

Review on the Active and Passive Control Systems for the Planing Boats

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Abstract This paper presents a review of active and passive control systems used in planing boats, emphasizing their design, function, and hydrodynamic impact. Control surfaces including trim tabs, stern flaps, interceptors, rudders, hydroplanes, and T-foils are categorized by function (pitch, yaw, roll control) and type (active or passive). Their roles in improving dynamic stability, maneuverability, and fuel efficiency are analyzed. An additional attention is given to their influence on reducing motion-induced discomfort, including motion sickness incidence (MSI), through attenuation of heave and pitch accelerations. A cost assessment contrasts the complexity and operational advantages of active systems with the simplicity and reliability of passive ones. The paper also compares pressure distribution patterns and drag reduction effectiveness of interceptors and trim-tabs using experimental data and computational fluid dynamic (CFD) results. Furthermore, it explores strategies such as stepped hulls for minimizing porpoising instability and provides a procedural overview of fin stabilizer activation mechanisms. A review of many recent published papers offers broad insights into ongoing innovations and applications of control surfaces in high-speed boats. This work aims to support the optimal design and implementation of control systems that balance performance, stability, and onboard comfort.

Keywords: *Planing boats, Control surfaces, Passive and active types, Instability, Dynamic equations*

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1. Introduction

All floating or flying bodies are subject to motion in six degrees of freedom (DoF): three translational motions surge (forward/backward), sway (side-to-side), and heave (vertical) and three rotational motions roll (tilting side-to-side), pitch (tilting forward/backward), and yaw (turning left/right). These movements, especially in dynamic environments like waves or turbulent air, often become harmonic and oscillatory, leading to instability, discomfort and reduced performance. To manage and reduce these unwanted oscillations, control surfaces are employed. They generate counteracting forces and moments that help dampen these motions, stabilize the vehicle, and ensure smoother operation. In marine vessels, this means reducing roll and pitch in rough seas; in aircraft, minimizing pitch or yaw oscillations during flight. Control surfaces are thus essential tools for maintaining dynamic equilibrium and enhancing the safety and comfort of vehicles operating in fluid environments. Figure 1 shows six-DoF of a boat and its impacts to someone onboard.

Control surfaces play a vital role in the performance and safety of marine vessels, particularly high-speed

crafts. Their primary function is to maintain and improve dynamic stability by controlling the motion responses of the vessel in the face of external disturbances such as waves and high-speed maneuvers. These surfaces whether active or passive are used to regulate motions like pitch, roll, and heave, thereby stabilizing the vessel's orientation and enhancing navigational control. However, beyond their technical function in hydrodynamic optimization, control surfaces serve a critical human-centered purpose as well.

When vertical (heave) or angular (pitch) accelerations become excessive, they lead to discomfort for those onboard, often resulting in seasickness. This not only affects the ergonomics and well-being of passengers and crew but can also hinder operations during long or rough sea voyages. Control surfaces help mitigate these issues by reducing the magnitude and frequency of such accelerations, providing a smoother and more comfortable ride. Therefore, the purpose of using control surfaces extends beyond improving vessel dynamics it also encompasses enhancing onboard comfort and minimizing physiological strain. Their design and implementation are essential for ensuring both operational stability and passenger satisfaction in modern marine transport.

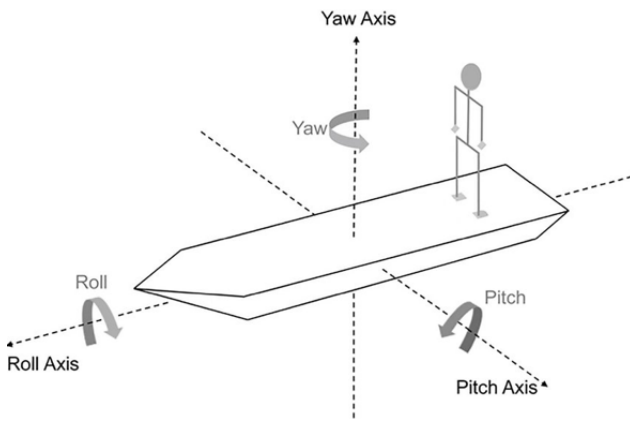


Figure 1. Six-degree of freedom (DoF) of a planing boat [60]

Control surfaces are mechanical or structural elements designed to manage and influence the dynamic behavior of a vehicle whether it's a marine vessel, aircraft, or any other controllable platform. These surfaces act as tools to control motion by generating forces and moments that adjust the orientation, stability, and path of the vehicle. In marine applications, they help regulate trim, reduce drag, enhance maneuverability, and improve seakeeping. In aviation, they are essential for adjusting pitch, roll, and yaw. Control surfaces can be either active adjustable in real time or passive fixed components that rely on hydrodynamic or aerodynamic shaping. Their importance lies in providing the operator with the ability to maintain control, efficiency, and safety in various operational conditions, making them fundamental to the performance and handling of high-speed and dynamic vehicles.

Interceptors can significantly reduce drag and improve overall vessel efficiency, thereby contributing to advancements in high-performance yacht design. The potential of active control systems in optimizing the performance of planing boats are underscored [1]. Interceptor height variation significantly influences hydrodynamic forces, effectively reducing porpoising in high-speed planing crafts. Interceptors not only improve performance but also enhance overall vessel stability by mitigating this common dynamic instability [2]. Interceptor systems reduce unwanted trim angles at high speeds, resulting in lower drag, increased forward speed, and improved operator visibility. The effectiveness of interceptors is influenced by deployment depth, mounting location, and vessel speed, highlighting their value as a trim control solution under varying operational conditions [3].

