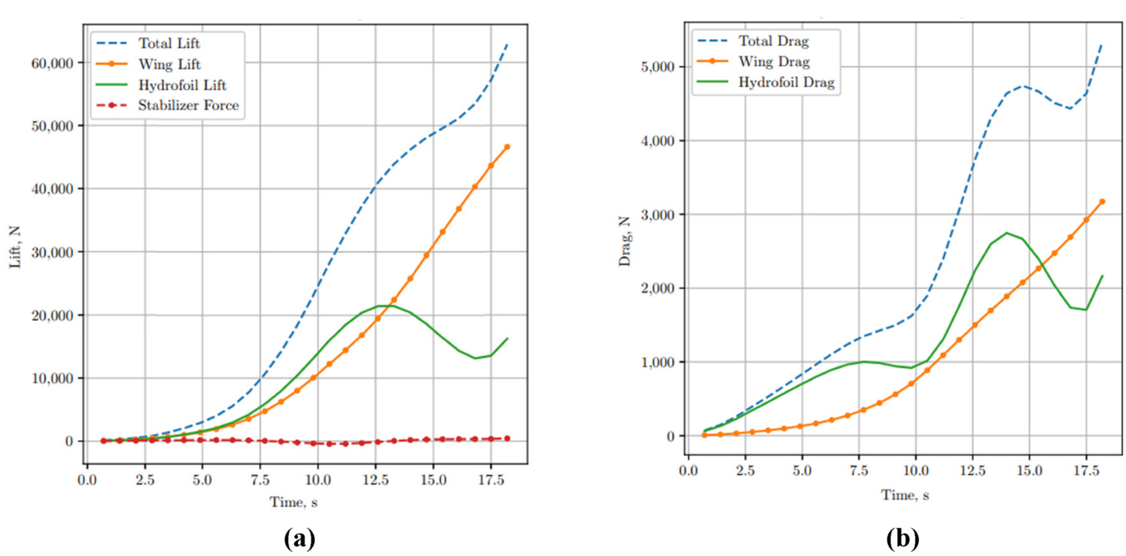


Figure 14: (a) Lift forces of components during water-take and (b) drag forces of components during the water-take-off process [43].

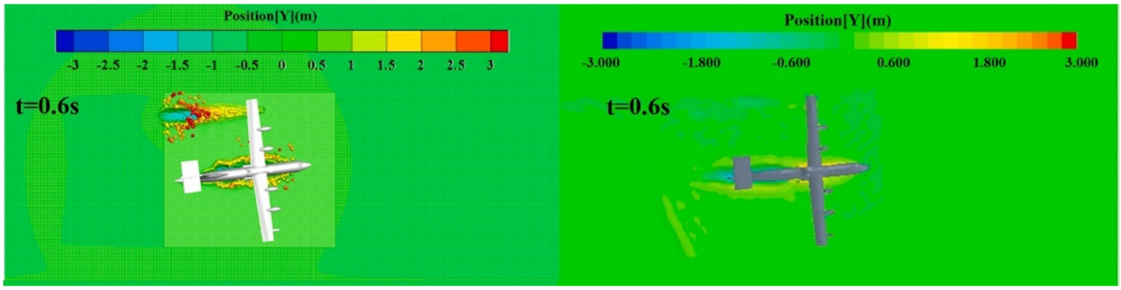


Figure 15: Simulation of seaplane's hydrodynamics [47].

Recent research in the hydrodynamics of seaplanes has provided significant insight into how hydrostructure relates to hydrodynamic design. This research has involved numerical simulations, physical experimentation, and the development of mathematical models to understand factors that influence lift, drag, and stability. In recent years, advancements in hydrodynamics technology have facilitated the exploration of seaplanes as a more efficient transportation option, particularly in areas with challenging topography. Therefore, it is crucial to have a comprehensive understanding of the interaction between seaplanes and water, including lifting, drag, and stability studies. This understanding is essential for environmental sustainability and developing a more inclusive transportation infrastructure.

This literature review focuses on understanding hydrodynamics, particularly lift, drag, and stability. Studies with at least 15 publications published between 2014 and 2024 were studied. The quantitative approach was used for publications that examined mathematics, simulation models, and statistics. The qualitative approach was used to examine the character or nature of the publication more subjectively. Furthermore, region or vehicle function is not limited to the analysis of these publications. The review wants to study the hydrodynamics of hydroplanes from different water characteristics and types of hydroplanes. Essentially, large-scale model measurements enable the conduct of a wide range of hydrodynamic tests, covering areas such as stability, affordability, resistance, propulsion, cavitation, maneuverability, seakeeping, and structural loads [48]. However, it is essential to note that testing with numerical and simulation methods can be more cost-effective and still provide accurate results. Therefore, this review will primarily focus on simulation-based research.

6.1 Lifting

This segment analyzes seaplane lift, a crucial aspect of flight performance. Understanding the factors influencing lift is essential for enhancing operational efficiency and flight safety. The review presents recent research results using mathematical modeling, physical experiments, and numerical simulations to identify the impact of design elements and operating conditions on seaplane performance. This analysis aims to pave the way for more innovative and hydrodynamically efficient watercraft designs. Uncontrollably porpoising is one of the riskiest conditions during seaplane take-off. The seaplane's pitch attitude and height may occasionally wobble as it gathers velocity during planning. This is known as "porpoising," brought on by an unstable hydrodynamic force that runs along the fuselage hull's longitudinal direction. When a seaplane experiences severe porpoising, it may experience uncontrollable pendulum motion and crash into the water again, perhaps causing structural damage or even capsizing. Furthermore, extreme puffing frequently results in lightheadedness and trembling in the pilot and crew [49].

Pitch angles, wave height, speed, and time are the characteristics that the simulated seaplane model uses to depict the outcomes. For waterplane planning on water surfaces, buoyancy, hydrodynamic lift, and hydrodynamic drag are all integrated into the dynamics model. During the stepped planning stage, the pitch attitude and height change from a sluggish oscillation to a divergent oscillation with a vast pitch attitude, ultimately resulting in uncontrollable porpoising as velocity increases. There are particular pitch and angle limitations for seaplane porpoising. When the velocity rises, these barriers usually get smaller. When a waterplane stalls and is flying on the water's surface with a pitch that might go over the limit, it can recover by slowing down. In addition, it offers a theoretical framework for identifying and managing launch and landing hazards for novel watercraft models [49]. In one investigation, a high-speed planning vessel's porpoising instability was prevented *via* a ventilated cavity. When moving on an unobstructed surface, a ship or a water plane cannot keep speeding up. This results from the challenge of maintaining dynamic balance while moving forward and matching the propulsion – one of the most dangerous issues when a ship or seaplane speeds is porpoising instability. When a vessel's pitch and heave are linked, porpoising happens. Due

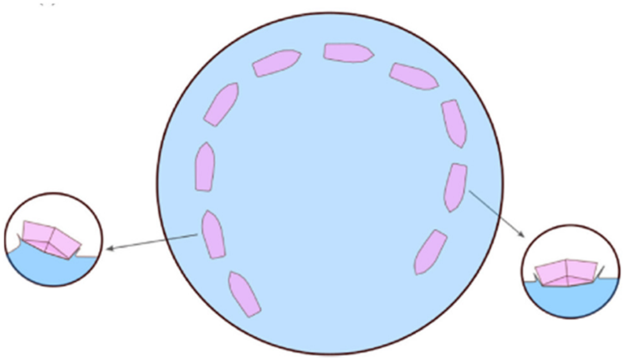


Figure 16: The concept of planning motions [50].

to this instability, the ship may jump out of the water or become submerged, possibly causing structural damage and putting the crew in danger. Despite the possible risks, the technical and academic community still needs to understand the issue entirely and has yet to find a solution. The stable planning regime (red backdrop) and the porpoise regime (red background) are divided by the small percentage of hydrodynamic lift in the overall lift (ε). The concept of planning motions can be seen in Figure 16. The hull will not roll significantly and will be flatter in one condition. On the other side, the hull may endure a more severe roll depending on the wave conditions.

In the original ship model (OSM) and the ventilated ship model (VSM) with ventilated cavities, the ratio of the dynamic displacement volume (ΔFr) to the displacement volume (Δ) at zero speed over Fr∇ was calculated (Figure 17). The ventilated model offers a higher (ΔFr/Δ) to Fr∇ ratio than the original model. The ventilated model reflects that the hull produces more significant hydrodynamic effects at higher speeds. The porpoise regime is shown in Figure 18. When ε is more than 0.8, the porpoising regime begins to occur; below 0.8, it falls into the stable regime, which can occur at any Fr_B value. The dashed arrow indicates the transformation of the OSM from the porpoise instability regime (red circle) to the planning ship model in the stability regime (gray circle). It was discovered in the reviewed work that decreasing the trim value causes the displacement volume to rise, which in turn causes the porpoising instability to disappear. The comparable displacement volume for VSM at high and ultra-high speeds is over 50% of that at zero speed, which is around five times the proportion observed in OSM. Therefore, the buoyancy in VSM produces a significant vertical force at high and extremely high speeds. The amplification of the hydrostatic lift lessens the impact of porpoising instability, which results from dynamic instability brought on by hydrodynamic pressure. As a result, even in the event of external disruptions, the spacecraft will swiftly reestablish its equilibrium and prevent a solid periodic alternation between restorative and inertial forces [52]. During take-off, a seaplane needs a lift force that creates waves that splash. Both mesh-based and particle-based numerical techniques can be used to study this phenomenon. The capacity of seaplanes to take-off and land on water surfaces distinguishes them from aircraft that are grounded. The smoothed particle hydrodynamics (SPH) approach is used in this work. The finite volume method (FVM) based on Euler's approach is contrasted with the results of the SPH method. The work uses Lagrangian modeling to mimic the taxiing procedure of seaplanes through numerical approaches. Drag and lift

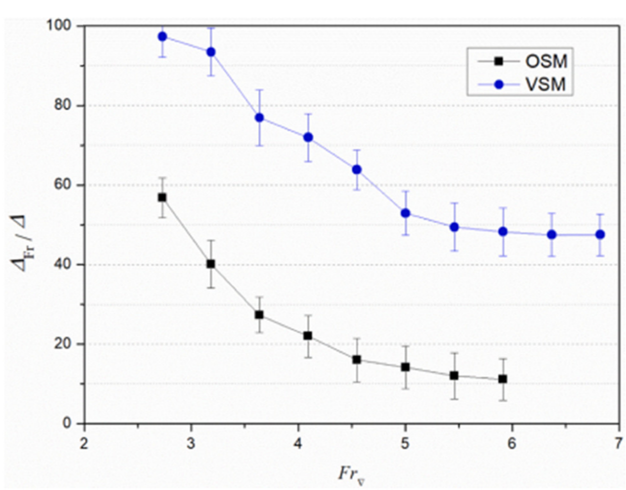


Figure 17: For both the OSM and the VSM with ventilated cavities, the ratio of the dynamic displacement volume (ΔFr) to the displacement volume (Δ) at zero speed over Fr∇ was calculated [51].

