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Designing a Kiteboard Hydrofoil: Fluid Flow Assessment
Structural & Fluid Analysis AMCA6010

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1 Introduction

This report will investigate the Reynolds number and its importance in the application of hydrofoil designs, along with its influence on flow. To achieve this, an estimation of the Reynolds number will be calculated to understand the type of flow the hydrofoil is likely to experience. This will be used to analyse boundary flow, linking separation and turbulence to the specific wing design. Additionally, the report aims to appraise the assumed 500N vertical forces used previously and evaluate some of the implications of utilising Carbon fibre reinforced plastic (CFRP) to improve the strength-to-weight ratio of the foil.

Finally, these learnings will be compared to widespread CAE modelling and experimental techniques, discussing how a hydrofoil can be simulated and assessed for fluid flow and estimating resulting structural forces.

2 Theory Review

2.1 Reynolds Number

The Reynolds number is a dimensionless quality and is used to predict the types of fluid flow around hydrofoils and general surfaces. The Reynolds number (Re) can be expressed as shown in Equation 1. Re is used to determine if a fluid's flow over a surface is laminar, turbulent or transitional. These flow characteristics dictate how inertial forces in the fluid interact with nearby surfaces, and in turn how the kinetic energy in the fluid affects pressure and velocity near the surface.

$$Re = \frac{\rho v d}{\eta} \text{ or } \frac{v d}{\nu}$$

v = velocity

ρ = density

d = diameter (or critical length)

η & ν = bulk & kinematic viscosity

Equation 1 Reynolds Number Expression

As indicated by Equation 1, the Reynolds number is primarily dictated by the properties of the fluid (velocity, viscosity and density); if these factors are not controllable, as with a hydrofoil, the Reynolds number is proportional to the critical length/diameter. Additionally, Reynolds number has an important influence over the lift and drag generated by any wing; below a critical value, little lift is generated over a hydrofoil (Folkersma et al., 2019). The Reynolds number is a crucial indicator of how a wing interacts with the fluid it's placed in, and different values are needed based on how a component is expected to perform.

At low Reynolds numbers, the flow remains laminar, and velocities remain high closer to the surface (Singh et al., 2018), which delays the separation point along the chord length of the hydrofoil at which the wake begins. This creates higher lift, but also higher drag over the hydrofoil. Laminar separation bubbles (LSBs) form at the low-velocity separation points at the start of turbulent flow. As the Reynolds number increases through transitional flow, this point moves towards the leading edge of the hydrofoil (Delafin et al., 2014), reducing the effective area a hydrofoil can generate lift over, but equally reducing drag. The shape of the blade needs to correspond with the amount of lift it needs to generate within the operational speeds it's expected to work within.