A controllable interceptor effectively mitigates vertical motions of high-speed planing vessels in wave conditions, enhancing both stability and ride quality. Such systems improve overall vessel performance, offering valuable insights into the design and implementation of active control solutions for planing boats [4]. Interceptors can significantly reduce resistance and improve vessel stability across a range of operating conditions [5]. While interceptors are effective for trim control, incorrect sizing can lead to negative trim and instability. The boundary layer thickness at the stern is a critical factor in determining interceptor performance, recommending that the interceptor height should not exceed 60% of this thickness, with an optimal span length being seven times the height [6]. As the interceptor height increases, stern

bottom pressure rises and trim and rise of center of gravity (CG) decrease. Quantitatively significant, the influence of interceptor height on vessel attitude at high speeds is found to be [7]. Performance enhancement through interceptor implementation, driven by nonlinear interactions between ship motions and transom flow, is demonstrated using pressure fields reconstructed via advanced PIV techniques [8].

Trim control enhancement and drag force reduction, achieved by altering pressure distribution through optimally sized hydrodynamic interceptors, are demonstrated using CFD simulations based on Reynolds-Averaged Navier–Stokes (RANS) equations [9]. Resistance reduction and stability improvement, influenced by interceptor design parameters, are demonstrated through numerical simulations for optimizing high-speed marine vessels [10]. Resistance reduction, trim improvement, and stability enhancement in planing boats through spray rails, chine strips, and V-shaped spray interceptors are demonstrated by experimental and numerical analyses [11]. Drag reduction of 5–15% and trim reduction of 32–45% across planing speeds through transom interceptor use are demonstrated, with interceptor height found to be critical for optimizing hydrodynamic performance [12].

Hull resistance reduction and hydro-energy generation using a novel interceptor model are achieved through CFD analysis, while certain configurations at higher speeds cause resistance to increase [13]. Interceptors enhance lift and reduce resistance by increasing pressure at the stern, thereby improving vessel performance [14]. Adding interceptors, especially at 100% of the design size, significantly improves rotary maneuverability by reducing tactical diameter [15].

Drag reduction and efficiency improvement under varying loading conditions through combined air lubrication and double interceptor systems are achieved using experimental and CFD approaches, highlighting the potential of integrated control systems for planing hull optimization [16]. Interceptors significantly reduce drag and trim, especially at high Froude numbers [17]. Lift force generation by interceptors on planing vessels, influenced by velocity, height, angle, and draft, is analyzed experimentally, revealing their role in enhancing stability and efficiency of high-speed boats [18]. A 25% resistance decrease and 57% trim reduction at design speed through integrated use of interceptors and flaps on planing hulls are revealed by CFD simulations, underscoring their effectiveness in enhancing hydrodynamic performance [19].

A 4–4.5° wedge angle is as most effective at a speed of 35 knots [20]. The alteration of the wake field and shaft speed due to stern flaps subsequently influences the ship's exciting force characteristics and propeller cavitation performance [21]. Resistance performance improvement, cavity behavior control, and porpoising inhibition through varying stern flap angles on double-stepped planing hulls are investigated experimentally and numerically, with CFD results validated for accurate hydrodynamic analysis [22].

Reduction in fuel consumption, energy efficiency design index (EEDI), and emissions through optimal stern flap design on a high-speed displacement vessel is established using resistance data, operational profiles,

CFD analysis, and experimental testing [23]. A zero-degree angle stern flap significantly reduced resistance (up to 7.2% at 23 knots), decreased effective power requirements, and improved overall vessel performance [24]. Wave energy reduction near riverbanks by up to 50% through optimized stern flap design on barges is demonstrated using numerical simulations, physical model tests, and in situ measurements [25].

Optimal stern flap configurations can significantly reduce hull resistance and improve fuel efficiency [26]. The near-field fluid phenomena associated with lift enhancement and provides a comprehensive examination of the interactions between the flap and the planing surface [27]. The mechanisms by which flaps mitigate speed loss and improve propulsion efficiency in resonant wave conditions [28]. Total resistance reduction of up to 5.53% and improved lift and trim performance on a 60-meter fast boat through optimal stern flap configuration (2% LPP length, 90° trailing edge down) are achieved using CFD analysis [29]. Resistance reduction and improved flow characteristics on a patrol boat through optimized stern flap width and angle configurations are identified using CFD simulations and validated with multiple software tools [30].

Lift enhancement at the stern, trim reduction, and resistance lowering through optimally sized stern wedges on planing craft are identified via 3D simulations, improving stability and enabling higher speeds [31]. Stern wedges reduce trim angle, resistance, and fuel consumption while increasing speed and improving hydrodynamic performance [32].

Vertical acceleration reduction and passenger comfort improvement through active control of transom flaps and a T-foil on fast ships are demonstrated using validated mathematical and experimental models integrated into a MATLAB-SIMULINK simulation environment [33].

Resistance reduction at multiple speeds and optimal appendage designs for a fast monohull vessel are identified through CFD simulations comparing various stern flap and wedge configurations [34]. The optimized stern flap significantly reduces total resistance and improves wake characteristics, thereby enhancing the ship's efficiency at different speeds [35].

Stability enhancement and dynamic control improvement in planing boats through optimized control devices are confirmed using CFD simulations and experimental methods [36]. The artificial neural network (ANN) model significantly outperforms the other models in predicting ship speed and pitch motion under varying sea conditions, achieving lower average absolute errors and higher correlation coefficients [37]. Resistance reduction through optimization of trim angle and longitudinal center of pressure using trim-tabs on planing boats is established via Savitsky's method, confirming their effectiveness as active control surfaces across varying speeds [38]. Resistance and propulsion power reduction, along with improved hydrodynamic performance at a 15° trim-tab angle on a 6-meter speed boat, are concluded through simulations analyzing flow behavior, pressure, and wave characteristics [39].

Hull motion reduction, slamming force mitigation, and decreased water entry impulse and strain energy during wave impacts through ride control systems (RCSs)

especially nonlinear pitch control are quantified experimentally on a high-speed catamaran using a hydroelastic model [40]. Nonlinear pitch control significantly reduces motions and improves passenger comfort [41]. Active pitch control most effectively reduces peak slam forces and bending moments [42]. Heave and pitch response analysis of a high-speed wave-piercing catamaran equipped with active ride control surfaces is conducted using towing tank experiments and a validated numerical model, identifying control surface combinations for achieving pure sinkage and pure trim [43]. Active ride control significantly reduces vessel pitch and heave motions [44]. Ride control significantly reduces slamming events, providing actionable insights for vessel operation [45].