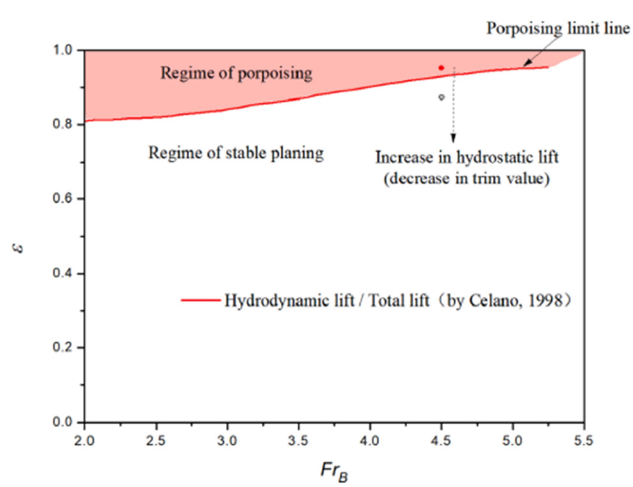


Figure 18: The porpoise regime (red background) and the stable planing regime are separated by the limited fraction of hydrodynamic lift in total lift (ε) from Celano in 1998 [51].

SPH results at a speed of 30 and 80 m/s are validated with FVM data, as shown in Figure 19. At high speeds, whether 30 or 80 m/s, the lift force is greater than the drag force, which is highly helpful for the seaplane's subsequent take-off. Both the seaplane's lift and drag rise with the taxiing speed. The SPH approach can record the peak FD between 0 s and 0.05 s at either 30 m/s or 80 m/s. Figure 20 compares the free surface splash results obtained from FVM and SPH. The two approaches yield remarkably similar findings when viewed macroscopically, with the SPH method producing results that are on par with commercial software regarding precision. The findings show that the SPH approach is very good at capturing the waves' splashing during taxiing and offers the same level of accuracy as the FVM [52].

6.2 Drag

This section focuses on analyzing the drag experienced by seaplanes – a critical aspect of hydrodynamics affecting flight efficiency and fuel consumption. Recent research findings, ranging from numerical simulations to physical experiments, are outlined, exploring factors such as aerodynamic design and fuselage shape. The main emphasis is discussing strategies to reduce drag, enhance fuel efficiency, and improve flight performance. A comprehensive understanding of seaplane drag contributes to developing more hydrodynamically efficient designs, promoting sustainability in the aviation industry. A decoupling model is used in a numerical method to examine the motion of the planned seaplane, as shown in Figure 21. According to the graphic, the most frequent drag region is located near the center of mass or COG. A common way to assess drag on a seaplane is to look at the hull's resistance to the water as it moves.

The cavity is the airflow pattern, as shown in Figure 22, and a range of speeds was used to replicate the two-phase flow surrounding the flying boat. The greatest resistance occurs when the seaplane speed is low, which is characterized by extensive water contact with the hull. As the velocity rose, the water eventually parted from the step,

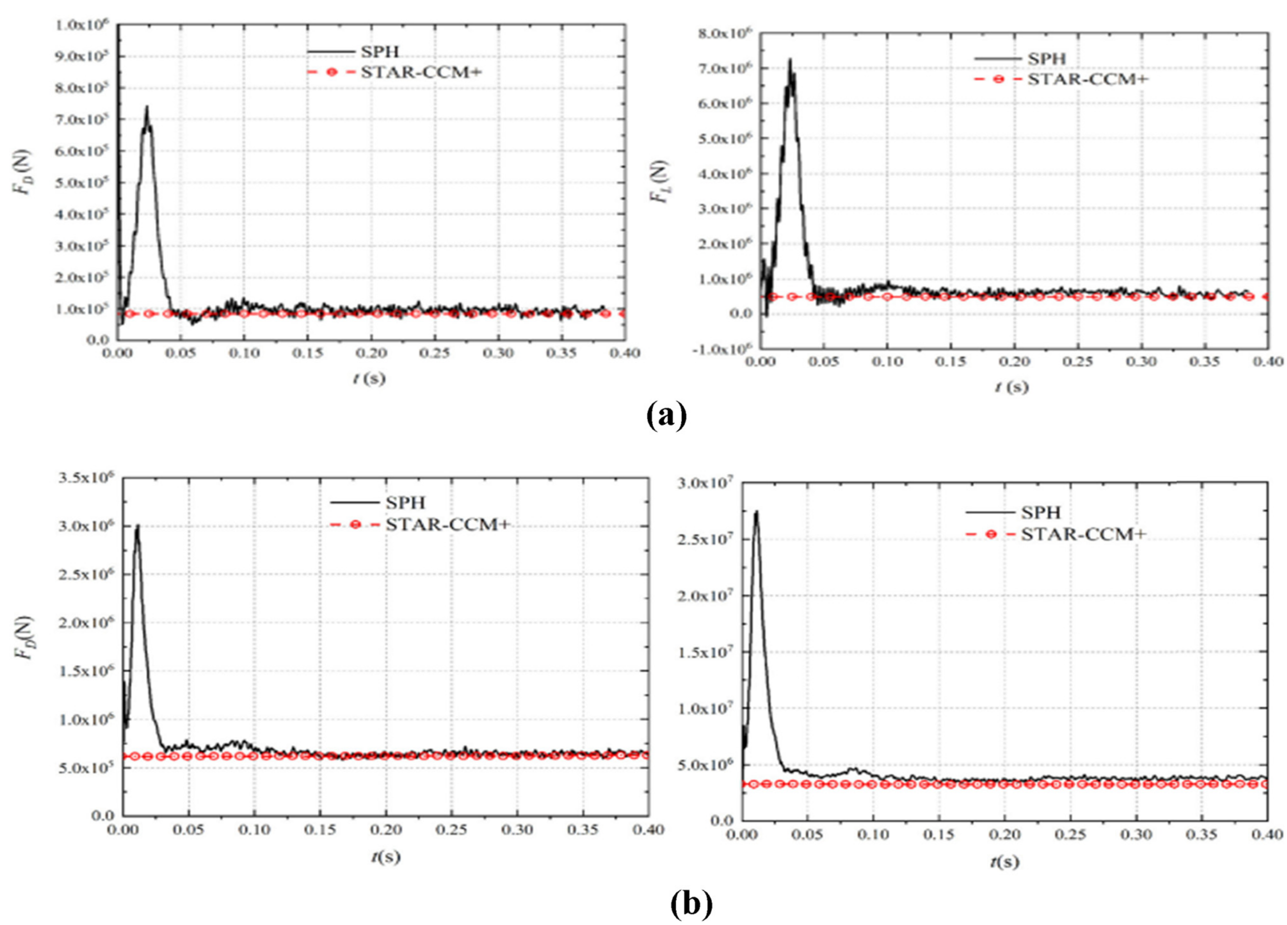


Figure 19: The SPH results of drag and lift force validated with FVM results with a speed of (a) 30 m/s and (b) 80 m/s [52].

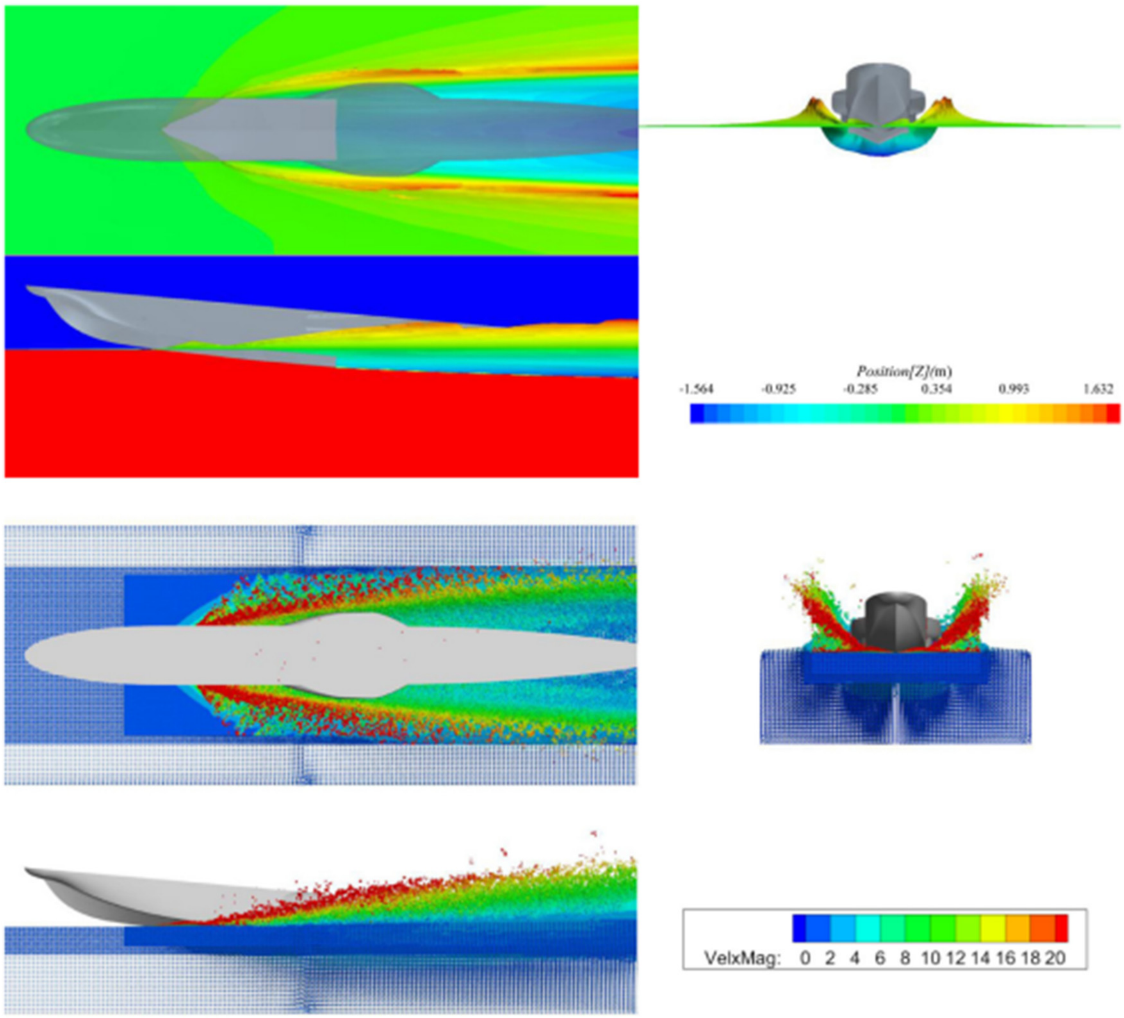


Figure 20: The comparison of the splashing of free-surface between (top) FVM and (bottom) SPH results [52].