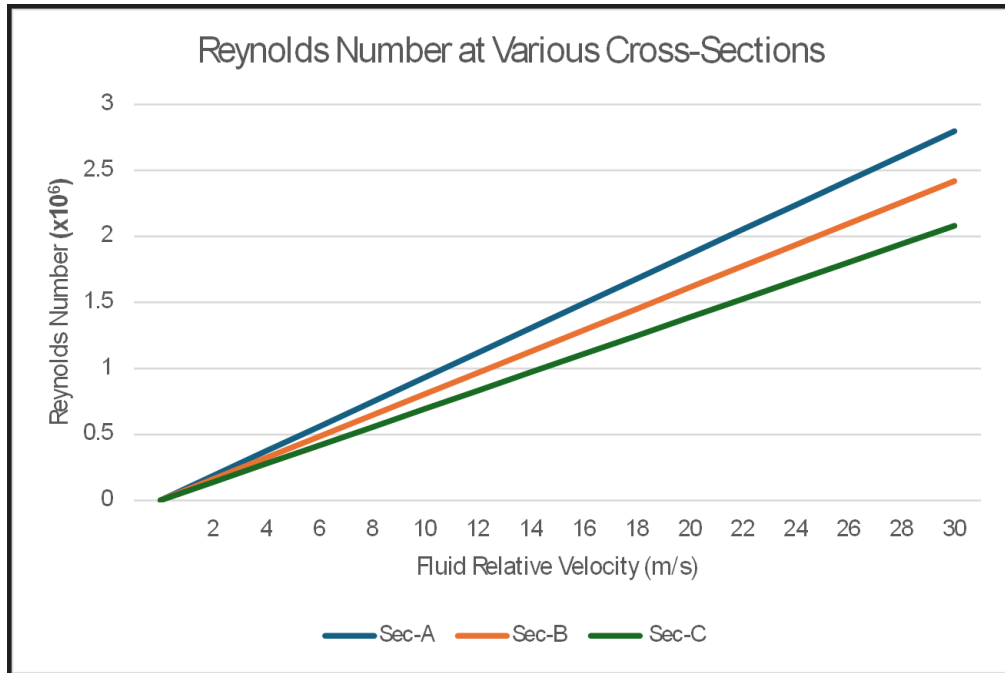


Figure 2 Reynolds Number at each Cross-section

The maximum predicted value in Figure 2 across the foil at the origin is $Re = 2.8 \times 10^6$, and 2.08×10^6 near the tip (but not at the end, as the chord length rapidly becomes 0).

2.2 Boundary Flow

The flow, as shown in Figure 2, is in the range of $Re = 0 - 2.8 \times 10^6$. This value, in actuality, only applies to the widest-span point over the wing. As the wing tapers toward the end (with the furthest end only about 74% of the width of the stem), the Reynolds number reduces proportionally with the chord length. This is likely to reduce the force induced on the wing towards the end of the foil, as forces concentrated at the end of the hydrofoil's span will act as a cantilever, with a greater influence on deflection.

Additionally, the Reynolds number is very unlikely be such a high value during general operation. More common speeds are around 30mph, or 13.5m/s (O'Shea, 2022), producing a Reynolds value of approximately 1.3×10^6 to 0.98×10^6 across the span of the wing. (Genç, 2012) found that flow transitions from laminar to turbulent around $Re = 2.8 \times 10^6$ for some specific NACA foil geometries, and more generally that flow enters an 'intermediate zone' for hydrofoils when $10^4 < Re < 10^6$ in which environmental factors, such as the initial velocity and flow state of the fluid, begin to influence the overall flow. Within this zone, when is approximately $Re > 10^5$, the foil is able to generate substantial lift (Hua Shan, 2005).

Taking these constraints from both general findings and specific cases of NACA, we can say that when $10^5 < Re < 10^6$, hydrofoils generate significant lift and still exhibit laminar flow characteristics. As applied to this case, we can say that this hydrofoil has been designed to be able to start generating lift as quickly as possible at low speeds to lift the user out of the water quickly and reduce drag. At 2m/s (~4.5mph or a brisk walk), the hydrofoil is estimated to have a Reynolds number of 1.86×10^5 - 1.38×10^5 , which quickly brings it into this range.

As discussed, the specific Range of flow types depends greatly on the type of hydrofoil profile being exposed to a flow. To this end, the provided model was split into sections and measured in order to find the closest NACA match to compare to. Figure 3 shows one cross-section, which was used to find a close match of a four-digit NACA profile. A section with a chord length of 116.87mm was used, with the closest NACA profiles being NACA 2312 and NACA 2412.