A unified mathematical model integrating hydrodynamic effects, nonlinear damping, and environmental forces for ship maneuvering and seakeeping is developed and validated on the S-175 container ship, demonstrating applicability for advanced autopilot and dynamic positioning system design [46]. Hydrodynamic performance and stability characteristics of a trimaran planing hull are investigated experimentally, with resistance and stability data provided to enhance design and control for optimized planing boat performance [47]. An increase in lift coefficient with decreasing (even negative) deadrise angles up to 30° alongside side wetting at moderate speeds and lift-to-drag trade-offs due to increased wetted area in negative-deadrise hulls is established through CFD analysis, confirming greater weight-carrying potential in calm water yet higher impact loads in waves [48].

Superior steering effectiveness and flow field uniformity at lower speeds through X-rudder configurations on submarines are demonstrated via towing tank experiments, supporting improved stern control surface design for enhanced underwater maneuverability [49]. The influence of center of gravity positioning on planing craft design parameters is revealed, prompting further experimental and numerical research to refine performance modeling and optimization [50]. Total resistance reduction of up to 20% through optimization of hull aspect ratio, dynamic trim angle, and trim-tab use on planing hulls across various Froude numbers is demonstrated using Savitsky-based Python computations [51].

2. Types of Control Surfaces

Control surfaces in marine and aerospace applications can be categorized based on their operating principles and functions. Broadly, they are divided into hydrodynamic control surfaces, used in high-speed crafts, displacement vessels, and submarines, and aerodynamic control surfaces, found in airplanes. Additionally, these surfaces can be classified into active control surfaces, which are adjustable and dynamically modified during operation, and passive control surfaces, which remain fixed and rely on their shape and positioning to influence stability and performance.

Active control surfaces include components such as flaps, trim-tabs, rudders, Interceptors and ailerons, which are mechanically adjusted to optimize maneuverability,

trim, and lift forces. These systems allow for real-time adjustments to adapt to changing environmental conditions and operational requirements.

Passive control surfaces include fin stabilizers, stern wedges, and hydroplanes, which function without direct mechanical adjustments, instead utilizing their hydrodynamic design to enhance stability and performance. Figure 2 presents a general categorization of Control surfaces.

Table 1. Control surfaces applications in different types of vehicles

Control surface / application	Aircraft	Ship	Submarine	Planing boat
Interceptor				Pitch
Trim-tab				Pitch
Wedge		Pitch		Pitch
Aileron	Roll			
Elevator	Heave & Pitch			
Hydroplane			Heave & pitch	
Rudder	Yaw	Yaw		
Stabilizer		Roll		

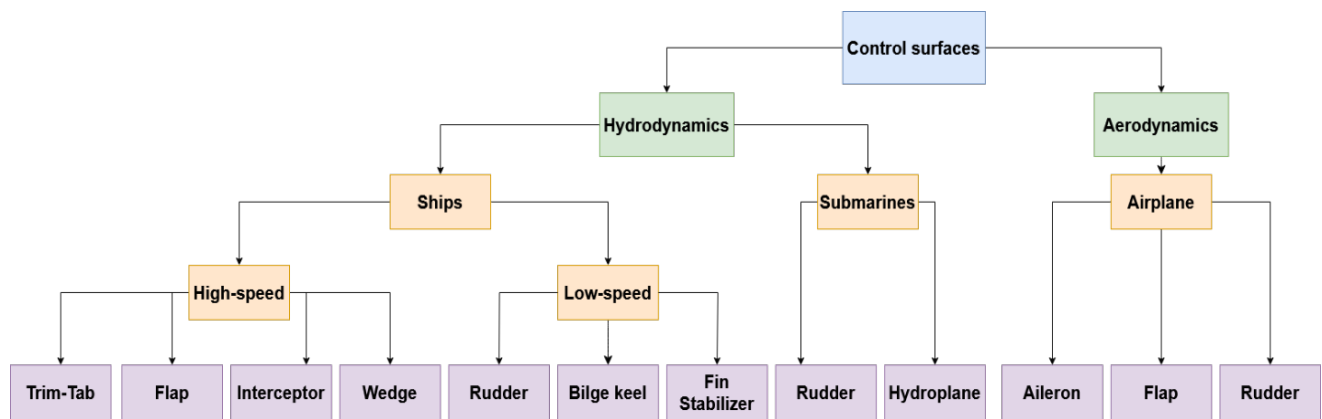


Figure 2. General categorization diagram of control surfaces

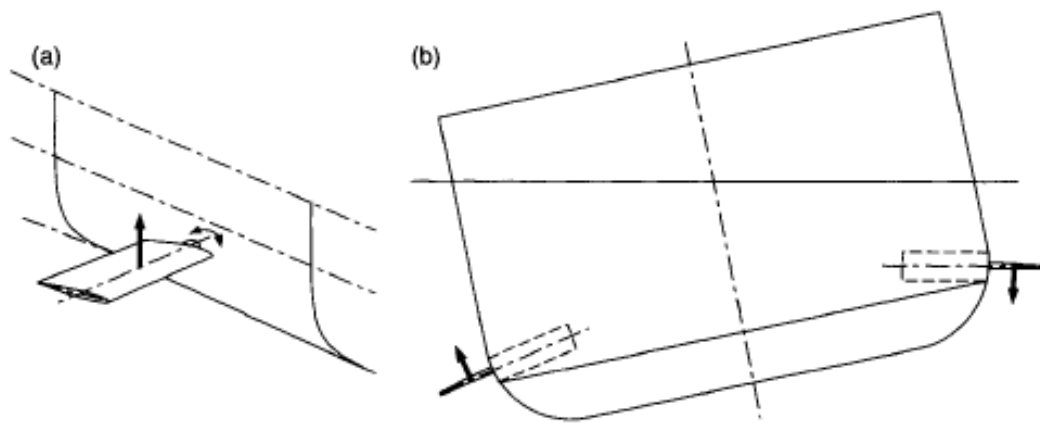


Figure 3. Fin Stabilizers deployment [52]

2.1. Passive Control Surfaces

Passive control surfaces are fixed or minimally adjustable components designed to enhance stability, reduce resistance, and improve the overall performance of vessels without requiring active mechanical input. These surfaces rely on their hydrodynamic shape and positioning to influence the vessel's movement and trim. By passively interacting with water flow, they contribute to improved seakeeping, roll reduction, and efficient planing. While they lack real-time adjustability, their carefully engineered

This classification provides a clear framework for understanding how different control surfaces contribute to the efficiency and stability of planing boats, submarines, and aircraft, ensuring optimal performance across various operating conditions. Some examples of applications of control surfaces are mentioned in Table 1.

design plays a crucial role in optimizing hydrodynamic efficiency. These surfaces are: Stern-wedges, Fin Stabilizers and Hydroplanes.