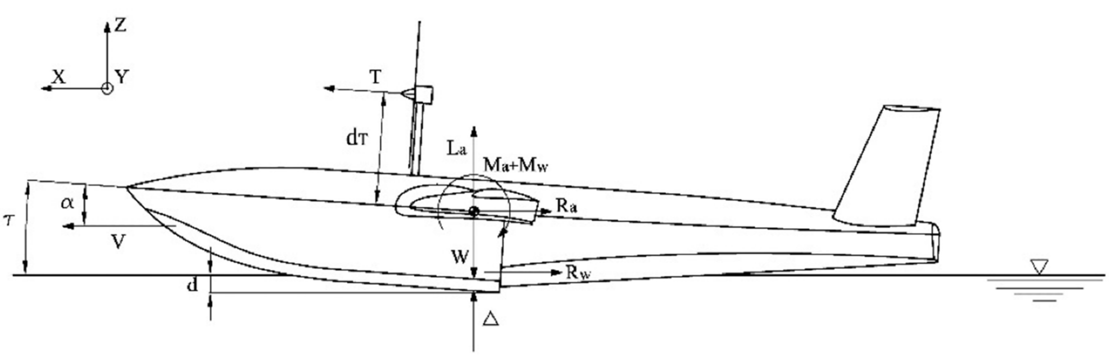


Figure 21: Sketch of hydrodynamic forces on the hull [53].

creating an air-filled hollow behind the step. Three steps make up the take-off process: pre-planning, planning, and displacement. The flying boat was functioning as a displacement vessel at very low speeds. The flying boat began pre-planning when the step was fully vented. Then, both the forebody and the afterbody of the flying boat were pre-planning. When the afterbody ultimately emerged from the water, the air cavity stretched quickly towards the

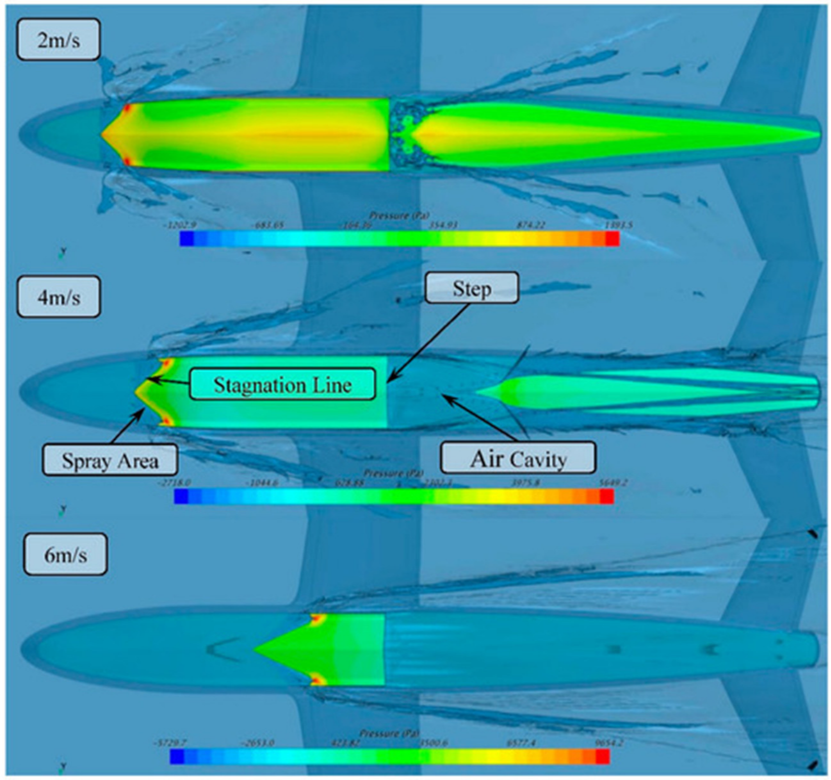


Figure 22: Inside the cavity is the airflow pattern at various speeds [53].

stern, signaling the start of the planning phase. The seaplane only used its forebody when it lifted off the water during the planning phase. The aerodynamic lift and pitching moment at high speeds would noticeably impact the hydrodynamic resistance, which is the primary factor in total resistance. According to the hydrodynamic study of the flying boat, the hydrodynamic pressure force acting on the afterbody during the preplanning phase may produce a forward component, which enhances the hydrodynamic [53]. Shape variations have reached extreme uniqueness in the advancement of modeling on seaplanes. Previous research has suggested that planar surfaces with a negative deadrise can produce a higher ratio of lift to drag than planar surfaces with a positive deadrise. The research model used is shown in Figure 23. Hulls with negative deadrise angles are unusual in the maritime world. However, more systematic experiments need to be conducted that vary deadrise while keeping all other parameters

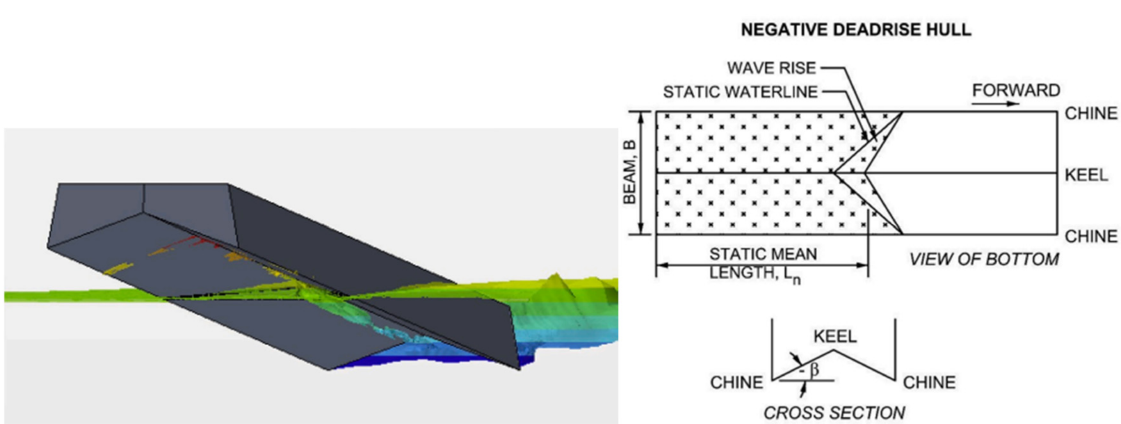


Figure 23: Used model for the experiment [54].

constant. This study simulates a fixed attitude model with varying deadrises using STAR-CCM+ computational fluid dynamics software [54].

Figure 24 illustrates the relationships between CD and different parameters. The drag coefficients drop at greater Froude numbers as the hydrostatic forces' contribution diminishes. This decrease is the result of normalizing by the square of the speed. The hydrodynamic force also becomes increasingly significant as the center of pressure moves forward with higher Froude numbers. The drag coefficients and the center of pressure rise with hull length because of the expanding submerged volume. The numerical results accord well with Savitsky's correlations despite the approximations inherent in empirical correlations, demonstrating the efficacy of the numerical approach for planning surfaces. Optimizing the construction and analysis of drag reduction for the Indonesian N219 Aircraft Catamaran Buoy is the subject of the following study. This research aims to reduce the drag of a pontoon buoy using a biomimetic-based design by mimicking the hydrodynamic characteristics of sailfish (*Istiophorus platypterus*). ANSYS Fluent will be used to determine the reduction in drag from the conventional design to the biomimetic design. Furthermore, the adaption design will be refined in light of deadrise angle dimensions, trimming tests, and clearance testing. The optimum design improvements reduce drag by thirty percent of the total drag created by the traditional design, according to the biomimetic adaptive design results [55]. The research shows a substantial difference in the resistance to float design between Wipeline® 13000 and the biomimicry adaption design, which uses the hydrodynamic properties of sailfish to reduce drag on the Indonesian N219 seaplane catamaran float. The sailfish design exhibits an 18.32% decrease in resistance. The trim analysis unveils varying total resistance values concerning trim adjustments and Froude numbers, with the biomimicry design featuring a 30° deadrise angle demonstrating the most effective resistance reduction. Furthermore, adjusting the clearance value (S/L) proves efficacious in altering the catamaran float's drag coefficient, and a negative interference factor signifies optimal conditions for reducing resistance [55].

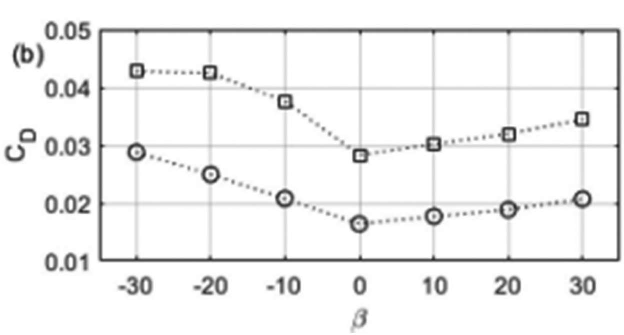


Figure 24: Hydrodynamic characteristics were calculated for hulls with variable deadrise at hull trim angle τ = 4° and beam Froude number Fr = 4. Squares represent hulls with Ln/B =4 results, and circles correspond to hulls with Ln/B =2 [54].

6.3 Stability

In amphibious aircraft design, achieving an optimal balance is crucial, considering factors like water stability, spray control, seaworthiness, aerodynamic and hydrodynamic performance, buoyancy, and ease of manufacturing and operation [40]. This section focuses on analyzing the stability of seaplanes, which is vital for maintaining balance during flight and water landings. The review synthesizes recent research contributions, including mathematical model development, hydrodynamic experiments, and practical assessments, to identify factors influencing stability. Analyzing design effects on stable performance aims to enhance watercraft safety and operational efficiency. The analytical methods used to predict the performance of seaplanes are used to improve hull stability. The aim is to study the different analytical methods for predicting seaplane performance to define each method's weaknesses and extend the analytical approach to include nonlinear (instability) terms. It was found that these approaches rely on different assumptions and reasoning. The procedures studied are the Savitsky procedure, the Morabito procedure, the central aero-hydrodynamic institute (CAHI) procedure, the Payne procedure, and the Shuford procedure. More specifically, the Savitsky method and the CAHI method will be the subject of discussion. The results of the Savitsky and CAHI methods, with particular emphasis on the stability limit of the porpoise, are compared in this section. CAHI predicts higher drag because it assumes that the wetted area increases as the deadrise angle increases. Also, Savitsky assumes a constant trim angle, while CAHI assumes a trim angle that increases with the angle of climb, explaining the higher trim angle of the Savitsky procedure [35]. The heave and pitch equations and the Savitsky method are used to study the stability against porpoising of planing hulls with a constant 10° deadrise. Analysis shows that higher deadrise increases stability, allowing larger trim angles without porpoising. The heave and pitch equations are predictive for higher speed regimes and lift coefficients, while the Savitsky method is appropriate for lower speed regimes and lower lift coefficients. The lift and pitch equations provide more accurate predictions over various conditions. Therefore, no analytical method is suitable for all types of seaplanes. Prediction depends on hull geometry and operating conditions [35]. The present study explores porpoising motion in high-speed seaplane planning over water numerically. A customized two-phase flow solver in OpenFOAM examines the porpoising phenomena, considering several complex real-world factors such as slipstream, ground effects, and hydrodynamic and aerodynamic forces. The sixDoFRigidBodyMotion and the actuator disk approach improve the interDyMFoam solver [56].