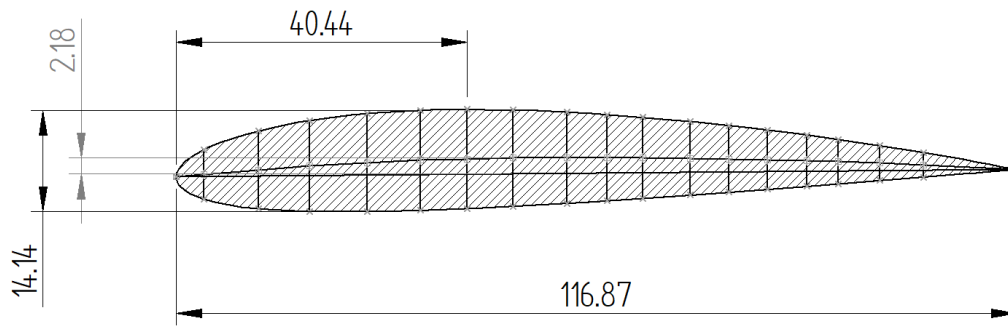


Figure 3 Arbitrary Cross-section Bisected to Approximate Nearest NACA Profile

During the intermediate zone, the total friction drag coefficient (C_f) is determined by combining the laminar zone skin friction drag over the forward part of the foil with the turbulent zone (rear) skin friction drag over the remaining part. This total friction coefficient helps determine the final location of the transition, or zero velocity point, relative to the chord length (Ferdous and Haider, 2023). Additionally, Ives et al. (2018) found that the flow tends to remain attached during high Reynolds numbers at greater angles of attack. The increased velocity over a surface area experiencing laminar flow results in a higher maximum lift coefficient. Both improving the drag coefficient and refining the angle of attack push the point of separation down the cord length, improving the efficiency of the hydrofoil.

4 Flow Appraisal

4.1 Hydrofoil Downforce Behaviour

The force generated by a hydrofoil is proportional to the coefficient of lift for that profile. This is often determined experimentally and is primarily influenced by the geometry of the hydrofoil, and the angle of attack (AoA) the foil is at relative to the direction of flow. To closely approximate the forces acting on the given hydrofoil, the coefficient of lift needs to be determined, usually experimentally.

Hassan et al. (2022) conducted a study of the coefficient of lift (C_L) on the aerofoil NACA 2412, which, as previously noted, is the closest match to the actual profile in this study. Figure 4 shows a graph of several predictive models, along with experimental data to find C_L values for NACA 2412.

Other variables required to find a generated down-force are (Benson, 2024):

- Density of the fluid in question (ρ)
- Wing area exposed in the direction of the downforce (A)
- Velocity of the fluid (v)

The relationship between these factors is expressed in Equation 2. The density, area and velocity can be calculated highly accurately, and so a key limiting factor is the dependence on the closeness of the behaviour of NACA 2412 to the subject hydrofoil.

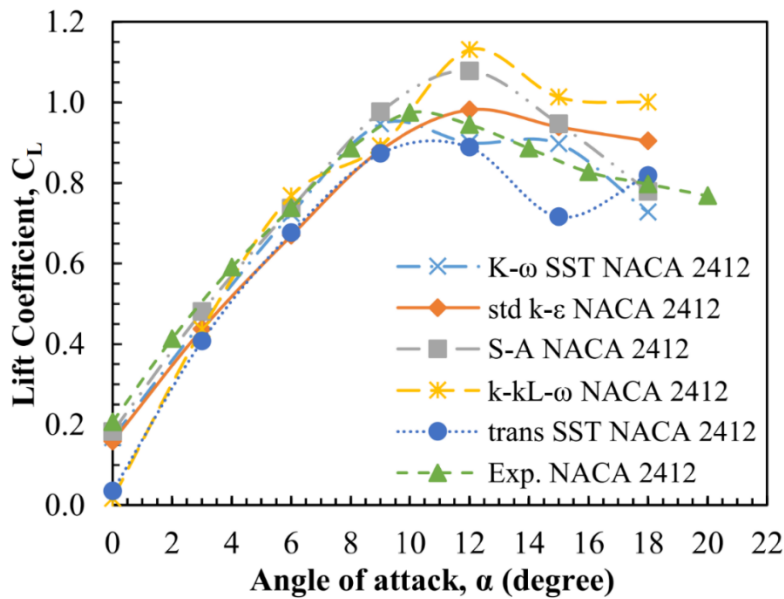


Fig. 12 Comparison between experiment data and numerical results of five different turbulence models of the lift coefficient curve for NACA 2412 airfoil.

Figure 4 Lift Coefficient per AoA for a NACA 2412 airfoil; experimental and predictive data (Hassan et al., 2022).

$$F = \frac{1}{2} C_L \rho A v^2$$

Equation 2 Downforce Equation (Benson, 2024)

To calculate the working area of the wing, CAD software was used to find the top-down area of the wing, as shown in Figure 5 in the hatched region. This provided a value of $A=0.0297\text{m}^2$. The density, as discussed, is $\rho=1026\text{kg/m}^3$ (2) for seawater at 15°C .