2.1.1. Stern Wedges

These are fixed wedge-shaped structures mounted at the stern of a vessel to modify water flow, improve trim, and reduce resistance. They are particularly useful in high-speed planing boats, helping to maintain optimal running angles and enhance fuel efficiency.

2.1.2. Fin Stabilizers

Fin stabilizers are hydrodynamic surfaces attached to the hull to reduce rolling motion caused by waves. They operate by generating lift forces, which counteract the rolling motion. These fins can be either fixed or retractable and are commonly used in high-speed crafts, ferries, and large ships for passenger comfort and cargo stability. Fins can also be found in active versions as they have been shown in 4.1 section of this paper. A practical example of fin installation on hull is presented in Figure 3.

2.1.3. Hydroplanes

Hydroplanes, also known as diving planes, are used in submarines and underwater vehicles to control depth and pitch. Positioned at the bow or stern, these control surfaces adjust their angle to generate lift, allowing the vessel to ascend or descend in the water. A practical arrangement of hydroplanes on a submarine is shown in Figure 4.

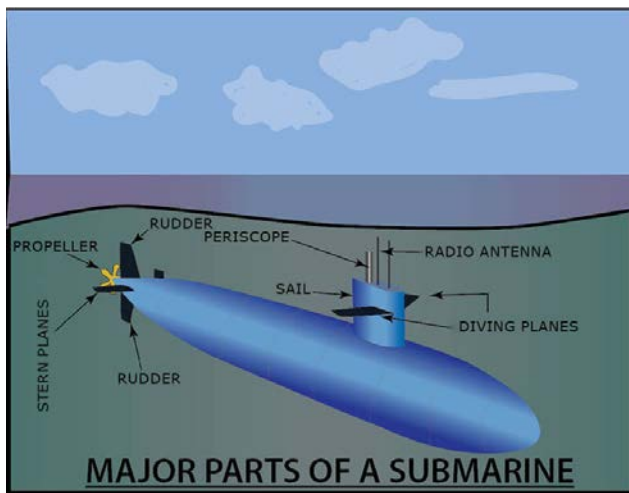


Figure 4. Hydroplanes used on a submarine hull [61]

2.1.4. Bilge Keels

Bilge keels are one of the simplest and most reliable forms of roll stabilization devices used in marine vessels. These long, narrow fins are mounted along the turn of the bilge and function passively to dampen rolling motions caused by waves. Unlike active stabilizers, bilge keels have no moving parts and therefore require no specialized maintenance beyond routine hull upkeep. They are effective across a wide range of operating speeds and can be used alongside active fin stabilizers, with segmented designs allowing for integration. The main drawback of bilge keels is the additional hydrodynamic resistance they introduce; however, this can be significantly minimized by carefully aligning them with the natural flow streamlines along the hull. Such alignment is typically achieved during the design stage using flow visualization techniques on scale models, with the cruising speed selected as the reference condition. As a result, bilge keels provide a low-maintenance, robust solution for improving roll stability with only a minimal impact on overall resistance.

2.2. Active Control Surfaces

Active control surfaces are adjustable components that play a crucial role in enhancing the maneuverability, stability, and efficiency of both marine vessels and aircraft. Unlike passive control surfaces, they can be dynamically adjusted in real-time to optimize performance under varying conditions. In planing boats, elements such as trim-tabs, transom flaps, T-Foils and interceptors are used to regulate trim, reduce drag, and improve fuel efficiency by altering the flow of water at the stern. Rudders provide directional control by pivoting to redirect water flow, while in aviation, ailerons adjust asymmetrically to control roll, ensuring smooth and stable flight. These control surfaces, whether hydrodynamic or aerodynamic, are essential for maintaining optimal performance, improving handling, and enhancing the overall efficiency of high-speed crafts and aircraft.

2.2.1. Trim-tabs

Trim-tabs are small, adjustable metal plates mounted on the trailing edge of a boat's hull, usually on the transom. They work by changing the angle of the boat's running surface in response to water pressure and speed. By adjusting trim-tabs, boats can maintain a level ride, reduce fuel consumption, and improve stability in rough waters. These are especially useful for small high-speed crafts and recreational boats. Different components of a trim-tab system are presented in Figure 5.

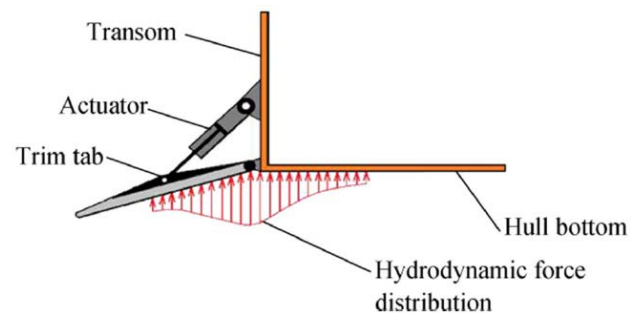


Figure 5. Trim-tab components [53]

2.2.2. Stern Flaps

Stern flaps are small adjustable plates located at the bottom of the transom (rear part of the hull). They help optimize running trim and minimize resistance at high speeds. By adjusting the angle of these flaps, vessels can achieve better fuel efficiency and stability. They are particularly useful for planing and semi-displacement crafts. a stern flap is shown in Figure 6.

