Aerodynamic Stability Measurement of Seaplane Twin Floats: The Role Type of Control Surface Variations

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ABSTRACT

The aerodynamic design of twin-float amphibious aircraft is challenging because airflow interactions between the fuselage, wings, and pontoons can interfere with one another. Most prior work has examined water performance but offers less analysis of aerodynamic control authority. This study fills a gap in the literature by measuring aerodynamic stability derivatives and control surface effectiveness for a twin-float configuration in subsonic flow. Wind tunnel tests were conducted at flow speeds of 35–65 m/s and angles of attack from −10° to +18°. A six-component balance was used to record forces and moments for different aileron, rudder, and elevator deflections. The analysis indicates that the effectiveness of the control surfaces is linked to the wake produced by the float in a non-linear way. Aileron deflection increased the rolling moment coefficient (C_{roll}) slope by about 60%, which preserved lateral control authority even at high angles of attack. In contrast, increasing rudder deflection raised the yawing moment coefficient (C_{yaw}) by about 90%, but it also increased yaw–roll coupling, so crosswind maneuvers required corrective inputs. Elevator deflection demonstrated strong control over longitudinal stability. Positive deflections increased the nose-down pitching moment by about 70%, which helped offset the pitch-up tendency associated with the float. These results provide aerodynamic data that can be used to refine flight control laws and to define stability envelopes for designing next-generation amphibious aircraft.

Keywords-estimation; seaplane; amphibious aircraft; control surface; aerodynamic performance; wind tunnel test

I. INTRODUCTION

Seaplanes are crucial for navigating Indonesia's extensive archipelago, providing access to remote islands that lack conventional runway infrastructure [1]. Beyond facilitating tourism, logistics, and emergency care, safe operations require deep understanding of how floats alter aerodynamic stability. Engineers typically validate performance using Computational Fluid Dynamics (CFD) [2] alongside wind-tunnel testing [3] to assess how design variables, such as float placement, impact lift and drag [4, 5]. While standard flight control systems manage roll, pitch, and yaw [6], and flaps assist with lift during take-off and landing [7, 8], the addition of floats introduces unique aerodynamic interference. These structures can modify local airflow and generate cross-axis coupling, often overlooked in traditional aircraft analysis. Consequently, float geometry is a significant design factor, governing both hydrodynamic handling on the water and aerodynamic efficiency in the air [9, 10].

Control surfaces are central to aerodynamic performance in conventional aircraft and in seaplanes and amphibious aircraft [11]. Authors in [12] reported that adding floats to a conventional aircraft changes its aerodynamic characteristics. This indicates that float installation alters the baseline aerodynamic behavior and can influence the available stability margins. Authors in [13] conducted wind tunnel tests and reported that deflecting flaps, ailerons, and the rudder can increase drag and reduce lateral and directional stability, which suggests that control inputs may introduce performance penalties and coupled effects. Authors in [14] reported that both the float arrangement and the control-surface settings affect lift, drag, pitching moment, and glide ratio, indicating that aerodynamic performance and stability depend on float layout as well as control inputs. Even with these results, the published work does not fully address a key stability issue in twin-float amphibious aircraft design. There are still few experiments that report the isolated contribution of each main control surface to roll, yaw, and pitch moments at the level of stability and control derivatives when twin floats are installed. It also remains unclear where float-induced effects end and control-surface-induced effects begin. As a result, much of the research on seaplanes has focused on float design and stability while operating on water. Prior studies have examined float geometry and its placement [15] and also reported hydrodynamic stability problems, including porpoising during water take-off and landing [16]. Authors in [5, 17-20] investigated ground effects and the take-off and landing behavior of seaplanes, offering insights into these operationally critical phases. Taken together, these studies provide useful hydrodynamic and operational context, but they do not consistently provide a quantitative account of how control surface deflections change aerodynamic moments and stability responses in twin-float configurations.

This study addresses existing gaps in the analysis of twin-float amphibious aircraft by investigating how control surface deflections influence aerodynamic stability through a structured wind tunnel program. The research isolates the specific effects of aileron, rudder, and elevator manipulations on roll, yaw, and pitch moments, thereby enabling a direct evaluation of control effectiveness and potential cross-axis coupling induced by the float installation. The scope is strictly limited to experimental data derived from these primary control surfaces, with no reliance on CFD simulations. Testing was conducted under subsonic conditions at freestream speeds between 35 and 65 m/s, with angles of attack ranging from −10° to +18° and surface deflections up to ±20°. Subsequent sections outline the experimental methodology, instrumentation, and data processing techniques used to derive the relevant aerodynamic coefficients.

