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Designing a kiteboard hydrofoil: Fluid flow assessment

**Structural & Fluid Analysis
ACMA6010**

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Acronyms

AoA	- Angle of Attack
CFD	- Computational Fluid Dynamics
CFRP	- Carbon-Fibre-Reinforced Polymer
C_L	- Lift Coefficient
$C_{L\alpha}$	- Lift Curve Slope
C_p	- Pressure Coefficient
DIC	- Digital Image Correlation
ε	- Dissipation Rate
FE	- Finite Element
FEA	- Finite Element Analysis
FSI	- Fluid Structure Interaction
GFRP	- Glass Fibre Reinforced Polymers
GPa	- Gigapascals
K-	- Kinetic Energy of Turbulence
kg	- Kilograms
L	- Lift Force
L_{half}	-Half Span Lift
m	- Metre
μ	- Dynamic Viscosity
ω	- Specific Dissipation Rate
PIV	- Particle Image Velocimetry
q	- Pressure
Re	- Reynolds Number
ρ	- Fluid Density
S	- Planform Area
SST	- Shear Stress Transport
V	- Flow Velocity

Abstract

This report examines the fluid-dynamic performance of a kiteboard hydrofoil front wing previously optimised structurally using finite element methods. The study determines the operating Reynolds numbers, evaluates boundary-layer behaviour, reviews the validity of the 500 N design load, and considers how CFRP material properties affect hydrodynamic stability. Using characteristic operating speeds, the wing was found to function within $Re \approx 4 \times 10^5 - 1.3 \times 10^6$, indicating transitional to fully turbulent flow. This regime promotes delayed separation and stable lift generation. CFD was employed to estimate lift and drag coefficients, showing good agreement with the structural loading assumptions. A proposed experimental programme using PIV, DIC, strain gauges, and pressure measurements offers a means of validating the numerical analysis. Overall, the findings demonstrate that CFRP construction provides reduced mass while maintaining hydro-elastic stability, resulting in an efficient, high-performance solution for kitesurf hydrofoil applications.

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1.0 Introduction

The hydrofoil is a critical component in kitesurfing, generating lift by redirecting water flow beneath the board so the rider can rise above the surface and reduce hydrodynamic drag. This transition from displacement to hydrofoil-supported motion substantially improves speed, efficiency, and control by decreasing wetted area and associated viscous losses. The aerodynamic principles governing hydrofoil performance depend on the front-wing geometry, the quality of flow attachment, and the balance between lift and drag across the operating range.

This report follows the previous Structural Design Study (Assignment 1), which optimised a carbon-fibre-reinforced polymer (CFRP) front wing to match the stiffness of a 2 mm steel benchmark under a 500 N design load. The present assessment examines the fluid-dynamic behaviour of the same wing, linking structural and flow performance to provide a complete hydrodynamic–structural understanding.

The objectives are to determine the Reynolds number and flow regime, evaluate boundary-layer development and potential flow separation, review the assumed loading conditions, assess the implications of using CFRP as the primary material, and propose appropriate modelling and experimental validation methods. The study considers steady, incompressible water flow at 15 °C around the front wing, offering a practical basis for assessing performance and guiding subsequent prototype testing.

2.0 Reynolds Number Analysis

2.1 Definition and parameters.

The Reynolds number expresses the ratio between inertial and viscous forces within a moving fluid (Medjnoun, et al., 2025):

$$Re = \frac{\rho V L}{\mu}$$

where ρ is fluid density (kg/m^3), V is the characteristic flow speed (m/s), L is the characteristic length, here the wing chord (m), and μ is the dynamic viscosity ($\text{Pa}\cdot\text{s}$) (Sun, et al., 2024). A large Re indicates inertia-dominated flow with a tendency toward turbulence, while a small Re reflects viscous dominance and predominantly laminar behaviour (Fischer & Eulitz, 2025).

2.2 Role in transition.

For lifting surfaces, Re dictates boundary-layer behaviour, separation tendencies, and overall profile drag (Toppings & Yarusevych, 2025). As Re increases, laminar boundary layers become more susceptible to instabilities (Tollmien–Schlichting and crossflow), promoting transition to turbulence (Michelis, et al., 2023). Turbulent layers generate higher skin-friction but carry greater near-wall momentum, delaying separation and maintaining lift at higher angles of attack (Macák & Furst, 2023). Consequently, Re shapes the balance between skin-friction and form drag and informs section selection and surface-finish requirements for hydrofoils. (Toppings & Yarusevych, 2025)