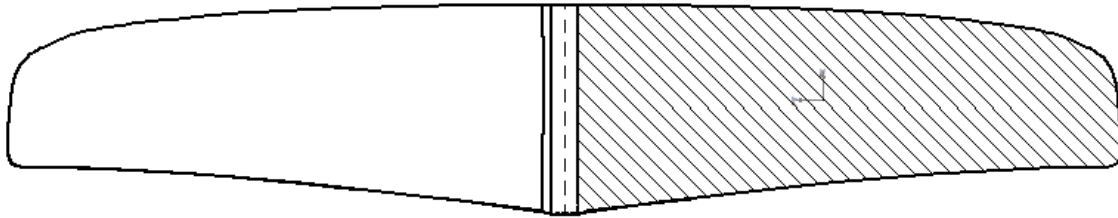


Figure 5 Perpendicular Surface Area of Hydrofoil

4.2 Downforce Calculation

The velocity is the biggest factor in determining the down-force, as the force increases with $1/2$ velocity squared. As the velocity isn't constant, but is determined by the user, the force has been plotted against the speed of the fluid, according to the assumptions laid out above in Figures 6 & 7. Figure 6 shows several lines, each corresponding to a different AoA and subsequent C_l . At an AoA of 8° , and 30m/s , the overall force generated would be $\sim 11\text{KN}$, far in excess of the assumptions used in the previous report.

However, this is a completely unrealistic scenario. For one, 30m/s is an exceptional speed at the edge of what could actually be achieved. Secondly, having a high AoA wouldn't happen at a high speed, as inclining the hydrofoil would only happen at low speeds to increase lift and raise the board out of the water. By the time the board reaches high speeds, it would level out in order to reduce drag.

As such, 2742.5N is a reasonable maximum to which the board would be subjected. Additionally, the typical speed for those not performing at the height of the sport is around 13.5m/s as previously discussed. At this cruising speed, the force on the board is 555N (Figure 7).