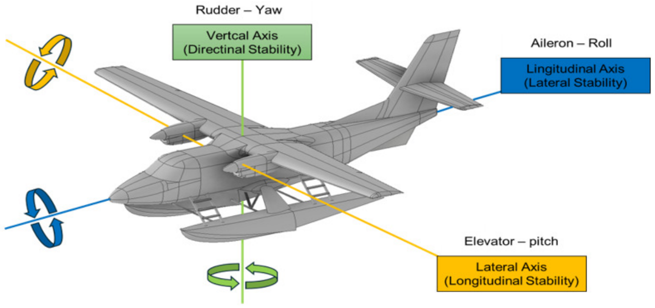

Fig. 1. Basic aircraft movement.

II. METHOD

The experiment was carried out using a 1:6.3 ratio scale model of an amphibious aircraft, built to study aerodynamic interference in twin-float layouts and to assess control surface effectiveness under those conditions (Figure 2). The wind tunnel model was made from a high-fidelity resin and reinforced with aluminum spars to maintain its shape under aerodynamic loads. It has an overall length of 2617 mm, a wingspan of 3095 mm, and a Mean Aerodynamic Chord (MAC) of 349 mm. To match the physical behavior of the full-scale aircraft as closely as possible, geometric similarity was maintained throughout, with particular attention to the twin pontoons. Each float is 1555 mm long and installed symmetrically about the fuselage centerline, with the hydrodynamic step located aft of the 25% MAC position. To align with the study's focus on control authority, the main control surfaces were scaled using fixed area ratios. The aileron chord was set to 25% of the wing chord, and the rudder and elevator areas were set to 30% of their respective stabilizer areas.

To ensure high reproducibility and minimize aeroelastic distortion, control surface deflections were established using interchangeable, precision-machined brackets rather than continuous actuators. The test matrix evaluated specific discrete settings for the ailerons (-10° to +20°) and rudder (0° to -25°), alongside a comprehensive elevator sweep ranging from -20° to +20°. Experiments were conducted at the Indonesian Low Speed Tunnel (ILST), a closed-circuit subsonic facility [21]. The model was mounted in an inverted position using a rigid strut system attached to the wing spar; this configuration was chosen to mitigate support interference within the float wake. Prior to testing, model alignment was rigorously verified using digital instrumentation to establish an accurate zero reference, as illustrated in Figure 3. Testing was conducted at a freestream velocity of 65 m/s (Mach ≈ 0.19), allowing the flow to be treated as incompressible. The Reynolds number was calculated based on the MAC. Pre-test calibration confirmed high flow quality, with turbulence intensity, velocity uniformity, and flow angularity maintained within strict tolerances. Throughout the campaign, ambient conditions, including temperature and static pressure, were continuously monitored to ensure precise dynamic pressure calculations.

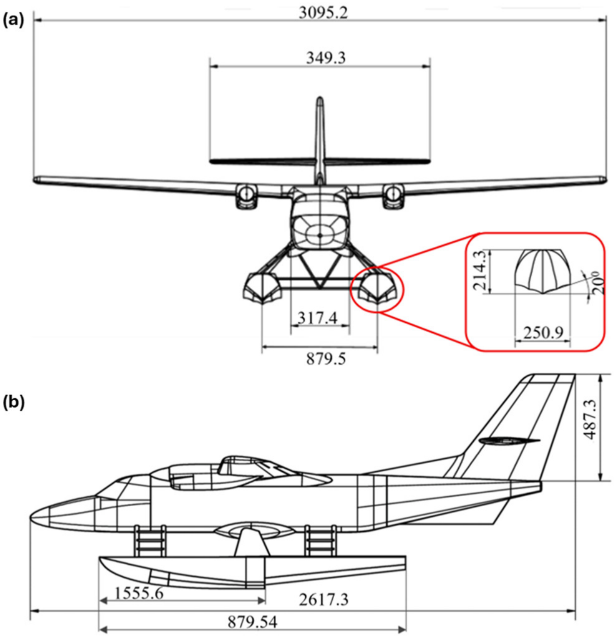

Fig. 2. Wind tunnel model of a twin-float seaplane geometry: (a) front view and (b) side view.

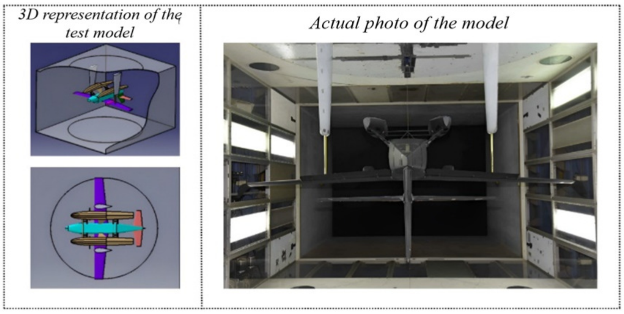

Fig. 3. Experimental setup of the model in the test section.