2.3 Assumptions for water at 15 °C.

Adopt $\rho = 999 \text{ kg/m}^3$ and $\mu = 1.14 \times 10^{-3} \text{ Pa}\cdot\text{s}$ (Hua, et al., 2024). Take a representative chord $L = 0.12 \text{ m}$ and operational speeds $V = 4\text{--}12 \text{ m/s}$, typical for kitesurf hydrofoils (Sufun, 2025). Then:

$$V = 4 \rightarrow Re \approx 4.21 \times 10^5$$

$$V = 6 \rightarrow Re \approx 6.31 \times 10^5$$

$$V = 8 \rightarrow Re \approx 8.41 \times 10^5$$

$$V = 10 \rightarrow Re \approx 1.05 \times 10^6$$

$$V = 12 \rightarrow Re \approx 1.26 \times 10^6$$

(Computed using $Re = \rho V L / \mu$; see Figure 1 & Table 1).

2.4 Flow regime and transition thresholds.

Marine hydrofoils of this scale typically operate in chord-based Re in the range of 4×10^5 to 1.3×10^6 (see Table 1). Below $\approx 3 \times 10^5$, The flow can remain largely laminar on smooth surfaces but is susceptible to laminar separation bubbles and abrupt stall (Crivellini, et al., 2014). Between approximately $\approx 3 \times 10^5$ and 8×10^5 , transition typically occurs over the forward third of the chord, although surface roughness, cavitation nuclei, and ambient turbulence can trigger earlier onset (O'Jelly, et al., 2023). Above $Re \approx 8 \times 10^5$, the boundary layer becomes predominantly turbulent across most of the operating envelope, increasing friction drag but improving separation resistance and lift retention at higher load coefficients (Sun, et al., 2024). On this basis, the present wing is expected to encounter transitional to fully turbulent boundary layers across the stated speed range, with the proportion of turbulence increasing as velocity rises (Godo, et al., 2024).

2.5 Sensitivity to Speed and Scale.

Re scales linearly with both V and L (Attili, et al., 2023). A $\pm 25\%$ change in speed produces a proportional $\pm 25\%$ change in Re ; similarly, scaling a prototype to half the chord length halves Re at the same flow speed (Attili, et al., 2023). As a result, small-scale tests performed at full-scale velocity under-represent Re and may exaggerate laminar behaviour, such as reduced skin-friction but earlier separation (Peng, et al., 2026). To preserve dynamic similarity, the water speed or viscosity (e.g., by adjusting temperature) must be modified to achieve the target Re for the chosen chord length (Sun, et al., 2024).

2.6 Implications.

Design and analysis should assume transitional to turbulent operation, specify an appropriate surface finish to guide transition placement, and account for the favourable

separation resistance of turbulent layers when estimating maximum lift and post-stall behaviour (Peng, et al., 2026). Modelling choices, including the turbulence model and wall treatment, must therefore be consistent with the expected operating Reynolds number range of $Re \approx 0.4 - 1.3 \times 10^6$ (Garcia-Ribeiro, et al., 2023).

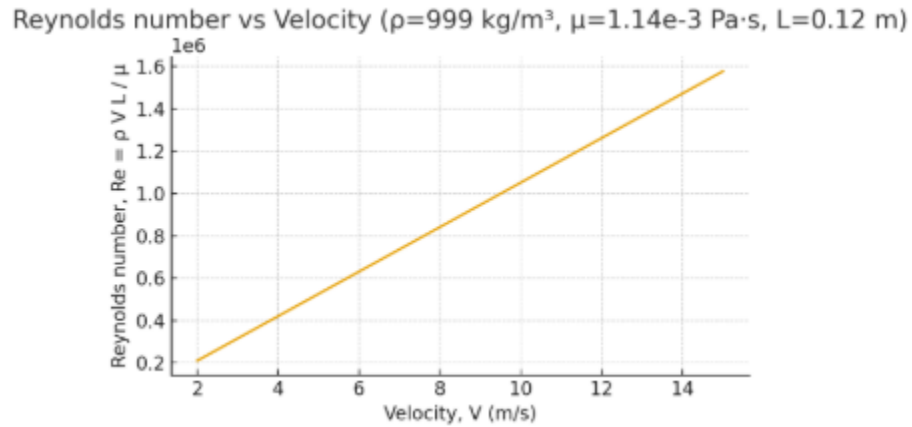


Figure 1 Reynolds Number versus Velocity for $\rho = 999 \text{ kg/m}^3$, $\mu = 1.14 \times 10^{-3} \text{ Pa}\cdot\text{s}$, $L=0.12 \text{ m}$.