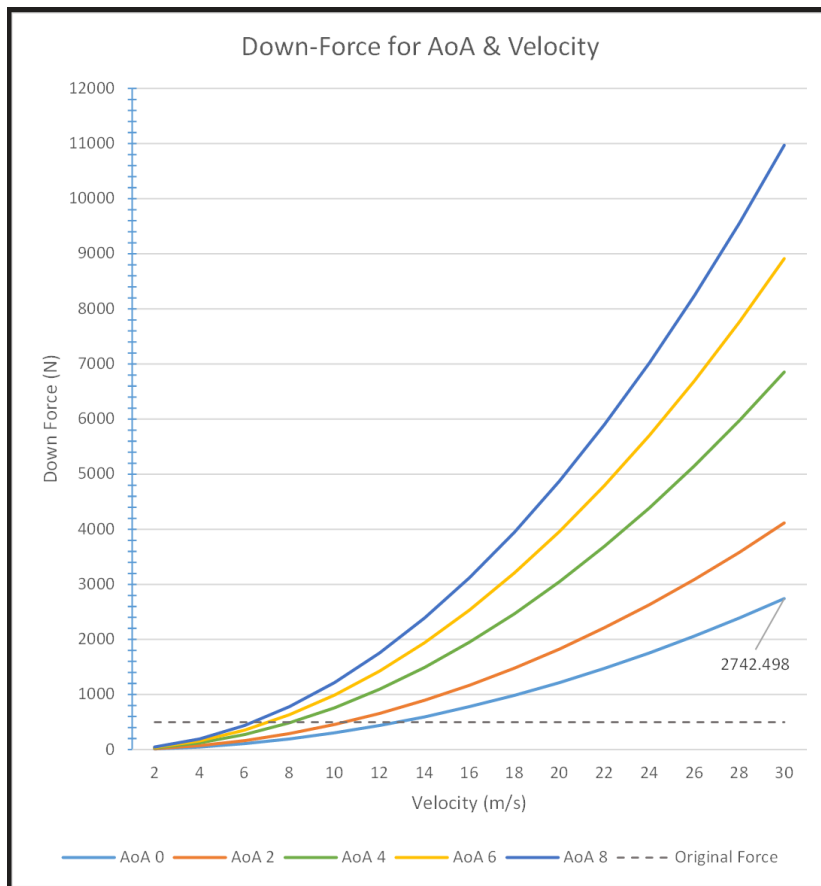


Figure 6 Downforce per m/s Increment for AoA up to 8°

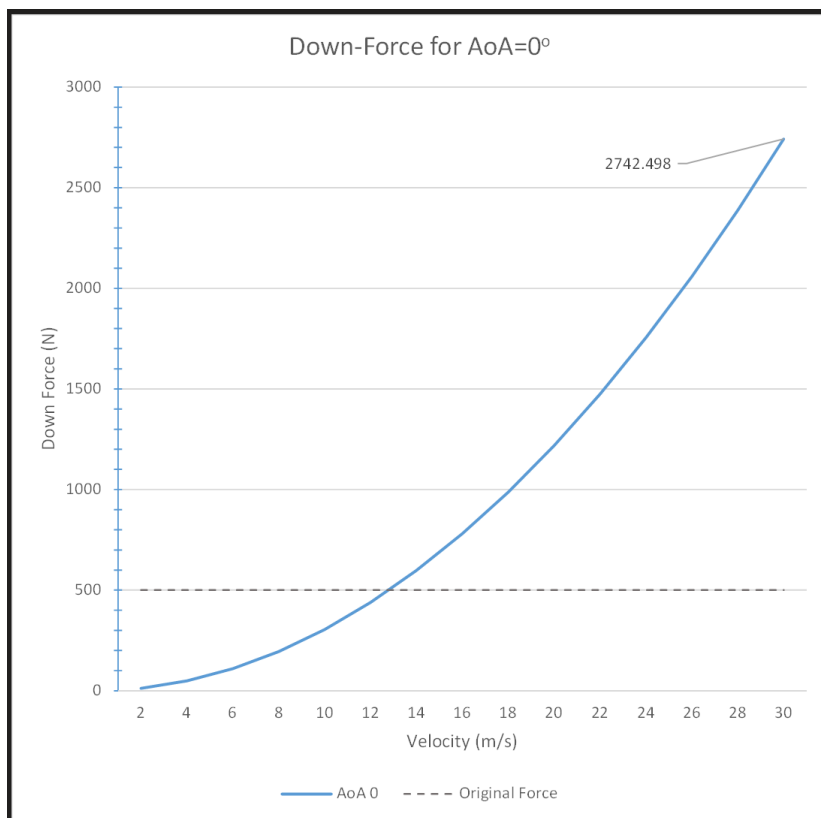


Figure 7 Downforce per m/s for AoA of 0°

4.3 Limitations

Despite this, 500N at the geometric centre is still not a good force to assume for a structural analysis for several reasons:

- Forces could significantly exceed 500N. At high velocities, the force will exceed the 500N limit. As there is no way to guarantee whether an experienced or novice user is going to use the board, designing the board to safely handle 500N opens it to fail at high speeds.
- Forces do not act at the geometric centre (Benson, 2025). The forces act at the 'centre of pressure', which is defined as Equation 3, which is complex to calculate. This point is usually biased towards the forward edge of the hydrofoil.
- Forces change rapidly, proportional to v^2 , which is not a static, continuous load. Cyclic loading at high strain can cause plastic deformation (Wang et al., 2022), gradually causing failure at loads lower than absolute yield stresses.

$$cp = \frac{\int xP(x) dx}{\int P(x) dx}$$

Equation 3 Integral for Location of Centre of Pressure (Benson, 2025)

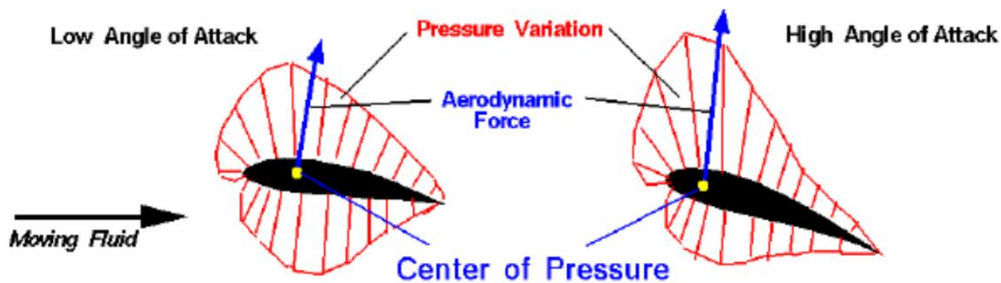


Figure 8 Diagram of Centre of Pressure, Based on Pressure Variation (Benson, 2025)