Experimental work was conducted at the ILST, a closed-circuit facility featuring a 4 m × 3 m × 10 m test section [21]. The study utilized a 1:6.3 scale model, fabricated from resin and reinforced with aluminum spars to ensure dimensional stability. Testing reached freestream velocities of 65 m/s, yielding a Reynolds number of approximately 1.5 × 106 relative to the MAC (c = 349 mm). Prior to operation, flow uniformity was confirmed via a five-hole pitot array, maintaining velocity deviations below ±0.2% and angularity within ±0.1%. Ambient environmental parameters were continuously tracked using precision sensors. Aerodynamic loads were quantified using a six-component external balance system with strain-gauge load cells (accuracy ±0.04%) [22]. This setup recorded the standard lift (L), drag (D), and side force (S_f), alongside pitching (M_{pitch}), rolling (M_{roll}), and yawing moments (M_{yaw}) [23], which are defined by:

Three-component aerodynamic forces:

$$L = \frac{1}{2}\rho U^2 S C_L \,,\ C_L = \frac{L}{\frac{1}{2}\rho U^2 S} \qquad (1)$$

$$D = \frac{1}{2}\rho U^2 S C_D,\ C_D = \frac{D}{\frac{1}{2}\rho U^2 S} \qquad (2)$$

$$S_F = \frac{1}{2}\rho U^2 S C_Y,\ C_Y = \frac{S_F}{\frac{1}{2}\rho U^2 S} \qquad (3)$$

Three-component aerodynamic moment:

$$M_{Pitch} = \frac{1}{2}\rho U^2 S\ c\ C_M,\ C_M = \frac{M_{Pitch}}{\frac{1}{2}\rho U^2 S\ c} \qquad (4)$$

$$M_{Roll} = \frac{1}{2}\rho U^2 S\ b\ C_{Roll},\ C_R = \frac{M_{Roll}}{\frac{1}{2}\rho U^2 S\ b} \qquad (5)$$

$$M_{Yaw} = \frac{1}{2}\rho U^2 S\ b\ C_{Yaw},\ C_Y = \frac{M_{Yaw}}{\frac{1}{2}\rho U^2 S\ b} \qquad (6)$$

where U is the wind speed [m/s], ρ is the air density [kg/m^3], S is the wing area [m^2], c is the MAC [m], b is the wingspan [m], and C_L, $C_{D,}$ and C_{SF} are the lift, drag, and side force coefficient, respectively. C_M, $C_{roll,}$ and C_{Yaw} are the pitching moment coefficient, rolling moment coefficient, and turning moment coefficient, respectively.

To ensure signal quality and mitigate turbulence effects, data were sampled at 300 Hz and averaged over 5-s intervals. The study utilized standard coordinate definitions for all force and moment components [23]. Data reliability was validated through a rigorous uncertainty analysis, which indicated a calibration nonlinearity of ±0.05% and derived coefficient uncertainties between ±1.2% and ±2.0% after necessary corrections. Furthermore, repeatability tests confirmed that deviations remained under 2%. Measurements were conducted under steady-state conditions across a sweep of angles of attack (−10° to +18°) and yaw (−20° to +20°), varying control surface deflections as defined in the test matrix.

III. RESULTS AND DISCUSSION

A. *Effect of Aileron Deflection*

The effectiveness of aileron deflection in generating rolling moments is critical for the lateral maneuverability of the seaplane, particularly given the potential aerodynamic interference from the twin-float configuration [6]. Figure 4(a) illustrates the influence of sideslip angle (β) on the yawing moment coefficient (C_{Yaw}) at different aileron deflections. The results show that C_{Yaw} increases as β increases, meaning a larger yawing moment is generated with greater sideslip, and this trend is consistent across aileron deflections, although with minor variations. As presented in Figure 4(b), the relationship between the rolling moment coefficient (C_{roll}) and sideslip angle (β) exhibits a linear trend, consistent with classical lifting line theory, indicating that the flow over the ailerons remains attached within the tested envelope. The slope of this curve represents the lateral stability derivative, or the dihedral effect. The data reveal that positive aileron deflections (Ar = −10°, A_l = 10° and A_r = −20°, A_l = 20°) significantly amplify the rolling moment. Quantitatively, the rolling moment gradient increases by approximately 25–30% at 10° deflection and reaches 50–60% at 20° deflection compared to the neutral baseline. A similar magnitude of authority is observed in the negative deflection cases.