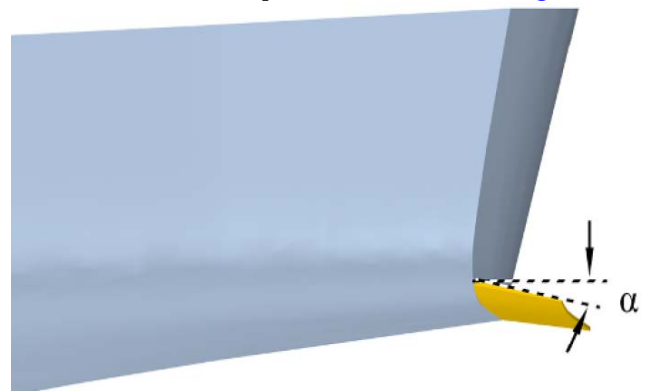


Figure 6. Stern Flaps Positioning on a Planing Boat stern [21]

2.2.3. Interceptors

Interceptors are vertical plates that extend downward from the transom to alter water flow and adjust trim. Unlike transom flaps, which rotate, interceptors move vertically to create an immediate and effective change in hydrodynamic pressure distribution at the stern. This adjustment not only improves trim but also plays a significant role in controlling pitch motion, particularly at high speeds. By generating lift and modifying the flow beneath the hull, interceptors enhance stability, reduce drag, and contribute to smoother and more efficient navigation. Due to their responsiveness and effectiveness, interceptors are widely used in modern high-speed vessels and waterjet-propelled crafts. In Figure 7, interceptor is illustrated on a hull.

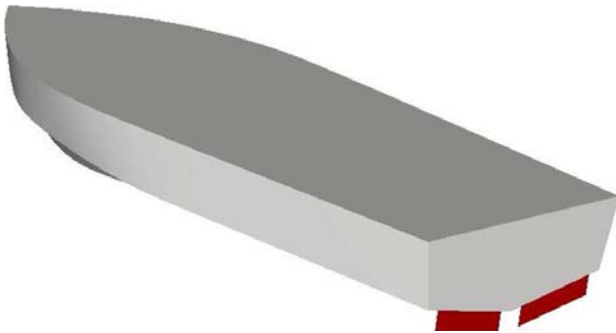


Figure 7. The implementation of an interceptor aft of a planing craft [6]

2.2.4. Rudders

Rudders are essential control surfaces used to manage the yaw motion of ships and aircraft, allowing them to turn and maneuver effectively. By deflecting water or airflow to one side, rudders generate a lateral force that changes the direction of the vessel or aircraft. In marine applications, the rudder is typically mounted at the stern and pivots to steer the vessel during navigation. In aviation, it is located on the vertical stabilizer and serves a similar directional function. Whether in water or air, rudders are critical for maintaining and adjusting the heading, enabling smooth directional changes and precise control during turns and course corrections, (Figure 8).

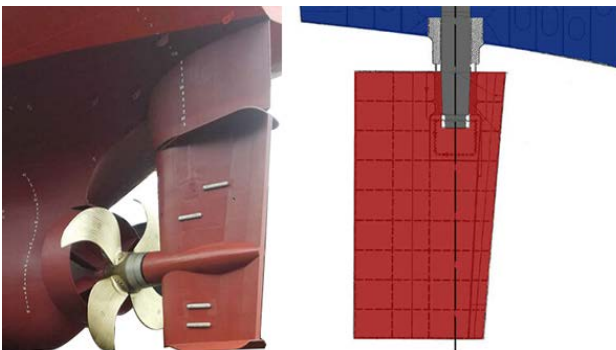


Figure 8. spade rudder attached to hull [62]

2.2.5. Ailerons

Ailerons are critical aerodynamic control surfaces located on the trailing edge of an aircraft's wings, typically near the wingtips. They function in pairs, moving in opposite directions to control the aircraft's roll motion. When one aileron moves upward, reducing lift on

that wing, the opposite aileron moves downward, increasing lift on the other wing. This differential lift causes the aircraft to roll and facilitates turning maneuvers. Ailerons are essential for maintaining lateral stability, enabling precise directional changes, and enhancing overall flight control. Their effectiveness is particularly significant in high-speed aircraft, where aerodynamic forces require continuous adjustments to ensure smooth and stable flight.

2.2.6. T-foils

T-foils are specialized hydrofoils shaped like an inverted "T" and typically mounted on the bow or amidships of high-speed marine vessels. They are used to generate lift and counteract heave and pitch motions, improving stability, ride comfort, and efficiency. One of the unique characteristics of T-foils is that they can function as either passive or active control surfaces, depending on the design and operational requirements.

In a passive setup, the T-foil remains fixed at a predetermined angle, providing constant hydrodynamic lift without any active adjustment during operation. In contrast, active T-foils are equipped with actuation systems, allowing the angle of attack to be dynamically adjusted in real-time based on vessel motion sensors and control algorithms. Active T-foils can significantly enhance performance by responding immediately to changes in wave conditions, vessel speed, or load distribution. The inactive T-foil maintains a static position, while the active T-foil can pivot to generate optimal lift forces, demonstrating its adaptability and effectiveness in controlling vessel motion.

RCSs are advanced solutions integrated into high-speed vessels to improve passenger comfort and reduce structural loads caused by wave-induced motions. These systems typically involve the use of active hydrofoils and control surfaces positioned at the fore and stern of the vessel to dynamically counteract ship motions such as pitch and heave. A common configuration includes a retractable T-foil mounted at the aft of the center bow and stern tabs installed on the demi-hull transoms, as widely applied by Incat Tasmania in their vessel designs. By adjusting the position and angle of these control surfaces in real-time, RCS significantly enhances ride quality, reduces impact forces on the hull structure, and allows high-speed vessels to maintain higher operational speeds even in rough sea conditions. Figure 9 and Figure 10 present T-foils activation system and RCS.

