

GENG4412 Engineering Research Project Part 2
Final Report

**Design and Construction of a Hydrofoil System for a Production
Personal Watercraft**

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Project Summary

Personal Watercraft (PWC), or Jet-Skis, are commercially available vehicles that operate by drawing in water and ejecting it rearward at high speed, using conservation of momentum to drive the craft forward.

Despite their widespread recreational use, this propulsion process is far from efficient. A significant proportion of the engine output power is lost to hydrodynamic drag, as a large surface area is continuously in contact with the water.

Modern hydrofoil technology has demonstrated that lifting the hull clear of the water can dramatically reduce drag, increase top speed and improve efficiency whilst enhancing ride quality. This technology has seen rapid commercial adoption in recent years across foilboards, eFoil, dinghies and ferries, but its application to production PWC remains limited.

The C-8 by Candela [2] is one of few recreational hydro-foiling watercrafts currently available commercially, it is built around a bespoke hull and powertrain rather than retrofitted to an existing production vessel and with a price tag of AU\$540,000 [3] is out of reach for the average consumer.

There is currently no documented methodology for designing and retrofitting a retractable hydrofoil system to a standard production PWC hull, despite the very large existing global PWC fleet that could potentially benefit from such a conversion. The *Hydroski* project at the University of Western Australia addresses this gap by designing, analysing and constructing an electric hydrofoil Jet-Ski built around a production Sea-Doo Spark hull.

This project develops a methodology for the conversion of a standard Jet-Ski to a hydro-foiling craft. With fully functional Spark hulls available for under AU\$10,000 and a total project budget of AU\$14,000, the Hydroski project will further the state of PWC hydro-foiling, producing a unique craft in an extremely sparse market.

This paper explores the design of components for a hydro-foiling jet-ski system, with particular focus on the front foil system which must generate a majority of lift for the system, be able to deploy for foiling operation and retract for conventional road trailer transport, as well as other design aspects affecting craft stability and agility.

The retractable nature of the front foil presents the key engineering challenge of this project. The mechanism must transmit the entire vertical lift force for the 400 kg combined rider-craft system, in moderate wave conditions. This must occur through a joint assembly that permits rotation of the foil out of the water for storage. This is a non-trivial structural problem that balances hydrodynamic load prediction, and integration with a pre-existing hull.

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Table of Contents

STUDENT DECLARATION.....	i
Project Summary	i
Acknowledgements.....	iii
Table of Contents	iv
List of Figures.....	vi
Nomenclature	viii
1 Introduction, Literature Review and Project Objectives.....	1
1.1 Introduction:.....	1
1.2 Literature Review.....	1
1.3 Project Objectives	9
2 Concept Design for Front Foil System	10
2.1 Design Overview.....	11
2.2 Design of a hull attachment system	13
2.3 Hull Clamp Calculations.....	14
2.4 Prototyping.....	17
3 Construction of Front Foil System	19
3.1 Hull Attachment System	19
3.2 Wing Control System.....	23
3.3 Assembly of Front Foil System	26
4 Design and Construction of a Hydrofoil Wingtip	29
4.1 Requirements for the Hydroski	29
4.2 Design process	30
4.3 Flexible TPU wingtip.....	31
4.4 Mechanical Linkage wingtip.....	38
5 Results & Discussion.....	42
5.1 Initial Testing and Observations	43

5.2 Contribution to the State of the Art.....	43
5.3 Alternative Designs.....	47
5.4 Limitations and Remaining Issues	48
6 Conclusions & Future Work.....	50
6.1 Conclusion	50
6.2 Future Work	50
Bibliography	52
APPENDIX A: Front Foil Assembly Schematic	A
APPENDIX B: Hull Clamp Calculations.....	B
APPENDIX C: Alternative Front Foil Designs	C