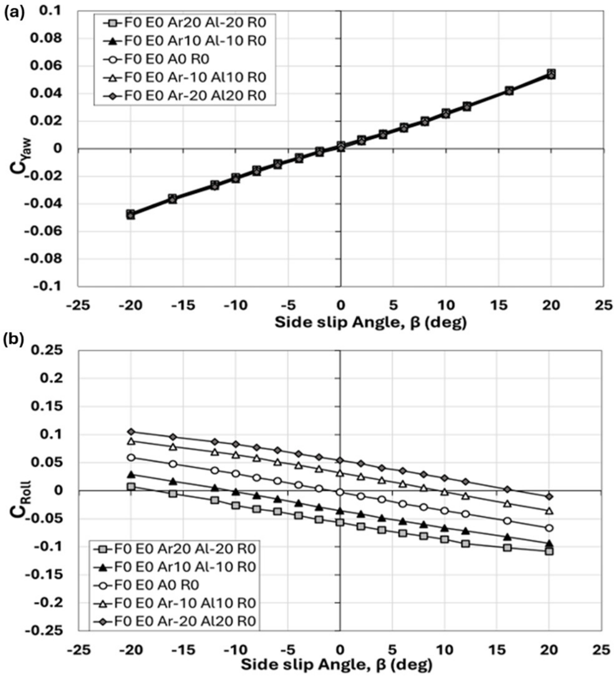

Fig. 4. (a) C_{yaw} vs. β, and (b) C_{roll} vs. β for various aileron deflections.

From a stability perspective, these results indicate robust lateral control authority. The substantial increase in rolling moment at higher deflection angles confirms that the ailerons provide sufficient authority to overcome the inherent roll stability generated by the high-wing and float configuration [7]. This is crucial for maintaining lateral control during crosswind landings or when countering the adverse yaw inherent in twin-float aircraft [24]. The linearity of the response suggests that despite the complex wake generated by the pontoons, the ailerons retain their effectiveness in regulating the bank angle and balancing centrifugal forces during coordinated turns [25].

B. *Effect of Rudder Deflection*

The rudder provides the primary means of yaw control, governing the aircraft's directional stability. In a twin-float configuration, the vertical tail must not only provide directional stiffness but also counteract the destabilizing yawing moments created by the aerodynamic drag of the floats. Figure 5(a) illustrates the yawing moment coefficient (C_{Yaw}) as a function of sideslip angle (β). The positive slope ($C_{Yaw} > 0$) across all configurations confirms that the aircraft possesses positive static directional stability. The deflection of the rudder introduces a significant change in the yawing moment, shifting the trim point. Quantitatively, the gradient of C_{Yaw} increases by 35–40% at 10° deflection and by nearly 90% at −25°. This non-linear increase at higher deflection angles suggests that the vertical tail efficiency is maintained even at high sideslip angles, providing high yaw control power. However, the interaction between yaw and roll is pronounced. Figure 5(b) highlights the cross-coupling effect, where rudder deflection induces a rolling moment (C_{roll}). The data show that at rudder deflections of −10° and −25°, the slope of the C_{roll} vs. β curve steepens by 25% and 60%, respectively. Theoretically, this is attributed to the vertical offset between the vertical tail's center of pressure and the aircraft's longitudinal axis, which creates a rolling moment arm. While this coupling assists in entering banked turns, the significant increase at −25° deflection indicates a risk of adverse roll, where excessive rudder input could induce an uncommented roll, potentially compromising lateral stability [25]. Therefore, while the rudder authority is sufficient for directional control, the substantial yaw roll coupling necessitates careful pilot compensation or the implementation of a yaw-damper system to maintain stable flight dynamics [26].