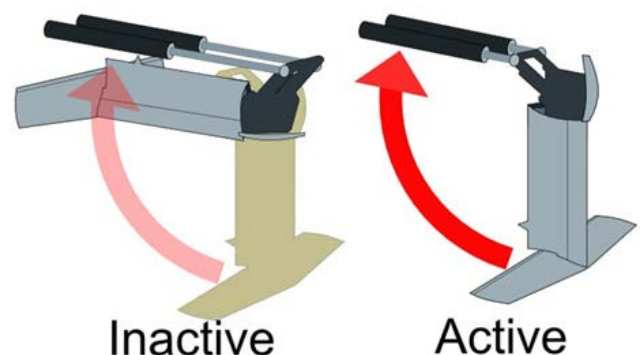


Figure 9. active and passive T-foils mechanism [59]



Figure 10. T-foil near the center bow [44]

2.2.7. Cost Assessment of Active and Passive Control Surfaces

When analyzing control surfaces from a cost perspective, a clear distinction emerges between active and passive systems. Active control surfaces, such as trim-tabs, interceptors, T-foils, and rudders, require complex actuation systems, including hydraulic or electric actuators, sensors, controllers, and power supplies. These components enable real-time adjustments but also significantly increase the initial installation cost, system complexity, and long-term maintenance requirements.

Additionally, the integration of software algorithms, feedback mechanisms, and redundancy systems for reliability adds to both the capital and operational expenses.

In contrast, passive control surfaces such as stern wedges, fixed hydroplanes, and fin stabilizers are generally simpler in design and construction, with no moving parts or control electronics. Their fixed nature means they are less expensive to manufacture and install, and they require minimal maintenance over time. However, the lack of real-time adaptability may result in suboptimal performance in varying conditions. Therefore, the selection between active and passive systems often involves a trade-off between cost efficiency and performance flexibility, with active systems offering superior dynamic control at a higher financial investment.

2.2.8. Wrap-up

Across the various types of control surfaces, each plays a vital role in enhancing stability, maneuverability, and performance depending on the specific application and operating conditions. Passive elements such as stern wedges, fixed hydroplanes, and fin stabilizers offer simplicity and cost-effectiveness, while active components like trim-tabs, interceptors, T-foils, and transom flaps provide dynamic control and adaptability. In aircraft, surfaces like ailerons and elevators are crucial for managing roll and pitch, just as marine vessels rely heavily on dynamic trimming devices to maintain optimal hydrodynamic behavior at high speeds.

Among all these control surfaces, however, the rudder stands out as the most critical and universally indispensable component. Whether in conventional ships, high-speed crafts, or aircraft, rudders are fundamental for controlling yaw motion, enabling precise steering and directional control. Without rudders, safe navigation and effective maneuvering would be impossible, making them

a central element in both hydrodynamic and aerodynamic control systems. Their widespread presence and necessity across nearly all types of vehicles highlight their unmatched importance compared to other control surfaces.

3. Comparison of Interceptor and Trim-tab

In the field of high-speed marine craft design, reducing resistance and optimizing performance are critical goals. Two common methods used for controlling trim and enhancing hydrodynamic efficiency are interceptors and trim-tabs. Both devices influence the flow of water around the stern of the vessel but do so through different mechanisms. Understanding the differences in how they modify pressure distribution is crucial for selecting the appropriate control surface for a specific design requirement. This comparison focuses on analyzing the pressure fields generated by an interceptor and a trim-tab, aiming to highlight their effectiveness in reducing resistance and improving the performance of planing boats.

A trim-tab is a small device as adjustable plate mounted at the trailing edge of the transom. When deployed downward, it redirects the flow of water downward, causing an upward reaction force that lifts the stern and adjusts the boat's running angle. In terms of pressure distribution, a trim-tab creates a localized high-pressure zone beneath the stern where it is deflected. However, the transition between the adjusted flow region and the free-flowing water can be gradual, which sometimes leads to moderate pressure recovery and only partial improvement in lift and drag reduction. The effectiveness of trim-tabs is highly dependent on the deployment angle and the vessel's speed, often requiring careful adjustments during operation to maintain optimal trim. Figure 11 illustrates the comparison of pressure distribution associated with interceptor and trim-tab of a planing craft.

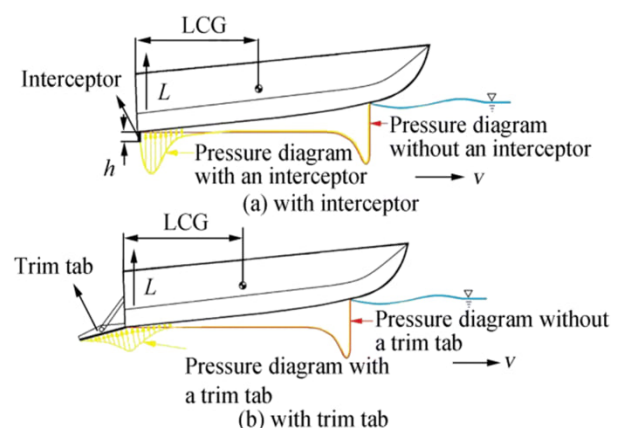


Figure 11. Comparison of the pressure distribution associated with interceptor (a) and trim-tab (b) [53]

An interceptor, by contrast, consists of a vertical blade that extends downward from the hull bottom at the transom. Unlike a trim-tab that deflects the flow, the interceptor induces a sharp discontinuity in the flow near the stern, causing a rapid increase in pressure upstream of the blade and a substantial lift force at the transom. This sharp pressure gradient creates a more efficient

redistribution of hydrodynamic forces along the hull. The pressure buildup behind the interceptor is more concentrated and immediate compared to the broader, slower-acting pressure field of a trim-tab. This stronger and more abrupt lift generation leads to better trim control and a more pronounced reduction in wetted surface area, which directly contributes to lowering drag forces. Figure 12 illustrates comparison of drag force of a planing craft in stern using an interceptor and a trim-tab.