6 Hydrofoil Appraisal

6.1 Hydrofoil Material

CFRP materials have distinct advantageous properties which make them ideal for replacing traditional materials in many applications. Centrally, as explored in the first report, carbon fibre offers major advantages to strength-to-weight ratios, which can be leveraged to improve the overall mass of the component and permit better overall performance. In the first report, the use of CFRP was able to reduce the weight of the hydrofoil by 58.9% while maintaining similar tensile strength in the loaded direction.

Secondly, polymer matrices aren't susceptible to crevice corrosion, which is driven by an electrolytic process (Jing Shen et al., 2019). This type of corrosion is often difficult to spot and creates weaknesses in ferrous materials. However, polymer matrices aren't immune to marine corrosion, and water ingress and absorption can weaken the polymer bonds. Yifan Li et al. (2025) noted that this has a limited impact on material properties in the fibre direction, but weakens the material further against the grain direction. In addition to this, composites have poor fatigue resistance when subjected to cyclic loading (Konur and Matthews, 1989; Yang et al., 2020), which could pose problems for the life expectancy of the part compared to the replaced steel component.

The evolution of materials used for hydrofoils reflects a broader shift towards greater performance, efficient, lightweight structures while maintaining the strength of components and smooth aerodynamic finishes. Initially, metal alloys, particularly aluminium alloys, were favoured for their high strength-to-weight ratios, which are crucial for marine applications (West & Mitchell, 1994). The need for lightweight construction drove innovations in composites, which are able to combine lightweight polymers with high-strength materials, typically in a fibre form (Lim et al., 2004), which is ideal for hydrofoil applications, which have consistent known stresses applied to them from hydrodynamic forces.

6.2 Modelling Techniques

CFD is commonly employed to simulate fluid flow around hydrofoils. This method computes the flow of fluid by breaking the flow into cells and applying the Navier-Stokes equations to predict how fluid interacts with surfaces. Among the various approaches, the Reynolds-Averaged Navier-Stokes (RANS) is notable due to a more robust simulation of turbulence. Lee et al. (2017) demonstrated the efficacy of hybrid RANS methods to simulate responses of hydrofoils. CFD provides detailed information about velocity and pressure around a component, which would otherwise be difficult or impossible to understand; an in-depth understanding of flow patterns and forces allows information to

be gathered on a hydrofoil without direct experimentation. It can also analyse flow conditions which may not be practical in a controlled, measurable environment.

Smoothed Particle Hydrodynamics (SPH) is an alternative to traditional mesh-based CFD methods. SPH utilises discrete particles with the Newtonian properties of the simulated fluid to calculate the behaviour of a system. This can handle large and complex free surface flows (Dinçer et al., 2019)(Takizawa et al., 2011). SPH can complete this without some of the difficulties associated with mesh calculations, including mesh sizing and boundary conditions. However, the SPH method can suffer from issues related to convergence, particularly in capturing detailed flow dynamics compared to traditional CFD methods (Takizawa et al., 2011).

6.3 Prototyping & Testing

In order to investigate the flow over the aerofoil, data collected in a controlled test needs to be compared with digital models, the comparison of which will allow an accurate understanding of the flow around the component. Due to the Reynolds number being proportional to the chord length, the flow boundaries are irrevocably tied to the scale of the model used to test. For this, it's crucial to have a full-scale model of a hydrofoil section with a fluid with the same viscosity if at all possible. Given the size of the hydrofoil, creating a full-scale model is practical to allow the boundary flow positions to be as accurate as possible.

To carry out an experiment on this, a 1:1 scale model of the cross-section being studied should be put in a flow chamber with seawater. A dye or other substance is typically used to visualise the flow over the component and identify points of zero velocity at which the flow detaches from the hydrofoil and the wake begins. The flow directed at the hydrofoil needs, ideally, be totally laminar. The walls of the chamber will affect this in much the same way as the test component. As such, the test piece needs to be placed in the chamber as far from all other surfaces as the size of the cavitation tunnel allows. Several cross-sections should be tested from the hydrofoil, and equal intervals of blade length, as well as a complete model. Studying individual cross-sections allows the behaviour to be better understood at each position along the foil, and may also mean a fewer resources and a smaller cavitation tunnel would be required.