List of Figures

Figure 1: WaveFlyer Hydrofoil [4].....	1
Figure 2: Total Resistance vs Speed for variety of watercraft [6]	2
Figure 3: Surface Piercing Foil HMCS Bras d' Or [18]	2
Figure 4: Fully Submerged Foils; Candela C-8, BMW Icon, Artemis e-Foiler [2] [17] [19]	3
Figure 5: Free Body diagrams of standard, surface piercing and fully submerged foils [7]	3
Figure 6: WaveFlyer foiling [20].....	4
Figure 7: Ripken Testing Configuration [9]	5
Figure 8: Wingtip geometries tested by Hoerner [13]	6
Figure 9: Rear foil of Generation 1 WaveFlyer	7
Figure 10: CAD render - Hydroski in deployed position.....	10
Figure 11: CAD render - Hydroski in retracted position	10
Figure 12: CAD render - Front foil rotation mechanism	11
Figure 13: CAD render - Concept control rod arrangement	11
Figure 14: CAD render - Aluminium hull clamp.....	13
Figure 15: CAD render - Supplementary hull attachment method	13
Figure 16: FBD displaying clamp slip along hull wall	14
Figure 17: Graph from hull clamp calculations (Appendix B)	16
Figure 18: Imported Spark Hull OBJ file with overlaid 3D scan section.....	17
Figure 19: Preliminary clamp model and 3D printed prototype	17
Figure 20: 3D printed prototype mounted on hull	18
Figure 21: Complete front foil assembly mounted on hull	19
Figure 22: Aluminium hull clamps assembled	20
Figure 23: Outer and inner hull clamps	20
Figure 24: Hull clamp mounted with temporary rubber pad.....	21
Figure 25: 3D printed TPU interface pad	21
Figure 26: TPU pad over hull lip and hull clamp over pad.....	22
Figure 27: TPU pad; thickened section along hull lip and clearance for bolts	22
Figure 28: Servo housing within mast sheath	23
Figure 29: Components for control rod mechanism	23
Figure 30: Control rod configuration for 20mm arm (N.T.S).....	24
Figure 31: Control rod configuration for 15mm arm (N.T.S).....	24
Figure 32: Bench testing setup for fully assembled front foil.....	25
Figure 33: Control rod limits using 15mm arm	25
Figure 34: Assembly Step 1.....	27
Figure 35: Assembly Step 2.....	27
Figure 36: Assembly Step 4.....	28
Figure 37: Assembly Step 3.....	28
Figure 38: Rear foil during initial water testing.....	29
Figure 39: Rear foil wing cross section and CAD render of profile	30

Figure 40: CAD render of tapered wingtip profile	30
Figure 41: Diagram showing boundary layer discontinuity for a hinged wingtip	30
Figure 42: Simulated wingtip breach, exposing groove to the free surface	31
Figure 43: Slicer preview – Test print 1 body and beam interlocking	32
Figure 44: Test print 1 flexure test.....	32
Figure 45: Test print 2 flexure test.....	33
Figure 46: CAD render – TPU wingtip profile.....	33
Figure 47: TPU wingtip prototype 1	34
Figure 48: Slicer preview- TPU wing prototype 1.....	34
Figure 49: TPU wingtip prototype 1 failure	35
Figure 50: Slicer preview – TPU wingtip prototype 2.....	35
Figure 51: TPU wing prototype 2 assembled with rear foil.....	36
Figure 52: TPU wing prototype 2 aileron movement	36
Figure 53: CAD render -Components of mechanical linkage wingtip.....	38
Figure 54: CAD render - $\pm 20^\circ$ Aileron limits of wingtip.....	38
Figure 55: Recommended print orientation for wingtip	39
Figure 56: Wingtip components	39
Figure 57: Rod in drill arrangement	39
Figure 58: Drilling of hinge rod in to wingtip	40
Figure 59: Rear foil with wingtips.....	41
Figure 60: Completed hydrofoil wingtip	41
Figure 61: Initial water testing – Hydroski in retracted position	42
Figure 62: Initial water testing - Hydroski in deployed position	42
Figure 63: CAD render - Gen 1 WaveFlyer and Gen 2 Hydroski.....	44
Figure 64: WaveFlyer wingtip vs Hydroski wingtip.....	45
Figure 65: NACA 2412 profile with hinged aileron [16]	46
Figure 66: Hull base plate and batteries.....	47
Figure 67: Concept design A attachment to baseplate	47
Figure 68: Concept design A section view showing attachment to base plate.....	48

Nomenclature

A	Cross-sectional area of each mast in the pair (m^2)
A_c	Clamp contact area per friction face (mm^2)
a	Craft acceleration (m/s^2)
C_L	Lift coefficient
D	Total front foil drag (N)
E	Elastic modulus of the mast material (Pa)
E_p	Elastic modulus of the TPU pad (MPa)
F	Axial force in each mast when a roll moment is reacted as a couple (N)
F_f	Friction force between the TPU pad and the hull lip (N)
F_{lip}	Force acting along the hull lip at each clamp (N)
F_N	Clamping (normal) force pressing the TPU pad onto the hull lip (N)
I	Second moment of area of a single mast about its weak axis (m^4)
k_{dual}	Roll stiffness of the mast pair ($\text{N}\cdot\text{m}/\text{rad}$)
k_{single}	Roll stiffness of a single central mast ($\text{N}\cdot\text{m}/\text{rad}$)
L	Lift force (N)
L_m	Mast length (m)
M	Roll moment applied at the foil ($\text{N}\cdot\text{m}$)
m_a	Mass carried through the clamps (kg)
N_{ach}	Clamping force available from pad compression (N)
N_{req}	Clamping force required to prevent slip (N)
n_s	Number of friction faces per clamp (2)
S	Planform area of the foil (m^2)
s	Spacing between masts (m)
t_p	TPU pad thickness (mm)
v	Freestream velocity, equal to craft speed (m/s)
δ	Compression of the TPU pad when the clamp is closed (mm)
η	Effective contact of the clamp contact area

θ	Rotation of the foil relative to the hull under a roll moment (rad)
μ_{TPU}	Friction coefficient between the TPU pad and the hull lip
ρ	Fluid density (kg/m ³)

1 Introduction, Literature Review and Project Objectives

1.1 Introduction:

The Hydroski project develops a retractable, dual-mast hydrofoil system for an electric personal watercraft, it builds on The University of Western Australia's Renewable Energy Vehicle Project (REV) which delivered the world's first electric hydrofoil jet-ski in 2019, dubbed the WaveFlyer [4].