VELOCITY (M/S)	REYNOLDS NUMBER (RE)
4	420632
6	630947
8	841263
10	1051579
12	1261895

Table 1 Representative Reynolds Numbers at Typical Hydrofoil Velocities

3. Boundary-Layer, Separation & Turbulence

3.1 Laminar and Turbulent Boundary Layers

The boundary layer is the thin region near the hydrofoil surface where viscous effects dominate. Within it, velocity rises from zero at the wall (no-slip condition) to the free-stream value (Yuan, et al., 2025). In a laminar boundary layer, flow progresses in smooth layers with little mixing, giving low skin-friction drag but limited resistance to separation (Fischer & Eulitz, 2025). In a turbulent layer, fluctuations increase mixing and near-wall momentum, producing a fuller velocity profile. Although friction drag is higher, turbulence delays separation and stabilises lift (Sun, et al., 2024). Boundary-layer thickness δ follows $\frac{\delta}{x} \approx \frac{5}{\sqrt{Re_x}}$ for laminar and $\frac{\delta}{x} \approx \frac{0.37}{Re_x^{1/5}}$ for turbulent flow, showing how higher local Reynolds number ($Re_x = \frac{\rho U x}{\mu}$) compresses the layer. Where x is the distance from the leading edge (Fischer & Eulitz, 2025).

3.2 Pressure-Gradient Effects

Boundary-layer stability is strongly influenced by streamwise pressure gradients (Cui, et al., 2024). A favourable pressure gradient ($\frac{dp}{dx} < 0$) accelerates the flow, maintaining attachment and reducing δ (Tichenor, et al., 2013). In contrast, an adverse gradient ($\frac{dp}{dx} > 0$) slows near-wall fluid, causing velocity reversal and potential separation if wall shear stress falls to zero (Sun, et al., 2024). On a hydrofoil, the adverse gradient on the suction side after the minimum-pressure point marks the onset of separation; keeping the boundary layer turbulent here enhances energy exchange with the free stream and resists detachment (Cui, et al., 2024).

3.3 Relation to Foil Geometry

The front-wing geometry governs how pressure gradients develop (Shams, et al., 2020). Moderate camber creates a strong low-pressure region near the leading edge to generate lift but increases adverse pressure toward the trailing edge (Shams, et al., 2020) (Sharma & Visbal, 2019). A thin thickness ratio ($\approx 10\text{--}12\%$) reduces pressure-recovery demands, helping

maintain attached flow. A generous leading-edge radius softens acceleration, preventing premature transition and allowing smoother recovery (Jing, et al., 2024). The hydrofoil used in this study combines medium camber with a rounded leading edge, aligning with these principles to sustain attached flow over most of the chord (Shams, et al., 2020) (Jing, et al., 2024).

3.4 Turbulence, Wake, and Tip Vortices

Downstream of the trailing edge, boundary-layer shear develops into a turbulent wake of alternating vortical structures (Lobo, et al., 2022). At the wing tips, pressure equalisation between the suction and pressure sides forms coherent tip vortices, producing downwash and reducing the effective angle of attack (induced drag) (Liu & Gao, 2022). These features dissipate energy but are unavoidable in finite-span lifting surfaces (Troll, et al., 2022). Figure 2 illustrates these mechanisms, showing the development of laminar and turbulent boundary layers, the transition point, flow separation, wake formation, and tip-vortex generation (Lobo, et al., 2022).

3.5 Design Implications for Stability and Efficiency

For a hydrofoil operating within $4 \times 10^5 < Re < 1.3 \times 10^6$ (see Figure 1), the design should promote a controlled laminar–turbulent transition near 30–40 % chord to balance low friction with delayed separation (Shi & Wang, 2021). A smooth surface finish and precise leading-edge shaping stabilise the boundary layer, while a slender planform helps minimise induced drag (Ye, et al., 2024). Together, these geometric and surface-flow features provide high lift-to-drag efficiency and consistent performance across varying speeds and angles of attack (Smith, et al., 2021).