Hydrodynamic forces dominate pitching oscillation during porpoising, with aerodynamic moments as a supporting factor. The hydrodynamic force center is displaced to the front of the gravity center, which causes unstable oscillations to amplify continuously. Controlling the trim angle precisely is essential for water planning because elevator adjustment becomes difficult once porpoising starts in forebody mode. It is advised to reduce power to idle if porpoising has started to steady the seaplane as it settles into the water [56]. Testing a motion planning study in shale waters could improve it, as it was modified for aircraft stability research. The research employing the Cartesian grid finite difference method on the stability and gliding motion of amphibious aircraft in waves is then discussed. This research uses the CGFDM to analyze the wave resistance of amphibious aircraft during wave hovers. The wave condition affects the aircraft's vertical load and motion responsiveness. The aircraft's sharp increase in vertical load during complete hovering has the most significant effect on the front of the hull. When waves reach 1.38–2.76 times the length of the fuselage, they can induce jumping motion and lessen the stability of the aircraft's motion. Predicting aircraft behavior while in motion and avoiding dangerous water areas are two benefits of this research [57]. Figure 25 shows seaplane motion without jump action. In this scenario, the seaplane's fuselage is fully immersed in the water and continues to move in a planned manner but in choppy water. In this condition, the seaplane is more stable and safer because the impact of waves is still minimal. Meanwhile, Figure 26 shows a seaplane simulation with regular jump motion. In this type, the seaplane starts to face slamming by waves when the fuselage changes pitch and heave. The fuselage part is immersed more in the peak and downhill wave data. Figure 27 shows the irregular jump motion. This is the most extreme condition, as the variable wave conditions make it difficult to control the pitch and roll of the seaplane. The peak force can be anticipated to avoid loss of control or structural damage.

The distribution of conditions for the occurrence of a jump motion, the influence of mesh parameters on the numerical results being analyzed, and the reliability of the numerical simulation will be verified through comparison with model experiments. At various gliding speeds, lift and pitch amplitudes, and bow and rudder vertical overloads show a pattern that increases and decreases with wavelength. At the same planing speed, the amplitudes of heave and pitch and the vertical overload of the ship

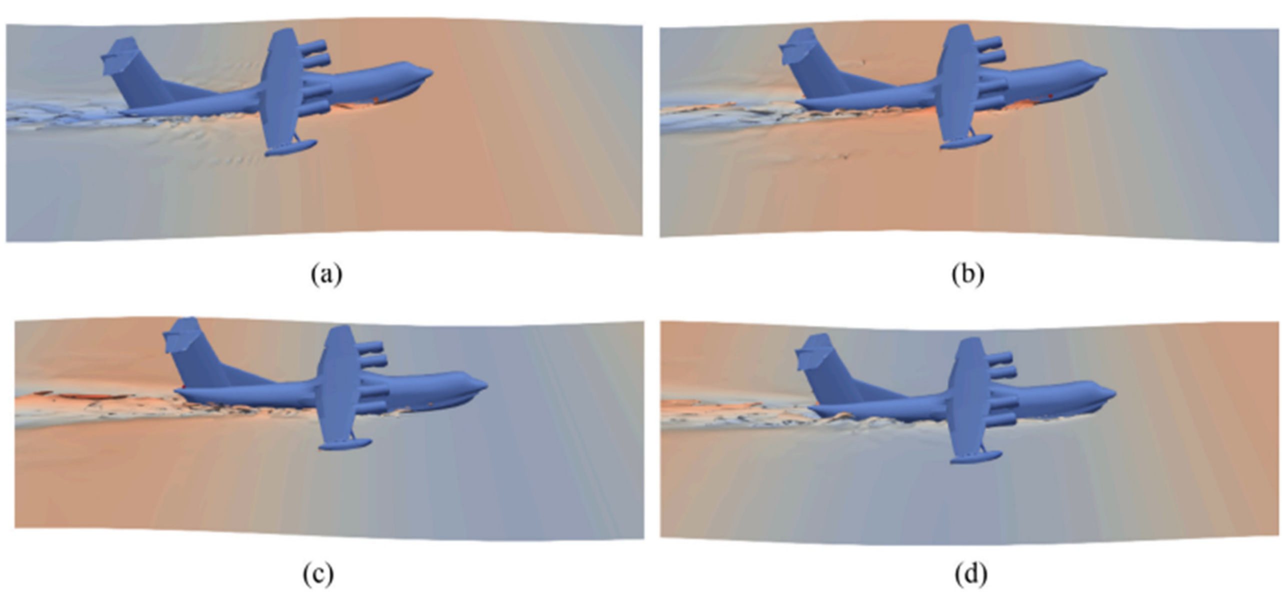


Figure 25: Simulation result for no jump action [57]. (a) The aircraft is on the uphill side of the wave. (b) The aircraft is at the wave peak. (c) The aircraft is on the downhill side of the wave. (d) The aircraft is in the wave trough.

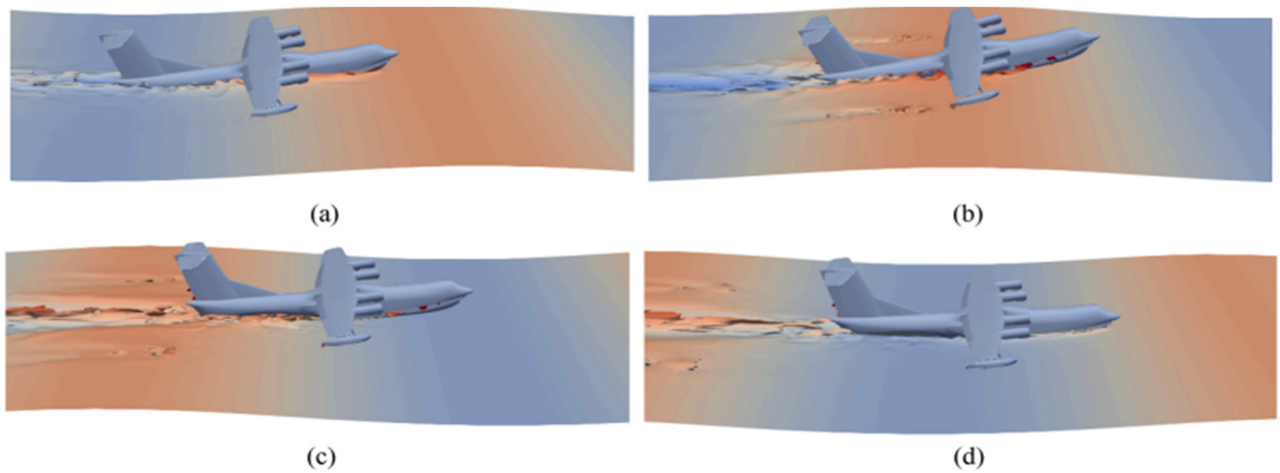


Figure 26: Simulation result for regular jump motion [57]. (a) The aircraft is on the uphill side of the wave. (b) The aircraft is at the wave peak. (c) The aircraft is on the downhill side of the wave. (d) The aircraft is in the wave trough.

increase with increasing wave height, showing an approximately linear relationship with wave height, and the linear relationship decreases with increasing speed.

6.4 Overall discussion

In the broad field of the hydrodynamics of seaplanes, a thorough study of the lift dynamics reveals the importance of ventilated cavities in mitigating the instability of splash waves, especially in high-speed planing vessels. Numerical studies using mesh-based and particle-based methods contribute to understanding the complex splash wave phenomena induced by seaplanes. In addition, the modeling and simulation of seaplane porpoising behavior enhances understanding of this dynamic aspect. Regarding drag, a great deal of information is available thanks to studies on negative deadrise planing surfaces and the hydrodynamic performance of single-hull seaplane models. Furthermore, optimization efforts in the biomimetic design serve as prime examples of strategic techniques to reduce drag in seaplane catamaran floats. Through the numerical analysis of porpoising motion and the planing motion and stability of amphibious aircraft in waves, the stability dimension offers essential insights into these intricate hydrodynamic phenomena. A systematic review of seaplane performance prediction analysis methods synthesizes different approaches in the literature, providing a comprehensive overview of

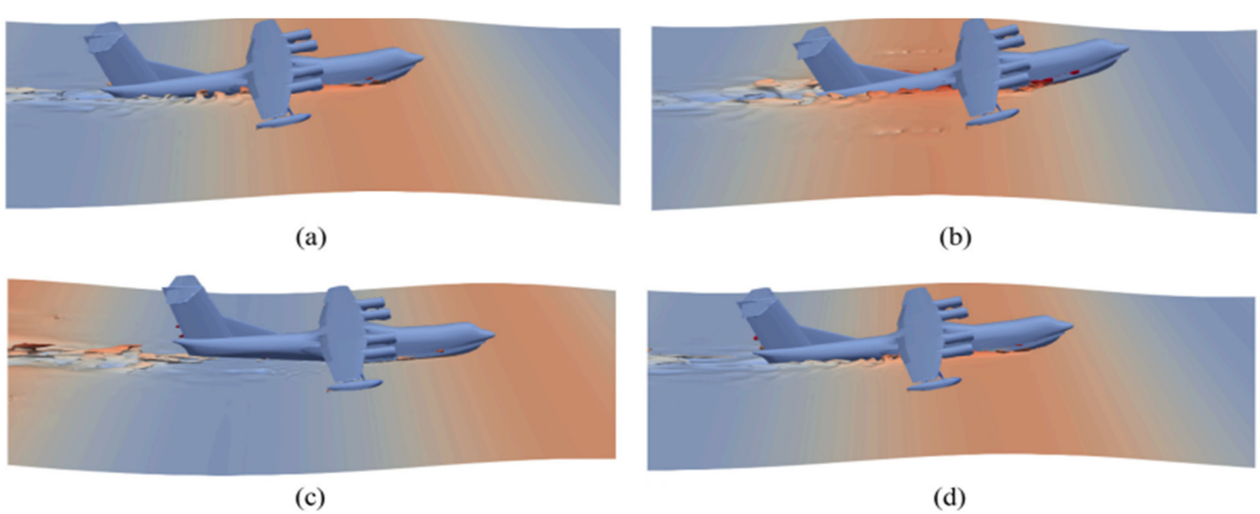


Figure 27: Simulation result for irregular jump motion [57]. (a) The aircraft is on the uphill side of the wave. (b) The aircraft is at the wave peak. (c) The aircraft is leaping over the whole trough area. (d) The aircraft enters the water at the second wave crest.

research trends. The comprehensive review highlights the progress of research in the field, ranging from fundamental concepts such as ventilated cavities to advanced numerical simulations. The synthesis of these findings provides an invaluable road map, guiding researchers through the nuanced and diverse world of the hydrodynamics of seaplanes, from earlier studies to current research efforts. More innovative models, such as VSM, an extension of OSM with numerical simulation methods such as SPH or FVM, are expected to be developed for seaplane hydrodynamic research. The seaplane will be studied to achieve hydrodynamic stability, especially during gliding, by studying the wave conditions and the geometry. Hydrodynamic phenomena will be exploited to achieve the best performance of the seaplane. These phenomena include air cavitation and porpoising (more phenomena are expected in the future). A significant focus will be the development of influence geometry in the design of water vehicles, which will be adapted to the changing needs of manned and unmanned water vehicles. This development makes it possible to carry out more complex studies, refining existing phenomena and discovering new aspects related to floatplane operation.