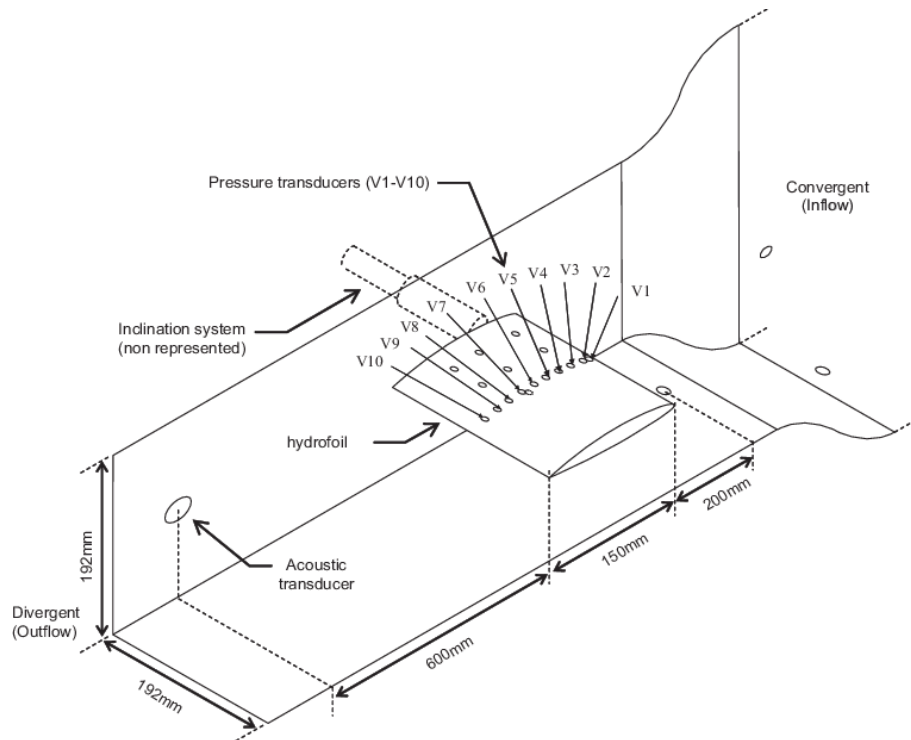


Figure 9 Diagram of Typical Cavitation Tunnel Test (Antoine Ducoin et al., 2009)

The collection of data needs to be in a variety of forms in order to give the widest possible picture of the behaviour. The flow can be observed as previously discussed with a dyeing agent to identify points of interest. In order to directly compare an experiment to the model, the pressure at points of interest along the cross-section needs to be measured and compared with the model to understand its accuracy and shortcomings, as shown in Figure 9. Additionally, the force exerted on the hydrofoil can be measured and applied as a second confirmation of the overall behaviour of the system. As previously discussed, the coefficient of lift is tied to complex factors not easily derived from the geometry of the model, and the true value of the exerted downforce can be expected to vary from the predictions made here based on close NACA profiles.

7 Conclusion

This report analysed the fluid flow characteristics and structural viability of the kiteboard hydrofoil design. The fluid assessment confirmed that the foil geometry is optimised to function within an intermediate Reynolds number zone ($10^5 < Re < 10^6$), which means the hydrofoil generates lift quickly at low operational speeds (e.g., 2 m/s).

However, the forces, which are proportional to the square of velocity, are dynamic, resulting in cyclic loading at high strain and potential for much higher loading than 500N. Composites are known for poor fatigue resistance, and water ingress weakens the material against the grain direction.

Furthermore, relying on approximations based on NACA profiles is limited because forces act at the complex 'centre of pressure' rather than the geometric centre.

Therefore, future work must transition from theoretical modelling (RANS or SPH) to experimental testing. Full-scale prototyping in a cavitation tunnel is essential to ensure that the Reynolds values and consequent Turbulent / Laminar flows are accurate. This should be conducted to verify the coefficient of lift and ensure the hydrofoil's durability against failure modes associated with cyclic strain.

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