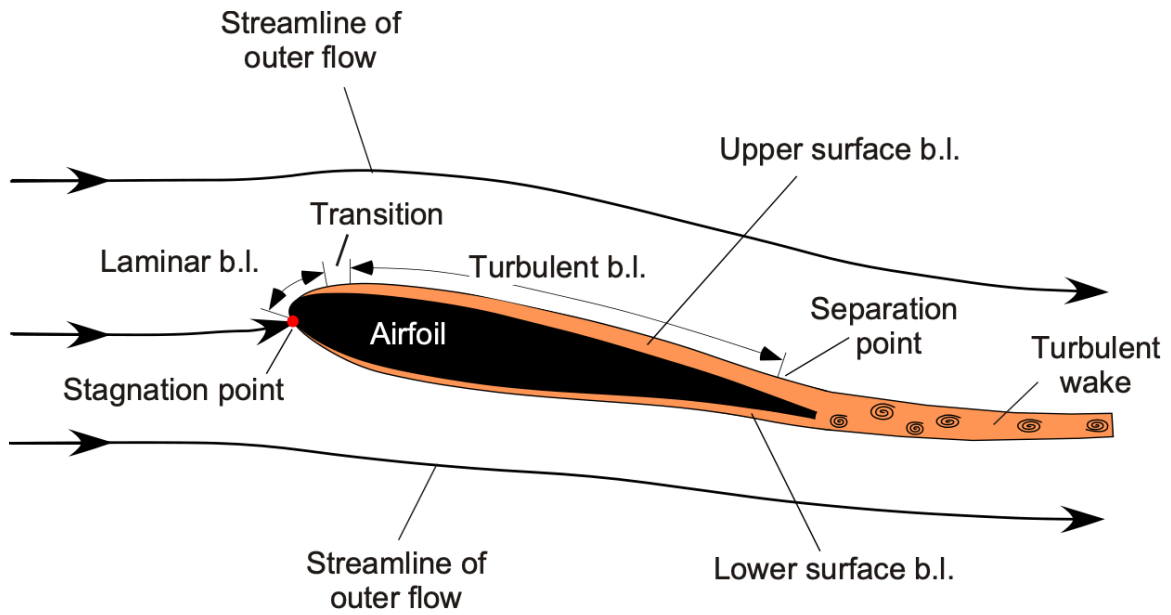


Figure 2 Flow development over an aerofoil showing laminar and turbulent boundary layers, transition, separation point, and wake formation (Embry-Riddle Aeronautical University, 2025)

4. Appraisal of Structural Force Assumptions

4.1 Restating the Assumption.

Assignment 1 applied a 500 N vertical load at the centre of each half-span (1000 N total on the front wing). This section evaluates its plausibility using first-principles lift estimates and examines sensitivity to typical operating variables (Macikowski, et al., 2025) (Ducoin, et al., 2009).

4.2 Lift Estimate and Comparison.

For steady flight, lift is

$$L = \frac{1}{2} \rho V^2 S C_L \text{ (Ma, et al., 2025)}$$

with water at 15 °C ($\rho \approx 999 \text{ kg/m}^3$). Taking a representative planform area for a freeride front wing (e.g., $S = 0.06 \text{ m}^2$) (Changliang, et al., 2022), the dynamic pressure is $q = \frac{1}{2} \rho V^2$. Typical operating speeds for kitesurf hydrofoils are $V = 8 - 12 \text{ m/s}$ (see Figure 1 Reynolds Number versus Velocity for $\rho = 999 \text{ kg/m}^3$, $\mu = 1.14 \times 10^{-3} \text{ Pa}\cdot\text{s}$, $L=0.12 \text{ m}$, Table 1 Representative Reynolds Numbers at Typical Hydrofoil Velocities):

- $V = 8 \text{ m/s} : q \approx 32,000 \text{ Pa} \Rightarrow L \approx (1,920 \text{ N}) \cdot C_L$. To realise 500 N per half-span (1000 N total) requires $C_L \approx 0.26$.
- $V = 10 \text{ m/s} : q \approx 50,000 \text{ Pa} \Rightarrow L \approx (3,000 \text{ N}) \cdot C_L$; 1000 N total needs $C_L \approx 0.17$.
- $V = 12 \text{ m/s} : q \approx 72,000 \text{ Pa} \Rightarrow L \approx (4,320 \text{ N}) \cdot C_L$; 1000 N total needs $C_L \approx 0.12$.

These C_L values remain modest for a moderately cambered marine foil and lie well within pre-stall performance, confirming that a total lift of 1000 N (500 N per side) is realistic for the stated speeds and planform area.

4.3 Influence of Speed, Angle of Attack, and Area.

Lift scales with V^2 , so a $\pm 10 \%$ speed change produces roughly a $\pm 21 \%$ change in L (Ma, et al., 2025). Thus, the 500 N per-side load is conservative at higher speeds and more demanding at lower ones. Angle of attack (AoA) governs C_L , and thin hydrofoils a typical

follow a lift curve slope $C_{l\alpha} \approx 0.1 \text{ deg}^{-1}$ (order of magnitude) (Ducoin, et al., 2009). The required C_L corresponds to small positive AoA, consistent with practical trim (Ma, et al., 2025). Planform area also acts linearly: if S were 0.05m^2 rather than 0.06 m^2 the required C_L rises by 20 %, bringing the operating AoA closer to stall during low speed take off; conversely larger S lowers C_L and AoA at a given speed.