7 Seaplane positioning

The motion of these water-based aircraft has been extensively studied in seaplane development. The three crucial times they have identified are when a seaplane lands, takes off, and anchors. These stages are critical because they determine how seaplanes function and maintain stability and how the hull and floaters are designed. It is essential to comprehend seaplane motion to improve and secure their operation. For instance, the tourism industry needs a uniform landing and take-off procedure [20]. Recently, unmanned seaplanes have been developed, different from conventional seaplanes, as shown in Figure 28, as a mooring position. This gave rise to organizing seaplane positioning on a larger scale. Although seaplanes are currently a promising research scope, the current use of seaplanes still needs to be expanded to a small capacity. This is because seaplane motion analysis must examine two aspects of habitat: water and air, which is quite challenging to do, and research costs are expensive. An example is Ekranoplan, which is used for military purposes or transporting super large loads, but after take-off, it can only fly low, relying on the ground effect [58]. Research on seaplane positioning is expected to increase information on designing a reliable seaplane.

Figure 28: Unmanned seaplane in the floating position [59].

What scientists discover when they delve into these stages is crucial for advancing seaplane technology. It covers more ground than the plane's construction and performance in various water situations. This section summarizes the studies on seaplane mooring, take-off, and landing. In the following sections, we will explore how researchers examine each phase, the difficulties they encounter, and the novel ideas they generate. The goal is to truly grasp how all these factors might help seaplanes become even better. Finding and understanding the evolution of seaplane position, including mooring, take-off, and landing, is the primary objective of this literature study. Prior pertinent studies were evaluated using either a qualitative or quantitative technique, depending on the research strategy. At least 15 papers published 10 years ago were included in the research under assessment. The quantitative methodology assessed the works that focused on mathematical models, simulation, and statistical data. Conversely, the qualitative technique was employed to examine the subjective aspects of the articles. Furthermore, these activities are more than just looked at in terms of specific regions or aircraft roles. This is because the review aimed to comprehend seaplane positioning research through various approaches.

7.1 Mooring

Mooring on a seaplane refers to the position when the seaplane is not in motion and its position is kept from shifting far. Mooring is included in the scope of seaplane positions because all seaplanes must be able to float in calm seas. Seaplanes can moor anywhere provided the waters are not too shallow, not choppy and windy, and in an area that meets the requirements for take-off and landing. Mooring is generally done with the help of a buoy, a pier, or a dock, generally in the coastal zone. It is thought that coastline expansion that facilitates seaplane docking operations can further boost regional growth [60]. Much research has not been done on mooring as the primary focus in the recent 10 years compared to take-off and landing. Seaplane mooring is covered in research on position usage, safety, and access to innovative seaplanes. This might be accomplished by the hull alone or involve other gadgets. When there is adequate mooring capability, its utilization can be expanded. Seaplanes, which are expected to be a multipurpose mode of transportation, must also utilize their various capabilities, such as when mooring. Seaplane operational time is generally divided into active when flying and inactive when mooring. If it is further specialized, it will be rested during operational hours and at night. These two flight strategies are based on differences in the distribution of solar radiation energy. Seeing this pattern, the idea arose to maximize the use of solar panels. Energy balance models have been crafted for the proposed seaplane system when solar energy is harvested while mooring on the sea and missions are performed while flying in the sky [61]. Adaptation to the seaplane mooring also affects the shape or configuration of the seaplane body. There are times when the port for mooring a seaplane is less able to accommodate a seaplane, so arrangements are needed, such as on the wings. This research resulted in a prototype seaplane that can bend its wings when mooring. This capability has been adapted to the Seagull aircraft developed by Novotech, Italy. A seagull is a hybrid-electric aircraft with a main hull, two auxiliary floats, and a v-tail [62].

7.2 Landing

A landing process is required when a seaplane is about to descend from the air to the water. Landing a seaplane is a complex situation where gases, liquids, and solids interact in a way that could be more straightforward [63]. At present, many studies have discussed the seaplane landing phenomenon and how to analyze it. Model testing and engineering estimating techniques were used in the early examination of seaplane landing issues. One approach that is frequently utilized before moving on to numerical computations is the mathematical model. The usage of numerical techniques has increased dramatically in recent years, coinciding with the rise of intelligent computers. Software is used to carry out simulations to produce reliable findings. CFD-based software, including LS-DYNA and ABAQUS, is employed. Research that does not necessitate high testing expenditures typically merely advances to the simulation stage. Nonetheless, there are instances where using small-scale models for testing is required [64]. Experimental methods will provide accurate data and illustrate phenomena that CFD cannot provide [65].

Research on the landing motion is crucial to enhance the seaplane's performance during the transition to the water. A competent landing analysis can also take passenger comfort into account. Moreover, uncontrollable motion like ditching must be avoided to protect the seaplane's structure from harm. The coupled Euler-Lagrangian (CEL) approach, based on the fluid volume method for hydrodynamic implementation, can be used to load assess a seaplane with two floaters. The CEL is integrated into the ABAQUS dynamic solver to enable fluid modeling [66].

The finished model is tied to a structure adjusted for height, angle, and roll. The model is then dropped freely so that the movement of its landing in the water can be seen. The test provides data such as the effect of wave height on impact load, motion characteristics, and load characteristics. The four examples of 0.04 m, 0.06 m, 0.08 m, and 0.1 m are used to create the wave height; the other variables, such as the wavelength of 5 m, altitude of 6 degrees, horizontal velocity of 15.19 m/s, and vertical velocity of 0.236 m/s, remain constant [66].

The air cushion effect is a critical feature discovered through research on seaplane landings. Air that is forced by the fuselage during landing and creates space between it and the water may be the source of the air-cushion effect. Studying this phenomenon is crucial since it can enhance seaplane landing performance. The Arbitrary Lagrangian–Eulerian (ALE) approach has been the focus of recent research efforts to tackle this situation. The process starts with creating the ALE's foundational equations before determining the material and spatial domains. After that, a contact algorithm is developed to determine how the structure affects the fluid that creates interfacial forces. After that, air cushion and water incursion are numerically verified. In the meantime, landing conditioning, material parameter formulation, and the finite element model method are used to verify the model. It is possible to ascertain the seaplane's proper speed and attitude angle using this study approach [63].

This study investigates an aircraft's landing procedure in detail while considering variable downward velocity. The changes in the aircraft's angles and accelerations at different initial horizontal speeds have been studied. It also explores the changes in the air cushion event during landing, and we examine the variations in impact force and pressure readings at a particular monitoring location. Meanwhile, the flow and pressure distribution fields are presented. In addition, this study examines seaplane landing mechanics in detail, considering various starting locations. The primary goal is to comprehend the changes in the seaplane's acceleration and angles during the landing. In addition, the study explores the air cushion properties that develop during landing and looks at how pressure values and impact forces vary at various process stages [63].

7.3 Take-off

A seaplane, as the name implies, must have the ability to take-off like a conventional airplane. However, a seaplane is different because it needs a floater or hull when it takes off. The floater must be able to walk on water, which is known to change its characteristics. Sufficient buoyancy and lift are needed to make it easier for the floater for the seaplane to take-off. When making a seaplane, it is essential to design it so that it can move smoothly through four different stages: the displacement phase, hump or plowing phase, planning or on the step phase, and airborne or liftoff flight [67]. In addition, proper analysis will produce the optimal shape and dimensions of the floater. The analysis starts by determining the research methodology. The research method used is generally numerical with mathematical models. Furthermore, application-based simulations are carried out, which vary according to the wishes and targets of researchers. This research is significant for making seaplanes work better when taking off from water. A recent paper discusses a new way to determine how well seaplanes can take-off from water [68]. Designing a seaplane is like finding the right balance between how it moves through the air and water. The goal is to ensure it performs well in the water without losing too much efficiency in the air. One big challenge for designers is figuring out how the plane will perform during take-off. This is tricky because the seaplane can tilt and move freely during take-off, dealing with forces from the water, air, and propulsion systems. The key is to predict how it will handle these forces and still perform well [53]. Researchers studying seaplanes have refined the take-off phenomenon for the last 10 years, emphasizing analysis accuracy, floater size, and efficiency. Computer software has been utilized to mimic the phenomenon despite the difficulties of numerical approaches, which has resulted in a rapid rise in simulation research. Although they are being investigated, experimental approaches that entail small-scale models put through testing at testing facilities are rarely employed because of their high costs and time requirements.