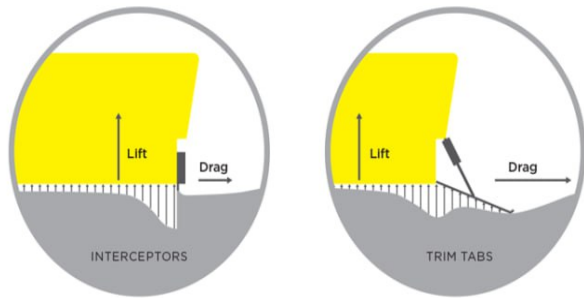


Figure 12. Drag force comparison [55]

Another important aspect to consider in the comparison is the behavior at different speeds and load conditions. Trim-tabs tend to be more sensitive to changes in vessel speed, requiring frequent adjustment to maintain effectiveness. Interceptors, on the other hand, due to their design and operation, provide a more stable and predictable pressure response across a wider range of speeds. Their vertical motion mechanism allows for rapid deployment and adjustment, making them particularly suitable for vessels that experience frequent speed and load variations. Furthermore, interceptors can be retracted fully when not needed, minimizing drag in calm conditions, a flexibility not as easily achieved with trim-tabs.

Overall, the planing boat equipped with an interceptor exhibits better reduction in resistance force compared to the planing boat fitted with a trim-tab. The sharper and more effective pressure distribution induced by the interceptor leads to greater lift generation and a more efficient reduction of wetted surface area, resulting in lower hydrodynamic drag. Consequently, vessels utilizing interceptors benefit from improved fuel efficiency, higher speeds, and enhanced operational flexibility under varying conditions, making interceptors a more advantageous choice for modern high-performance marine crafts.

4. Control Surfaces Performance

Control surfaces play a critical role in enhancing the seakeeping qualities of marine vessels. Their primary function is to reduce unwanted motions and accelerations, thereby improving onboard comfort and operational safety. By influencing the hydrodynamic forces acting on the hull, control surfaces such as bilge keels, trim-tabs, stern flaps, and interceptors can significantly alter the vessel's dynamic response to wave excitations. For instance, a bilge keel increases the vessel's roll damping, effectively lengthening the roll period and reducing roll amplitude. This directly contributes to increasing dynamic stability and mitigating excessive accelerations that can be uncomfortable or hazardous for passengers and crew.

These surfaces are designed not only to dampen motion but to reduce the domain of motion transforming a wide, uncontrolled range of movement (e.g., $\pm 30^\circ$ roll) into a narrower, more manageable motion envelope (e.g., $\pm 10^\circ$ roll). In summary, control surfaces contribute to: (1) reducing the amplitude and acceleration of motions such as roll, pitch, and heave, (2) enhancing dynamic stability, and (3) providing a smoother and more favorable ride experience. The overall result is a vessel that performs more predictably in waves, with lower structural loads and improved passenger comfort.

4.1. Controlling Procedure Diagram

The block diagram (Figure 13) illustrates the complete control loop of a fin stabilizer system used to counteract roll motions induced by wave moments. The process begins when an external wave moment acts upon the hull of the ship, generating a righting moment and initiating an undesired roll motion. This change in roll, or ship swing angle, is immediately detected by an angular velocity gyroscope, which senses the rate of rotation of the vessel. The gyroscope provides real-time feedback on the ship's roll motion and transmits this signal to the PID and comprehensive amplification unit, where the signal is analyzed and amplified to initiate an appropriate corrective response.

Once processed, the control signal is passed through an amplifier system and directed to an electro-hydraulic servo valve, which regulates the hydraulic flow to the fin cylinder. This valve adjusts the position of the fin by controlling a variable pump, based on the input from the pump swashplate displacement sensor. Simultaneously, a fin angle displacement sensor monitors the actual movement of the fin to ensure accuracy and provide feedback to the controller. The entire system works in a closed-loop manner, where continuous input from the gyroscope allows the captain or an automated controller to command real-time adjustments to the fin angle. The fin stabilizer, actuated by this process, generates a hydrodynamic counteracting moment to oppose the wave-induced roll, thus stabilizing the vessel and improving ride comfort and operational safety.

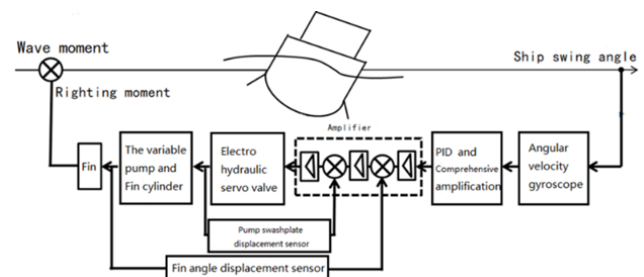


Figure 13. Block diagram of fin stabilizer control system [58]

5. Minimization of Resistance by trim-tab

Trim-tabs play a crucial role in reducing hydrodynamic resistance and improving the efficiency of planing boats by optimizing their running trim. These small, adjustable metal plates, mounted on the transom, help control the vessel's pitch angle by redirecting water flow and altering

lift distribution along the hull. By adjusting the trim-tabs to achieve an optimal trim angle, the wetted surface area of the hull is minimized, leading to a significant reduction in drag. This results in lower fuel consumption, improved speed, and enhanced stability, particularly in varying sea conditions. Properly calibrated trim-tabs ensure that the vessel maintains an efficient running posture, preventing excessive bow rise or stern squat, ultimately contributing to smoother and more economical navigation.

6. Porpoising Instability

Porpoising is a dynamic instability that frequently affects high-speed planing boats, characterized by a repetitive oscillatory motion involving both vertical (heave) and rotational (pitch) movements. This phenomenon arises due to the coupling of heave and pitch motions, where the vessel's bow repeatedly rises and falls in an uncontrollable manner. As the boat moves forward at high speeds, changes in hydrodynamic lift and moment cause the bow to pitch up and down cyclically, leading to unstable and uncomfortable ride conditions, increased structural stress, and potential loss of control.

To mitigate porpoising instability, active and passive control surfaces such as interceptors and trim-tabs are employed. These devices work by adjusting the pressure distribution along the hull, generating corrective lift forces at the stern to stabilize the vessel's motion. Interceptors, with their rapid deployment and retraction capabilities, and trim-tabs, through their adjustable deflection angles, serve to dampen the coupled oscillations of heave and pitch, thereby enhancing stability and safety.