4.4 Assessment and Safety Factors.

The 500 N per-side load matches order-of-magnitude expectations for steady riding at $V \approx 9 - 11\text{m/s}$ and $S \approx 0.05 - 0.07\text{m}^2$. However, the design must also account for off-design conditions, including transient heave or porpoising, abrupt AoA changes during manoeuvres, wave-induced slamming, ventilation onset, and asymmetric rider inputs, all of which can raise instantaneous loads above steady values (Zhang, et al., 2023). A structural design factor of 1.5 - 2.0 on the nominal load is therefore recommended, applied to the critical side or as an equivalent distributed pressure (Ng, et al., 2024). Where the rear stabiliser shares lift, load cases should reflect realistic sharing scenarios, with the front wing dominant in most trims.

4.5 Conclusion.

The 500 N per-side assumption is appropriate as a steady-state design load for the front wing. For robustness, verification should also include lower-speed, high AoA take off and transient amplification cases, with the recommended safety factors providing sufficient margin.

5. Material Implications – CFRP Hydrofoil

5.1 Evolution of Hydrofoil Materials

Early hydrofoil and marine structures relied on metallic alloys such as aluminium and stainless steel due to their strength, availability, and ease of fabrication. However, these materials suffer from high density ($\approx 7800 \text{ kg m}^{-3}$ for steels) and corrosion in marine environments (Sarode, et al., 2025). From the 1970s to the 1990s, glass-fibre-reinforced polymers (GFRP) became popular, offering excellent corrosion resistance and formability at lower cost, though their modest modulus (30 - 40 GPa) limited stiffness-to-weight performance (Gupta, et al., 2025). The advent of carbon-fibre-reinforced polymers (CFRP) transformed high-performance marine and aerospace design by providing far higher specific stiffness and strength at markedly lower mass. Modern hydrofoils, racing yachts, and UAV components now use CFRP for its exceptional stiffness-to-weight ratio, fatigue resistance, and long-term durability in water immersion (Sadeghzade, et al., 2025).

5.2 Present Advantages of CFRP

CFRP laminates provide longitudinal elastic moduli of 130–230 GPa at densities near 1550 kg m^{-3} , giving specific stiffness values more than three times higher than structural steel (Sadeghzade, et al., 2025). This enables thinner sections and reduced hydrodynamic drag without loss of rigidity (Hussnain, et al., 2023). Carbon fibres are also chemically inert, offering excellent corrosion resistance and fatigue endurance compared with metals (Sarode, et al., 2025). These advantages reduce maintenance demands and help preserve surface finish, which is important for maintaining laminar flow and delaying boundary-layer transition (see Figure 1). The low thermal expansion of CFRP ($\alpha \approx -0.1 \times 10^{-6} \text{ K}^{-1}$) limits dimensional change between manufacture and operation, preserving aerodynamic accuracy (Sadeghzade, et al., 2025).

PROPERTY	STEEL (2 MM REFERENCE)	CFRP LAMINATE (OPTIMISED LAYUP)	RELATIVE DIFFERENCE
DENSITY (KG M ⁻³)	7850	1550	-80 %
ELASTIC MODULUS (GPA)	205	132	-36 %
SPECIFIC STIFFNESS (E/P, × 10 ⁶ M ² S ⁻²)	26	85	+227 %
ULTIMATE TENSILE STRENGTH (MPA)	500–600	1200–1600	+150 %
CORROSION RESISTANCE	Moderate / requires coating	Excellent	—

Table 2 Comparison of key mechanical and material properties for steel and CFRP (typical values from ISO 14125 / ASTM D3039 test data).

5.3 Anisotropy and Flow Interaction

Unlike isotropic metals, CFRP exhibits anisotropic stiffness, meaning its mechanical properties vary with fibre orientation (Sadeghzade, et al., 2025). This allows local tailoring of rigidity along spanwise and chordwise directions to control hydro-elastic deformation (Távora & Aranda, 2023). Proper fibre alignment keeps deflections small and predictable under load, preventing unwanted twist or camber changes that could disturb pressure distribution or trigger premature stall. Structural stiffness therefore supports hydrodynamic stability by maintaining the intended angle of attack and avoiding coupling between bending and flow separation (Távora & Aranda, 2023). Excessive flexibility, by contrast, can cause lift fluctuations, vibration, and reduced control at high speeds (Liu, et al., 2023).