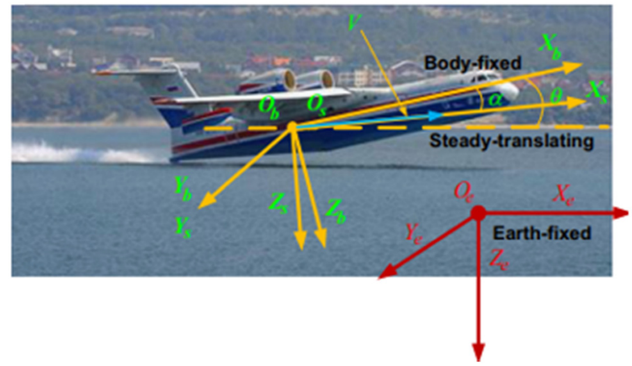
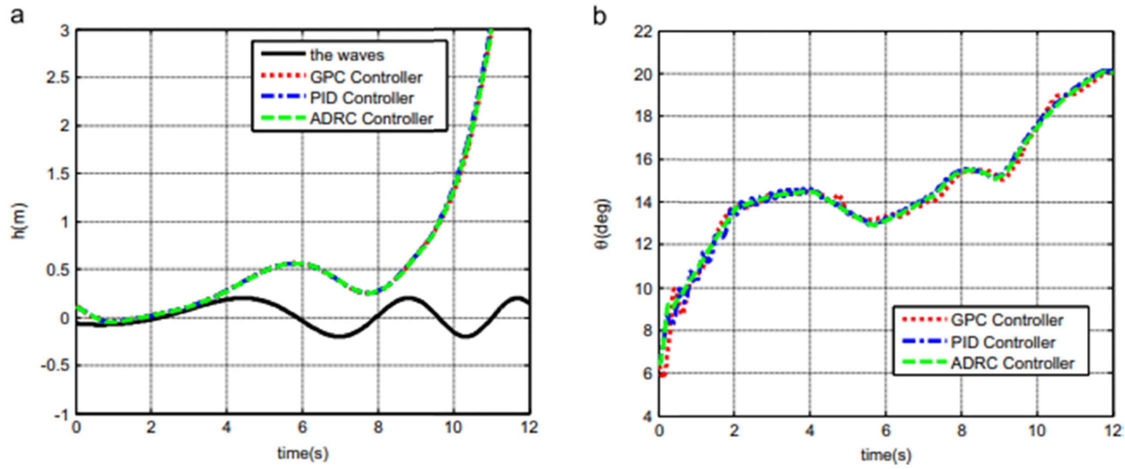


Figure 29: Seaplane geometry and coordinate [27].

A nonlinear mathematical model can analyze an unmanned seaplane's dynamic characteristics and motion stability. This method requires a coordinate system and a longitudinal mathematical model. In addition, this calculation model will include hydrodynamic and aerodynamic forces as critical factors. The studied seaplane model for mathematics is described in Figure 29. In learning this, it is necessary to define coordinates such as fixed on the earth and dynamic coordinates of the seaplane. After that, mathematical data can be processed to manage the take-off motion more precisely and effectively, such as using a controller.

The obtained calculation data will be utilized to design an autonomous control system using fuzzy T-S identification and generalized predictive control (GPC). The calculation parameters considered are speed and relative height. A linear CARIMA model describes local behavior. The GPC algorithm will derive the equations and define the trend of the wave motion through the autoregressive model. The controller will receive an input signal as a pitch angle [27]. In Figures 30 and 31, the performance of three controllers was evaluated in both regular and irregular waves. Figure 30, including 30(a) and 30(b), illustrate that the controllers performed well in facilitating the take-off of the unmanned seaplane under regular wave conditions. At the eleventh second, the three controllers coordinated their efforts to achieve take-off on a 0.5 m regular wave. The three controllers could also detach from the water at a comparable inclination angle for the θ parameter. However, in irregular waves, as shown in Figure 31(a), the PID and ADRC controllers exhibited unstable tracking performance. Specifically, the unmanned seaplane was thrown into the air at approximately 6 s and 7.5 s for the PID and ADRC controllers, respectively, resulting in significant wave impacts on the seaplane. Figure 31(b) reveals these two controllers led to various pitch angle oscillations. On the contrary, the GPC controller maintained its



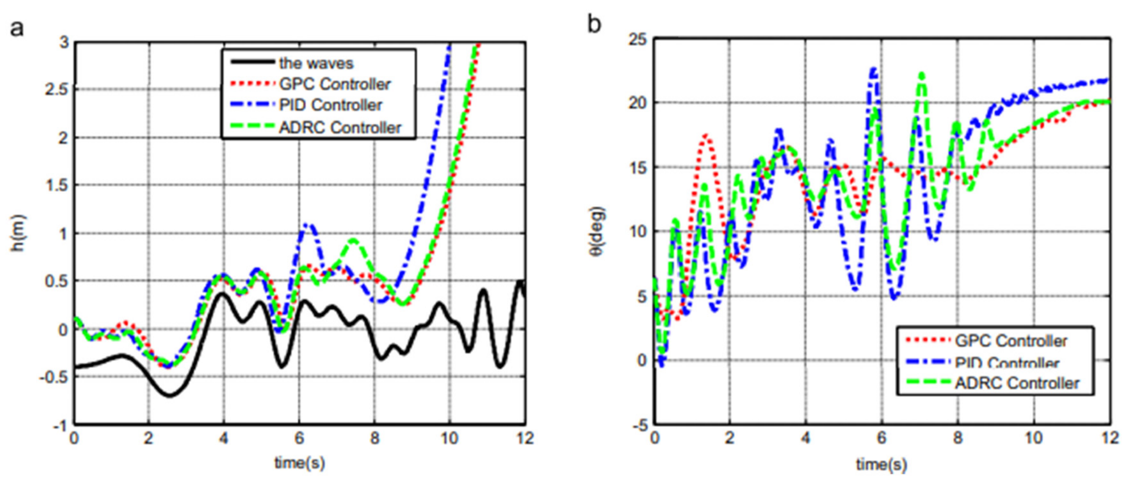
(a) (b)

Figure 30: GPC, PID, and ADRC controller performances in regular waves: (a) trimming values of the height, and (b) angle of pitch [27].

effectiveness in handling severe wave disturbances due to its capability to predict waves. This feature contributed to improving the sea-keeping ability of the unmanned seaplane in irregular wave conditions.

In Southeast Asia, A small seaplane, NAX-4, is designed by the Royal Thai Navy; it has a length of 19.88 ft, a maximum wingspan of 32.94 ft, and an empty weight of 880 lbs. In the design stage, the researcher wants to know the take-off performance of this seaplane. The method used is numerical with Matlab. The critical parameters used are force on the body, drag and resistance coefficient, buoyancy force coefficient, and speed coefficient. These parameters are processed as a function of the speed coefficient and the thrust-airspeed correlation to determine the trim angle and water resistance [67]. The take-off performance of NAX-4 for various test parameters and lift, drag, water resistance, hydroplane resistance, and displacement load *versus* water/air speed have varying results. Notably, the total resistance exhibits nonlinear behavior, peaking at a water speed of about 16. It is important to note that lift and drag are proportional to the water speed [67].

The development of the seaplane is not only in the shape of the hull but has reached the stage of adding parts to facilitate take-off. The part is a retractable hydrofoil embedded in the SEAGULL seaplane, has a wingspan of 11.5 m, a wing area of 13.7 m^2, a maximum take-off weight



(a) (b)

Figure 31: GPC, PID, and ADRC controller performances in irregular waves: (a) trimming values of the height, and (b) angle of pitch [27].

of 650 kg, and a take-off distance of 150 m. This study adopts a high-fidelity CFD approach using a multiphase fully turbulent RANS analysis modeling the free surface by a volume of fluid technique. The simulation uses a multiblock mesh of approximately 5 million hexahedrons with a computational grid half domain extended 4 m upstream and 6 m downstream of the foil [69].

The simulation results indicate that incorporating hydrofoils significantly reduces hydrodynamic drag and increases lift, facilitating smoother take-offs. This suggests that the benefits extend beyond reducing take-off time, improving landing runs, and increasing operational days throughout the year – the drag and lift force curve. The forces vary with each velocity, as shown in Figure 32. By reducing the take-off time, which peaks at 15 knots, and decreasing the trajectory, the foil greatly contributes to the lift force. A lighter hull performs better since, on the one hand, the resistance force also decreases, and the total is far less than the lift.

7.4 Overall discussion

The NAX-4 is a light amphibious aircraft designed to enhance seaplane take-off performance. The aircraft's move on the water involves four phases: displacement, hump or plowing, planning or on the step, and airborne. The water resistance coefficient – based on speed and trim angle – is essential for a good take-off. Successful take-off parameters in calm water conditions are demonstrated using a 2-D simulation of the NAX-4 amphibious airplane. According to the statistics, foiling ultralight seaplanes can shorten take-off distances and enhance landing performances, resulting in more operational days all year round.

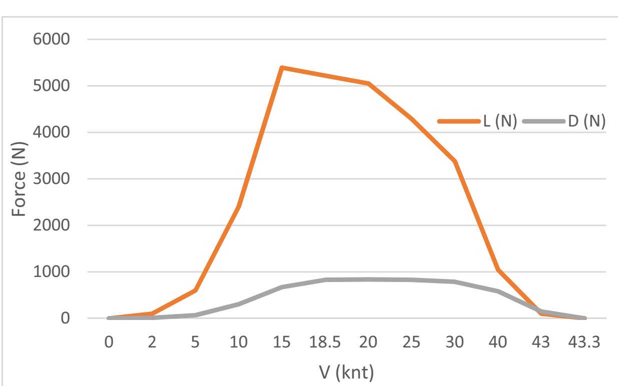


Figure 32: Force on the foils at varied velocities (redrawn based on data in Maglione *et al.* [69]).

Water spray is also decreased by raising the distance above the water's surface during most take-off and landing. The next phase will concentrate on the "dolphin motion" phenomenon to improve unmanned aerial vehicles' water take-off capability. The autonomous control system greatly enhances the autonomous take-off performance of unmanned seaplanes by integrating fuzzy identification and GPC.

For the landing performance, the accuracy of the model experiment findings is verified by using the ABAQUS/Explicit solver to simulate seaplane landings. The second wave arrives later due to more excellent waves, as the results demonstrate the bouncing effects. High-quality numerical waves are produced by applying pseudo-physical wave-making theory, emphasizing the attitude angle peak and how it relates to aircraft speed. A seaplane's landing is aided by the air cushion, which provides a cushioning effect, reducing peak pressure. However, sizeable initial attitude angles can exceed the impact peak, requiring optimal landing speed between 40m/s and 50m/s and an attitude angle of 5° to 8°.

For solar-powered airplanes, anchoring at night is an innovative way to maximize energy savings. An energy balancing system examines essential factors, with wing loading being the main emphasis. The local solar radiation energy density and wing loads dictate the mooring length. Seaplane designs that are creatively modeled are more flexible, and developments in bending wings make them affordable at any port. Computer-aided numerical techniques and CFD software-based simulations are used in in-depth seaplane studies to investigate various phenomena. These approaches confirm the validity of present approaches and suggest future directions for research into developing existing phenomena or applying new ones during takeoff, landing, or mooring. Significant advancements in geometric inventions for seaplanes are also anticipated.