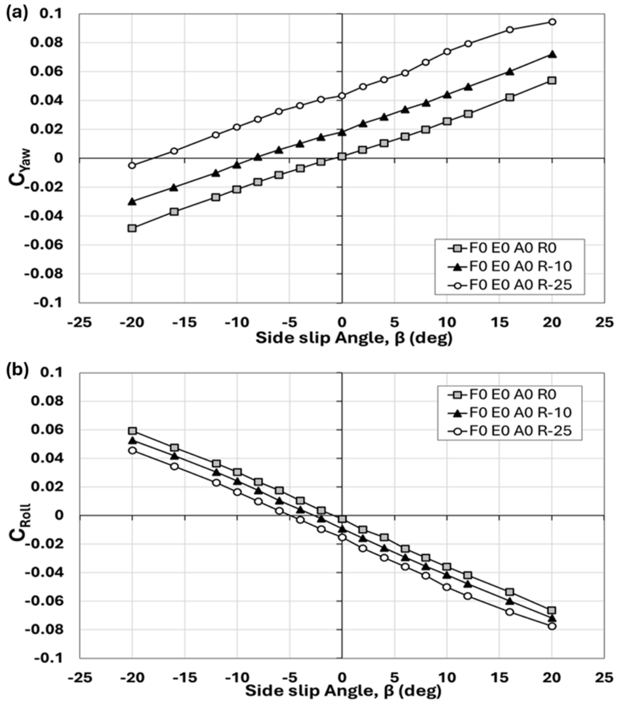

Fig. 5. (a) C_{yaw} vs. β, and (b) C_{roll} vs. β for various rudder deflections.

C. Effect of Elevator Deflection

The longitudinal static stability of the aircraft is determined by the slope of the pitching moment coefficient (C_m) versus the angle of attack (α), denoted as C_m. For a stable aircraft, this slope must be negative (C_m< 0). Figure 6 depicts the $C_m$vs. α curves for varying elevator deflections. In all tested cases, the slope remains negative, confirming that the twin-float seaplane maintains positive static longitudinal stability. The elevator deflection primarily acts to shift the C_m curve vertically, changing the trim angle of attack (α), but the data also reveal a change in the stability margin.

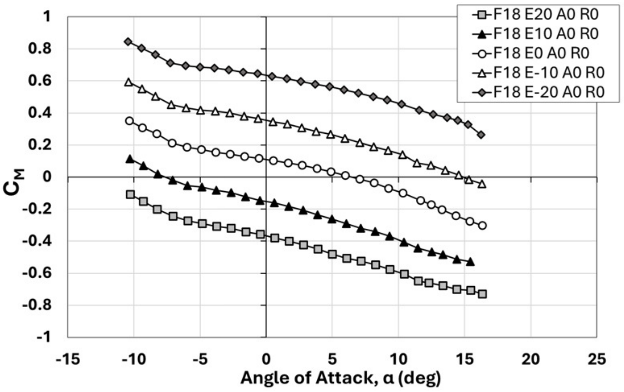

Fig. 6. C_M v.s α for various elevator deflections.

Positive elevator deflections (trailing edge down) result in a steeper negative gradient, with the nose-down moment capacity increasing by approximately 30% at +10° and up to 70% at +20°. This high authority is critical for pitch recovery, particularly to counteract the nose-up pitching moment often induced by float drag at high angles of attack [27]. Conversely, negative deflections (trailing edge up) produce the necessary nose-up moments for rotation during take-off. The results show that at -20° deflection, the restorative nose-up moment is sufficient to overcome the pitch stiffness. The variation in gradient magnitude, specifically the 75% change at −20°, highlights a strong elevator control power. This ensures that the pilot has sufficient authority to trim the aircraft across a wide range of operational speeds and centers of gravity, effectively managing the pitch behavior despite the aerodynamic penalties introduced by the pontoon structures [28].

IV. CONCLUSIONS

This study experimentally investigated the aerodynamic stability effects of aileron, rudder, and elevator deflections on a twin-float seaplane using subsonic wind tunnel testing. The results show that each control surface contributes differently to aircraft stability and maneuverability. Aileron deflections primarily influence rolling stability, increasing the rolling moment coefficient gradient by up to 60%, which enhances lateral control. Rudder deflection significantly increases the yawing moment coefficient, with gradients rising by nearly 90% at −25°, indicating improved directional control, although excessive deflection may introduce adverse rolling effects. Elevator deflections strongly affect pitching stability, where positive deflections increase nose-down pitching moments by up to 70%, while negative deflections enhance nose-up behavior useful for take-off and climb. These findings confirm that proper adjustment of control surface deflection angles is essential to maintain a balance between maneuverability and aerodynamic stability, and provide valuable reference data for the optimization of amphibious aircraft used in Indonesia's maritime environment.

For future research, it is proposed to compare experimental results with Computational Fluid Dynamics (CFD) simulations to validate aerodynamic coefficient behavior and provide detailed flow visualization around the floats and control surfaces. In addition, further investigation into scale effects, such as Reynolds number variation and the transition from model-scale to full-scale performance, will improve the accuracy of applying wind tunnel results to real aircraft operations. Expanding the study to include other configurations, such as flap deflection or different float geometries, may also provide deeper insights into seaplane stability during take-off and landing phases.

DECLARATION OF COMPETING INTERESTS

Not applicable to this work.

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DATA AVAILABILITY

Data acquisition and processing are described within this paper. No external dataset was used. Further details can be granted by the corresponding author upon request.

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