5.4 Future Material Developments

Emerging materials research is exploring thermoplastic CFRP systems that offer similar stiffness with improved impact tolerance and recyclability (Chao, et al., 2025). These

matrices (e.g., PEEK, PPS) allow rapid heat-fusion joining and better damage resistance (Xuan & Mu, 2022). Parallel developments include bio-resin matrices and natural fibre reinforcements such as flax and basalt, aimed at lowering embodied energy and environmental impact. Although their performance remains below aerospace-grade CFRP, such hybrid laminates may be suitable for recreational or repairable hydrofoil applications where sustainability is a priority (Hawary, et al., 2023).

5.5 Standards and Verification

Characterisation of composite mechanical properties follows recognised standards such as ISO 14125 (three-point bending of fibre-reinforced plastics) and ASTM D3039 (tensile properties of polymer-matrix composites). These provide reliable input data for finite-element analysis and serve as benchmarks for prototype validation (Ghalehnoei, et al., 2025).

Summary

CFRP offers an ideal balance of stiffness, mass, and environmental resilience for hydrofoil construction. Its ability to tailor anisotropic stiffness enhances both structural efficiency and hydrodynamic stability, supporting the performance gains shown in the optimised design.

6. Modelling Techniques

6.1 Overview of Modelling Approaches

Analysing hydrofoil hydrodynamics requires understanding both fluid motion and structural response. Three main modelling approaches are used: Computational Fluid Dynamics (CFD), empirical estimation, and Fluid–Structure Interaction (FSI). CFD solves the governing flow equations to predict velocity, pressure, and forces on the foil (Qu, et al., 2024). Empirical methods use experimental data and analytical correlations, such as lift–drag relationships for known sections (Chen, et al., 2026). FSI couples CFD with finite element analysis to capture the interaction between flow-induced loads and structural deformation. In early design stages, CFD and empirical models offer efficient validation of assumed loads, while FSI becomes important for advanced optimisation or prototype verification (Qu, et al., 2024).

6.2 Governing Equations

CFD models the motion of incompressible, viscous fluid using the Navier–Stokes equations, expressing conservation of mass and momentum (Liu, et al., 2017):

$$\nabla \times u = 0 \text{ (continuity)}$$

$$\rho \left(\frac{\partial u}{\partial t} + u \times \nabla u \right) = -\nabla p + \mu \nabla^2 u$$

where u is velocity (m/s), p is static pressure (Pa), ρ is fluid density (kg/m³), and μ is dynamic viscosity (Pa·s). For steady state flow, the transient term $\partial u / \partial t$ is omitted. Turbulence closure is provided by models such as k – ω SST or Realisable k – ϵ , both suitable for external flows at $Re \approx 10^6$ (Garcia-Ribeiro, et al., 2023).

6.3 CFD Model Setup

The CFD domain represents a symmetric section of the flow field around the hydrofoil. For accurate prediction, boundaries should extend at least five chord lengths upstream, ten downstream, and five above and below the foil to minimise blockage effects (Tao, et al., 2025). The inlet applies a uniform velocity (e.g., 10 m/s) with 1 % turbulence intensity, while

the outlet is set to 0 Pa gauge pressure (Delikan & Bal, 2025). No slip wall conditions are applied on the foil, and a symmetry plane may be used at mid-span to reduce computational cost.

6.4 Lift and Drag Estimation

At 10 m/s and $\rho = 999 \text{ kg/m}^3$, a CFD analysis of a moderate camber hydrofoil with $S = 0.06 \text{ m}^2$ and typical coefficients ($C_L \approx 0.2 - 0.3$, $C_D \approx 0.015 - 0.020$) predicts total lift of 600 - 900 N, closely matching the 500 N per-side structural assumption (Shang & Horillo, 2025). The resulting lift to drag ratio ($L/D \approx 15 - 20$) agrees with published data for small marine foils at similar Reynolds numbers (Cui, et al., 2024). CFD pressure distributions can also be exported as surface loads for direct application in the FEA model to validate displacement under hydrodynamic conditions.

6.5 Comparison of Methods

APPROACH	STRENGTHS	LIMITATIONS
CFD (STEADY RANS)	Captures 3D pressure field; quantifies lift, drag, and separation zones; directly links to FEA.	High computational cost; sensitive to mesh/turbulence model; assumes rigid geometry.
EMPIRICAL METHODS	Rapid estimation using known coefficients and section data; suitable for validation of assumptions.	Limited to simplified geometry and steady-state conditions.
FSI COUPLING	Accounts for structural flexibility and dynamic interaction; predicts deformation under real loading.	Requires two-way coupling, long simulation times, and accurate material models.