8 Structural design

As a particular kind of aircraft, seaplanes provide a unique combination of opportunities and challenges for structural design. This introduction explores the complex field of seaplane structural design, emphasizing three crucial areas: material selection, loading considerations, and stiffening system. Although we will focus mainly on the floater, we will also analyze other structural elements to provide a more thorough understanding. By carefully investigating these aspects, this study seeks to further the development of seaplane technology, guaranteeing improved performance, safety, and efficiency. Its stiffening system is essential for a seaplane to be structurally sound and functional. This research aims to disentangle the complex network of pressures. It stresses operating upon the stiffening system throughout different flight and water operations phases by incorporating a detailed analysis of current designs and theoretical frameworks. By identifying ideal stiffness configurations, we aim to improve the seaplane's structural robustness and ensure that hydrodynamic performance and waterborne stability work harmoniously. One of the main focuses of our research is how seaplanes operate under various loading conditions. A detailed grasp of loading scenarios is essential, from the dynamic forces during take-off to the static equilibrium during aquatic operations. This study aims to provide a framework that accounts for various situations and improves the overall structural efficiency of seaplanes using a comparative analysis of various loading scenarios. The resulting insights are intended to drive progress in load distribution systems, promoting a structurally more robust and versatile seaplane design. Material selection emerges as a critical facet in optimizing seaplane structural design. This material domain also deals with events such as water entry, commonly used in research on nonship structures such as hollow steel [70]. Delving into the vast array of materials available, ranging from traditional alloys to cutting-edge composites, our exploration aims to discern the most suitable materials for different structural components. By aligning material properties with the specific demands of seaplane operation, we strive to enhance seaplanes' overall performance, longevity, and cost-effectiveness. This research aspires to contribute valuable insights into material science applications, ensuring that seaplanes are structurally sound and at the forefront of technological innovation. The material in question is specific to the floater section, which plays a vital role in hydrodynamics. Proper material selection will affect the performance of the seaplane and keep the structure from damage, such as corrosion [71]. Commonly used materials include metal and composites. However, looking back to the early days of seaplanes, wood was the first choice. The first wooden seaplane appeared in 1924, the Savoia Marchett S55, and in 2018, a replica was developed [72].

However, composite materials are currently being researched more for effectiveness, strength, and good resistance to water conditions [73] (as shown in Figure 33). Extreme loading scenarios, including slamming or impact, are necessary for maritime constructions. Through material analysis, researchers are concentrating on enhancing seaplane performance. The composite materials under study can be a whole model or a chopped plate. Structural design considerations are customized to the expected loads, but seaplanes face continuous wave and turbulence impacts during take-off, landing, and water taxiing. Over the past decade, research on floaters has aimed to optimize seaplane performance by analyzing shape, theory, and simulation techniques. Landing impact, influenced by speed and wave conditions, is a critical load requiring anticipation [74]. The von Karman theory specializes in analyzing structures entering the water. In addition, Von Karman's theory is also very suitable for analyzing the water entry process in floating structures, which, in some instances, can present geometric innovations [75]. Studying the dynamic characteristics of seaplanes also becomes essential for preventing structural resonance damage and vibrational fatigue. The float, a vital part of the seaplane structure, is crucial for evaluating dynamic characteristics [76].

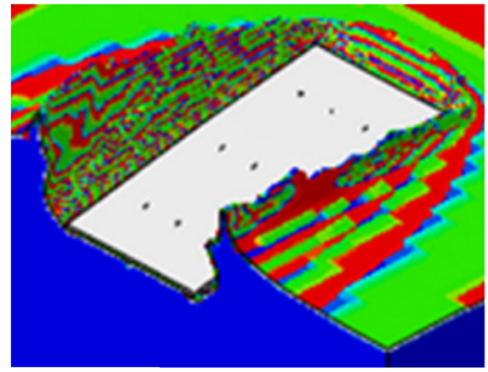


Figure 33: Composite plate at impact simulation [73].

The innovative stiffener system aims to offset the slamming force or impact load. A projectile experiences stress upon collision with water that could jeopardize its trajectory stability and structural integrity. Slamming loads can cause damage, deck diving, structural vibrations, and large permanent deformations. These loads may start a slow collapse in highly choppy water states, potentially dangerous for human life. Current research on stiffener systems focuses on impact analysis using numerical and simulation techniques made possible by software developments. Computational fluid dynamics-finite element method (CFD-FEM) can be used to examine phenomena such as hydroelectricity effects [77]. Beyond load analysis, stiffener design research introduces innovative models like spring buffers with extractable stiffness values [78]. An ongoing exploration exists for a control system to optimize the stiffener system [78]. Figure 34 demonstrates the stiffener system's construction and control mechanism in action. A novel stiffener model was created with sensor and actuator layers surrounding the carbon nanotube

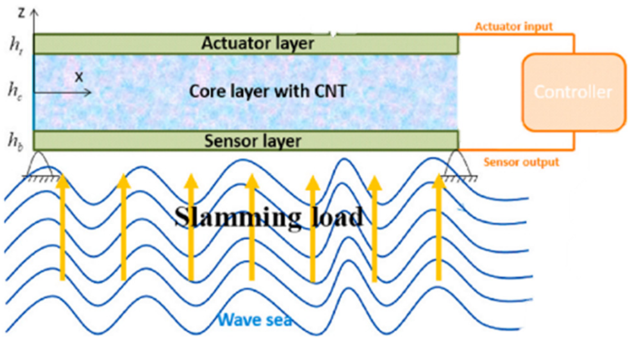


Figure 34: Control system for stiffener [79].

(CNT) core. This model is an intriguing innovation that can predict slamming loads.

8.1 Material

The amphibious transportation industry has brought attention to the need for a robust, lightweight seaplane. Rubber or metal floaters are considered lightweight, hefty, and prone to corrosion. The Japan Reinforced Plastics Society suggested employing fiber-reinforced plastic (FRP) as the floater's foundation material to solve this issue. FRP has a superior strength-to-weight ratio, specific rigidity, and corrosion and impact resistance. Its dynamic reaction was ascertained by experiments and numerical simulations [80].

Furthermore, in numerical analysis, the model, floater, supporting parts, weight, alighting area, and boundary wall are formed in computer-aided design software CATIA-V5, which will be divided into elements using HyperMesh 10.0. Solver for the finite element method by using SPH, PAM-CRASH is utilized explicitly. A floater was dropped into a test pool to measure the maximum acceleration, fall time, and strain under calm and wave conditions. For the central alighting, the left floater has a maximum vertical acceleration of 13.67 G and the Right float 12.27 G. Then, for the front alighting position, the left side gets 13.31 G. The right side gets 12.3 G. Finally, for the rear alighting position, the left side gets 12.34 G and the right side gets 13.35 G. It is possible to acquire the dynamic responses of acceleration *vs* time for both still and wave water [80].

It is known that a floater is a crucial component of a seaplane, requiring strength, effectiveness, and safety during operation. To calculate the force on the composite floater, the research begins by selecting the pitch and heave data of the model when porpoising. The test method

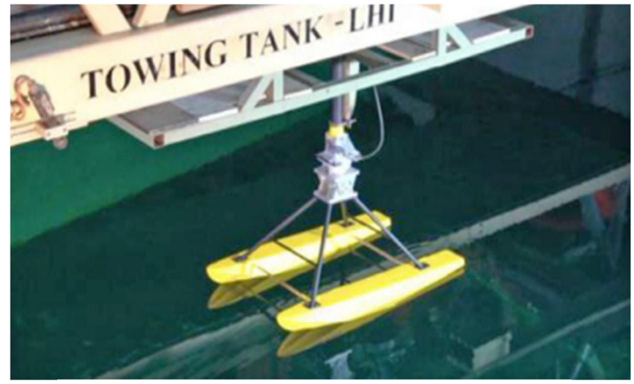


Figure 35: Floater experiment [81].

uses a towing tank to determine the floater drag at varying speeds. The model for the experiment is shown in Figure 35. The experimental method is the closest approach to reality because all phenomena can occur without limitations or assumptions. In addition, the data generated by experiments can also be validated because they involve a variety of expert labor and meticulous procedures.

The cyclic loads that the porpoising motion constantly applies to the hull of the floats might physically deteriorate the composite material. Even when stresses are below the ultimate strength of the composite, microscopic damage can develop with repeated cycling, which may lead to delamination, a failure mode when a material cracks into layers. The Palmgren-Miner cumulative damage rule offers a simple criterion for calculating the fatigue damage caused by constant amplitude cyclic loads in a loading sequence with varying stress amplitudes. This formula can also be used to calculate fatigue damage in composite constructions. The stress on the floater is calculated using the Euler–Bernoulli beam theory, revealing its average shear stress, maximum stress in heave, and maximum stress in pitch. Figure 36 shows the fraction of life for

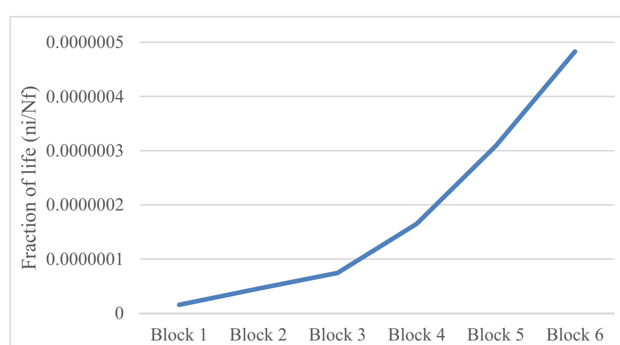


Figure 36: Fraction of life data for each block (redrawn based on data in Nugroho *et al.* [82]).

each block floater. The blocks represent the pressure range, with block 1 representing the slightest pressure and block 6 representing the most significant pressure. The total ni/Nf of 1.08×10^{-6} Hz, when combined with a 33-second load cycle, can be multiplied by $1/(1.08 \times 10^{-6})$ to determine the system's lifetime. This calculation results in a lifetime of 11.6 years, or 4 hours per day [82].

8.2 Stiffening system

A semisubmersible floating rig's bottom pressure is usually calculated during design by comparing the relative speeds in an air-gap analysis. It is critical to describe technological processes in language that is both clear and concise. Nevertheless, only some research studies have estimated design pressure using a comprehensive, reliable, and deep background method. We used the nonlinear FEM software LS-DYNA to simulate a simplified deformable stiffening plate with a zero-degree deadrise angle to study the slamming pressure on the bottom of a semisubmersible rig. This program can consider the influence of fluid–structure interaction (FSI). The effects of coupling stiffness, mesh size, velocity, stiffener size, air cushion, and structural flexibility on the pressure response of the plate resulting from the coupling of fluid and structure were studied parametrically. The effects of coupling stiffness, mesh size, velocity, stiffener size, air cushion, and structural flexibility on the pressure response of the plate resulting from the coupling of fluid and structure were studied parametrically. Every parameter's FSI effect was examined. A series of parametric investigations determined equivalent transient and static loads that produce the same maximum or permanent deformation as FSI for design purposes [80]. The plate panel stiffness model, with a thickness of 15 mm and a stiffness spacing of 800 mm, exhibits a young modulus of 210 GPa and a yield stress of 235 MPa [83]. With the assumption of an incompressible and inviscid fluid, LS-DYNA is a finite element program that simulates FSI problems. It makes use of Eulerian fluid computations and Lagrangian meshing. The ALE approach makes free surface modeling possible, which combines fluid calculations, advection stages, and multimaterial ALE.