6.1. Coupled Dynamic Equations of Motion in Heave and Pitch

The mathematical description of this coupled motion is captured by the equations of motion for heave and pitch, where the interaction between vertical forces and pitching moments is modeled. These equations serve as the foundation for designing effective control strategies to suppress porpoising.

6.2. Stepped Planing Hulls to Reduce Porpoising Instability

Stepped planing hulls are a widely adopted solution for addressing porpoising instability in high-speed vessels. In a traditional, smooth-bottomed planing hull, the pressure distribution under the hull is concentrated over a broad area, resulting in strong lift forces at limited points. This concentration can amplify vertical oscillations, leading to porpoising an unstable, repetitive pitching motion that reduces ride comfort and operational safety.

By introducing steps into the hull design, the continuous pressure distribution is strategically interrupted and divided into two or more distinct lifting surfaces. Each step creates a break in the water flow, redistributing the pressure and producing lift at multiple separated points along the hull. This separation significantly reduces the magnitude of pressure acting on any single area, thereby improving longitudinal stability. The result is a more

balanced lift distribution, a decrease in oscillatory pitch motions, and a smoother, more stable ride, especially at high speeds. Consequently, stepped hulls are highly effective in minimizing porpoising behavior, enhancing both performance and safety in planing crafts. Figures 14 and 15 illustrate how steps are designed on a planing hull.

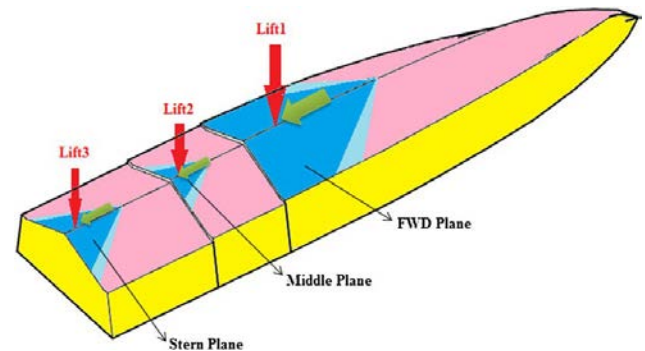


Figure 14. Wetted surface reduction and lift distribution using steps [57]

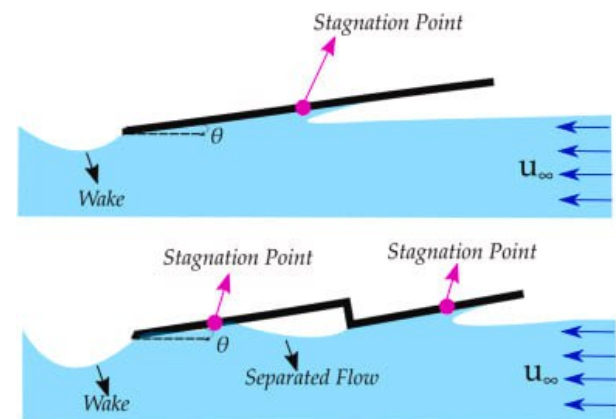


Figure 15. the effects of step on the fluid motion [56]

7. Motion Sickness Incidence

Motion sickness incidence (MSI) is a key parameter in assessing passenger comfort aboard marine vessels, particularly high-speed crafts. It is defined as the percentage of individuals likely to experience seasickness due to vessel motion over a specific period typically measured by observing how many out of 100 passengers exhibit symptoms after a set duration, such as two hours at sea. MSI is directly related to motion acceleration, especially in the vertical direction (heave) and angular motion (pitch). The location of individuals on the vessel significantly affects their exposure to these accelerations; for example, those on deck are more exposed to combined heave and pitch motions, whereas passengers near the center of gravity mostly experience heave, reducing their susceptibility. Additionally, individual tolerance, experience, and adaptation such as in the case of seasoned crew members play a crucial role in MSI response.

To reduce MSI and improve ride comfort, the integration of control surfaces is essential. Devices like trim-tabs, interceptors, T-foils, and fin stabilizers are designed to reduce the magnitude and frequency of heave and pitch accelerations, especially in rough sea conditions. By actively or passively modifying the hydrodynamic forces acting on the hull, these surfaces suppress

unwanted motions and dampen oscillations. As a result, the overall acceleration levels are decreased, which directly correlates with a lower MSI percentage. Therefore, control surfaces not only contribute to dynamic stability and vessel efficiency but also play a vital ergonomic role by minimizing the physiological impact of motion on passengers and reducing the likelihood of motion-induced discomfort or seasickness.

8. Conclusions

This study systematically reviewed the types, mechanisms, and applications of control surfaces in planing boats, distinguishing between active and passive systems. It was demonstrated that while passive devices such as stern wedges, hydroplanes, and bilge keels offer cost-effective roll and pitch stabilization, active systems like trim-tabs, interceptors, T-foils, and rudders enable real-time adjustments and superior performance under variable sea states. Through both qualitative explanation and quantitative analysis such as CFD simulations and pressure distribution comparisons the superior efficiency of interceptors in drag reduction and trim control was highlighted. The importance of rudders was reinforced due to their critical function in directional control across all vessel types.

Additionally, the paper explored the use of control surfaces in mitigating porpoising instability and minimizing hydrodynamic resistance, emphasizing the design value of stepped hulls and optimal appendage sizing. The relationship between motion accelerations and MSI was explained, underlining the ergonomic importance of motion control for onboard comfort. Control surface systems were shown not only to enhance hydrodynamic performance but also to reduce structural loads and improve passenger safety.

Finally, an evaluation of cost implications clarified that while active control surfaces require more sophisticated infrastructure and higher operational costs, they deliver unmatched flexibility and precision. The comprehensive literature review strengthens the case for tailored control system design based on mission profiles, vessel size, and environmental conditions. Overall, the integration of optimized control surfaces remains fundamental to the advancement of efficient, safe, and comfortable high-speed marine transportation.

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