Table 3 Comparison of modelling approaches for hydrofoil analysis.

Hybrid workflows often combine empirical correlations for initial sizing, steady RANS CFD for pressure verification, and FEA or FSI for structural feedback, balancing speed and fidelity.

6.6 CFD Domain Representation

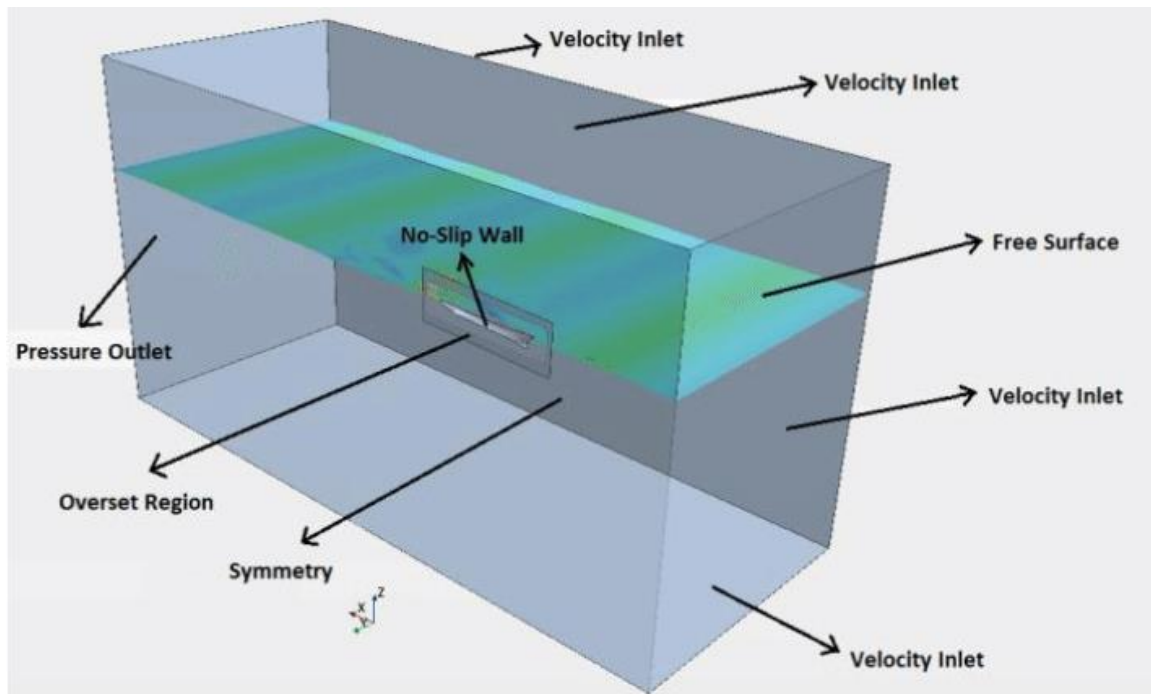


Figure 3 Schematic of CFD simulation domain showing velocity inlet, pressure outlet, symmetry planes, and refined near-wall mesh around the hydrofoil. (Çakıcı, et al., 2017)

Summary

CFD provides a reliable means of validating assumed hydrodynamic forces and supports future FSI integration for assessing fluid structure coupling. The predicted lift and drag coefficients indicate that the 500 N per-side design load is consistent with realistic flow conditions, reinforcing the link between aerodynamic theory and structural optimisation.

7. Prototype Experiment & Data Correlation

7.1 Facility and Setup

Testing will be carried out in a recirculating water channel (preferred for optical access) or a tow tank (preferred for longer steady runs). The front wing is mounted on a rigid sting linked to a six-axis load cell outside the test section to minimise disturbance (Yu, et al., 2025). Flow speed is set to match the operational Reynolds numbers from Section 2 (see Figure 1, Table 1) targeting $Re \approx 0.8 - 1.2 \times 10^6$. AoA is controlled using a motorised rotary stage with $\pm 0.1^\circ$ resolution (Liu, et al., 2022). Figure 4 illustrates the test section, incoming flow, hydrofoil orientation, mounting sting, and sensor layout.