In the effect of parameters on the pressure response, the penalty factor (it is used to track the relative displacement between the fluid and the structure) and mesh size (to study the effect of mesh size on the results) are determined. Using water moving at speeds ranging from 3 to 6 m/s, a simulation was run to ascertain the effect of water velocity on impact pressure. In addition, structural flexibility was investigated; flexible structures had a more extended pressure response, whereas rigid structures displayed an increased maximum mean pressure. This emphasizes how crucial FSI is. In FSI, stiffener size is essential because it influences maximum pressure distributions along the *x*-axis. While larger stiffeners result in more excellent active coupling, smaller ones encourage less stiffness and more active coupling. Air cushions between the water and bottom plate, reducing impact pressure peak and evening out the pressure response. The stiffener size and FSI are affected by both variables. One laborious technique for evaluating the strength of structures that will be slammed during the design stage is FSI analysis. Like FSI, equivalent transient analysis seeks to identify a reduced impact load that results in equivalent maximum or permanent deformations. Several simulations are run to determine equivalent transient and static loads [77].

8.3 Loading

This study explored sea-keeping performance in seaplanes through a wave model test, focusing on wave motion response features. It examined similarity criteria, test parameters, experimental equipment, and data processing methods. The study has highlighted the importance of model tests in engineering design and optimization despite the advancement of numerical simulation in hydrodynamics. A wave model was constructed to forecast seaplane performance utilizing formulae, parameters, and a similarity criterion. Parameters were chosen for best outcomes, including wave height, wavelength, and speed. Validity was ensured with wide wavelength intervals. In most cases, experiments do not utilize the original model; instead, they employ a scaled-up version., The model uses scaling such as length kL, inertia K^5I, mass K^3m, and velocity $K^{0.5}$V [84].

In free fall scenarios, researchers verified the relationship between starting vertical velocity and peak vertical acceleration using von Karman's momentum theory. To demonstrate the impact of slamming, they evaluated factors that determine maximum acceleration and provide comprehensive results, such as free surface shape and pressure distribution [82]. Von Karman's momentum approach and boundary conditions of computational design are presented in Figure 37(a) and (b). The von Karman momentum approach can start from undisturbed water and V0 for simple models. Meanwhile, the computational domain is divided into velocity inlet, symmetry, and pressure outlet for more advanced boundary conditions.

The impact of the forces operating on the floater was examined in this investigation. The test parameters

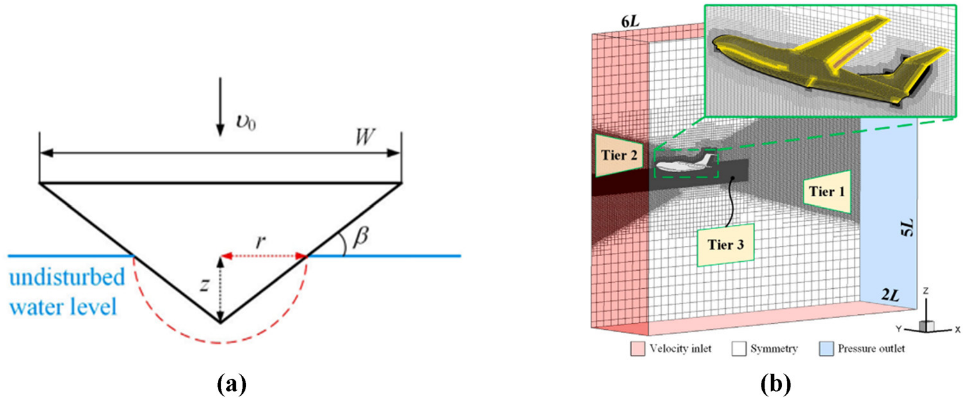


Figure 37: (a) Von Karman's momentum approach and (b) boundary conditions and domain of computational [85].

provide the analysis results once the computational and simulation settings are prepared. The impacts of both vertical and horizontal velocities were computed in the 2D simulation slice to get dynamic parameters like acceleration, test time, velocity angle, pressure coefficient, *etc.* Next, the computation was done for the 3D cabin segment, extending to the seaplane's V-shaped hull [84]. A summary of the comparison between simulation output and quantitative calculations is presented in Figure 38. Data from two hull models are obtained, where the red line is the theoretical estimate, and the magenta dashed line is the simulated, constant asymptotic value. At the same time, the black line represents the simulated trend that decreases as the data increases.

8.4 Overall discussion

8.4.1 Material

Using numerical simulations and alighting impact experiments, the study developed impact-resistant GFRP floats for seaplanes. The results confirmed the validity of the approach, with the stress generated in the floats well below the allowable stress of FRP. The floats have a fatigue life of approximately 11.5 years, providing a simple calculation method for estimating composite seaplane float structural components' strength, lifetime, and size. On the other hand, seaplane floater materials, from wood to composites, significantly impact hydrodynamics and performance. The research aims to improve durability and effectiveness. The Savoia Marchett S55 demonstrated this shift, with fatigue life calculations estimating structural components' strength and longevity.

8.4.2 Stiffening system

Using FSI and LS-DYNA simulations, impact stresses on stiffened plates can be examined, focusing on FSI. The study found that structural rigidity significantly impacted FSI, and fluid and structural mesh sizes must be adjusted. The transient analysis and the air cushion effect showed an immediate relationship between the impulse characteristics and the structural behavior. The new stiffener system aims to counteract slamming pressures, essential for

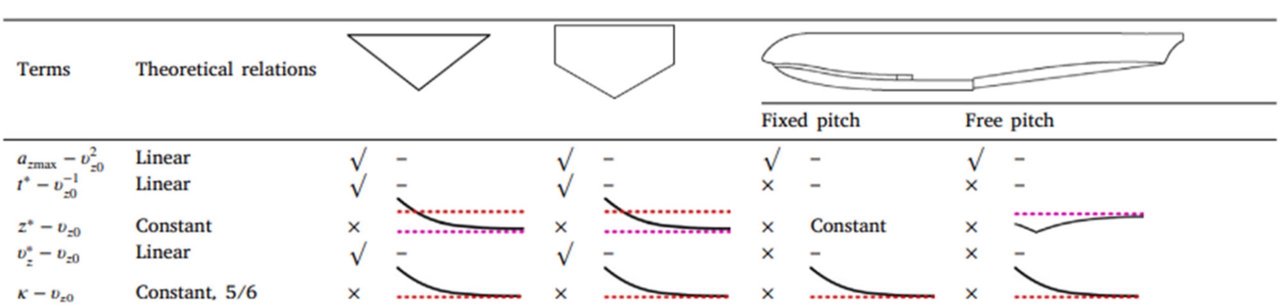


Figure 38: Summary of theoretical quantitative connections in contrast with simulated outcomes across three scenarios: simulated trend (solid black line); theoretical estimation (dashed red line); simulated asymptotic value (dashed magenta line) [85].

maintaining trajectory stability and structural integrity when hitting the water. Unfavorable outcomes like vibrations, damage, and deformations could pose risks, especially in highly arid sea states. Recent impact analysis work has used complex numerical and simulation methods like CFD-FEM and LS-DYNA. In examining the factors that affect water impact pressure, this study emphasizes the importance of mesh optimization, velocity, and structural stiffness – especially at moderate deadrise angles. Studies of transients show a direct relationship between impulse properties and structural behavior. Examples of active research include creating models such as spring buffers and searching for a control system to improve stiffeners.

8.4.3 Loading

For seaplanes to navigate the dynamic problems of waves and turbulence, complex structural designs are required. Recent developments in floater research aim to maximize performance using sophisticated simulations and shape analysis to handle important factors like landing impact affected by wave and speed conditions. Von Karman's theory comes in handy when analyzing the intricacies of water ingress in floating constructions. Beyond the weeds, knowing seaplane dynamics is essential to preventing structural damage and reducing vibrational strain, especially regarding the crucial role played by the float. Every aspect of it, from favorable correlations in motion responses to the complex interactions between simulated and theoretical results, contributes to our developing understanding of improving seaplane capabilities. With the advent of the instantaneous Froude number, we may better understand acceleration subtleties and deviations in certain forms and get new insights into directional dynamics.

8.5 Future work

A blend of cutting-edge computational tools, simulation approaches, and novel materials will influence future seaplane structural design. It is anticipated that scale models will be used to correctly measure loading on seaplane floaters through experimental testing in the future. Extreme scenarios, including free fall or impact testing, are performed to obtain the maximum loading. Comprehensive material testing to investigate mechanical qualities and adaptability under various loading scenarios is an anticipated breakthrough. Therefore, a composite, such as a fiber-on-plastic combination, is the best material choice for seaplane floaters because it is durable for up to 10 years and robust against loading. Researchers will maximize performance by adjusting the stiffness of system setups and applying sophisticated testing techniques to find and fix any vulnerabilities. For inventive slamming resulting from materials like CNTs, a stiffening system architecture is required in addition to material selection. Extensive numerical simulations will be essential for offering a fine-grained understanding of structural reactions. This cooperative approach is anticipated to usher in a new era of practical, durable, and flexible seaplane design.

9 Conclusions

Seaplanes have been essential to military and leisure aviation for many years. Their particular capacity to take off and land on water distinguishes them from conventional fixed-wing aircraft, adding to their versatility. This study, which further develops the general seaplane model, summarizes the key research findings and the related features of the research methodologies based on the classification review and analysis of seaplane hydrodynamics from the ship's perspective. Naturally, building an airplane that will function flawlessly even after the first design iteration is not easy. It is flawless in every area that has been examined (such as structures, aerodynamics, stability, *etc.*). The preliminary design aims to identify as many significant issues as possible before beginning the detailed design. Finally, the first findings highlight a few benefits of building seaplanes utilizing the trimaran idea and the improved performance when the floats are retracted. The trimaran's total drag can be decreased by the layout and arrangement of its outriggers. In an ideal trimaran design, one outrigger is half the length of the main hull and has 4% of the main hull's displacement. The findings indicate that a tiny transverse distance between the outriggers frequently produces a small heave amplitude RAO when sailing in a head sea.

Specifically, it was discovered that applying amphibious aircraft required a supercavitating airfoil profile. A framework for optimization has been developed to find the ideal span length and the angle of incidence to reduce the aircraft's water take-off distance. Our findings, however, demonstrated that without appropriate optimization, adding airfoils by themselves could not guarantee a performance increase. In addition, the negative impact on the aircraft's longitudinal stability regarding the horizontal stabilizer force needed to maintain the trim angle was minimized by determining the hydrofoil's ideal location concerning the aircraft's center of gravity. The hydrofoil met the necessary goals in terms of hull drag and buoyant load reduction, according to the findings of the water-take-off technique. The case study demonstrates the efficacy of the hydrofoil in enhancing the efficiency and performance of amphibious aircraft during water take-off, as indicated by the decrease in water take-off distance. This finding emphasized the advantages of optimization in design studies and the necessity of creating a thorough design framework for amphibious aircraft.

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