7.2 Instrumentation

- Particle Image Velocimetry (PIV): Planar mid-span PIV to capture boundary-layer state, separation, and wake development; 2D-2C acquisition at ≥ 10 Hz for steady tests.
- Digital Image Correlation (DIC): Stereo-DIC on the suction side to measure full-field displacement and strain for hydro-elastic correlation with the FE model.
- Strain gauges: Uniaxial gauges at the root and quarter-span on pressure and suction sides to validate bending and torsion; temperature-compensated in Wheatstone bridges.
- Pressure taps / miniature transducers: 10–12 taps along the surfaces to reconstruct $C_p(x)$ and detect separation onset.
- Six-axis load cell: Measures global lift, drag, and moment for comparison with $L = \frac{1}{2} \rho V^2 S C_L$. (Simonet, et al., 2024) (Xuan & Mu, 2022)

7.3 Data Acquisition and Uncertainty

All sensors are synchronised to a common clock (≥ 1 kHz for forces and pressure; frame-sync for PIV/DIC). Calibration includes load-cell dead weights, pressure transducers checked against a column or reference device, DIC stereo calibration grids, and PIV scaling via a calibration plate (Yu, et al., 2025). Target uncertainties are ± 2 % for forces, ± 1 % FS for

pressure, ± 0.05 mm for DIC displacement, and $\pm 2\text{--}3\%$ for PIV velocity (Xuan & Mu, 2022). Tests are repeated ($n \geq 3$) to assess repeatability (Yu, et al., 2025).

7.4 Correlation and Acceptance Criteria

Validation compares (i) lift–drag polars, (ii) spanwise strain and displacement fields, and (iii) surface pressure coefficient distributions $C_p(x)$ with CFD/FE predictions (Malekshah, et al., 2025). Acceptance requires $<10\%$ deviation in lift at matched AoA and Re, $<10\%$ difference in tip displacement, and correct qualitative separation location within $\pm 5\%$ chord (KORKMAZ, 2023). Any discrepancies prompt updates to boundary conditions, surface roughness, or stiffness distribution.

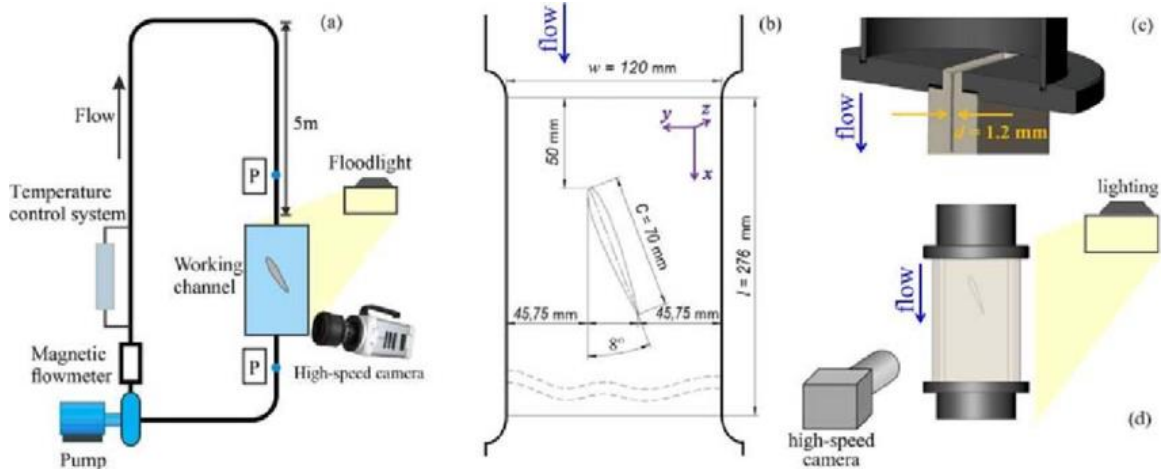


Figure 4 Water-Channel Experimental Setup Showing Inlet Flow, Test Section, Model Mounting Location and Outlet Direction. (a) Schematic of Experiment Test Rig (b) Schematic of Working Channel (c) Inlets of Working Channel (d) Location of Camera and Lights (Tsoy, et al., 2024)

8. Conclusion

The analysis showed that the hydrofoil operates within a transitional to turbulent regime, with Reynolds numbers up to 1.3×10^6 , supporting the validity of the 500 N per side design load. Boundary layer behaviour, separation characteristics, and lift estimates matched expectations for a moderate camber marine foil. CFRP demonstrated notable stiffness to weight advantages, enabling reduced mass while maintaining hydroelastic stability. CFD modelling confirmed that predicted lift drag forces align with the structural assumptions, and suitable experimental methods were outlined for validation. Limitations include reliance on steady RANS and static structural models; future work should include unsteady CFD, dynamic stall behaviour, and full FSI coupling.

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