Figure 1: WaveFlyer Hydrofoil [4]

Three architectural choices distinguish the front foil arrangement of the Gen 2 model from the original WaveFlyer: a dual front-mast arrangement in place of a single central mast, an external non-permanent clamping system that distributes mast loads across the hull sides, and a rotating mechanism that allows full out of water transport and storage.

1.2 Literature Review

Background:

The lift generated by a hydrofoil is described by the fundamental lift equation,

$$L = \frac{1}{2} \rho V^2 \cdot S \cdot C_L$$

Equation 1: Fundamental Lift Equation

For a hydrofoil craft, L must be equal to the vessel weight for steady foiling.

The take-off transition is a defining point for any foiling craft. At low speed the hull supports the vessel through buoyancy and planing, as velocity increases, foil lift grows quadratically until it equals vessel weight, the hull lifts clear of the water's surface and total drag drops proportionally to the now reduced wetted surface area.

Published data for the C-8 [2] shows the significance of this effect, stating that foiling at a speed of 22 knots uses the same amount of power as conventional travel at a speed of 5 knots - about 1.2 kWh per nautical mile [5]

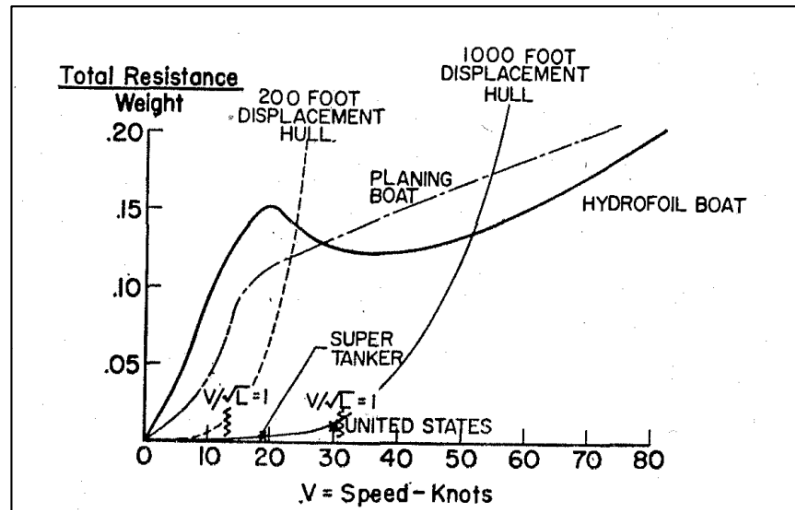


Figure 2: Total Resistance vs Speed for variety of watercraft [6]

The above figure from 'High Speed Small Craft' [6] clearly illustrates this drop in drag as foiling initiates, and how the resistance compares to other watercraft.

Types of Hydrofoil

Hydrofoil arrangements divide into surface-piercing and fully submerged configurations.

Surface-piercing foils are typically arranged in a V or ladder shape and intersect the free surface, they self-stabilise in heave: as the craft rises, wetted foil area decreases, lift drops, and the craft settles to an equilibrium altitude without active control. The trade-off is that the foil's interaction with the air-water interface generates significant wake and spray, transmits surface waves directly through to the hull, and constrains movement as the foil cannot bank steeply without ventilating.



Figure 3: Surface Piercing Foil HMCS Bras d' Or [18]

Fully-submerged foils eliminate the air-water interaction at the foil itself, producing much cleaner wake characteristics and substantially better wave rejection. They also permit aggressive bank angles in turns as the lifting surface remains fully immersed throughout the manoeuvre.

The WaveFlyer, Gen 2 of the Hydroski and a majority of modern high-performance foiling craft, adopt the fully-submerged foil configuration.



Figure 4: Fully Submerged Foils; Candela C-8, BMW Icon, Artemis e-Foiler [2] [17] [19]

The penalty is that fully submerged foils are inherently unstable because lift below the surface is approximately depth-independent: once perturbed upward, the foil, unless properly controlled, continues to lift until it surfaces and ventilates.

Control Systems

Magini and Burroughs, in *Control of the Hydrofoil Ship* [7], identified that a fully submerged hydrofoil craft possesses no inherent roll-restoring moment. Instead, this moment must be generated by underwater control systems that respond to the hull's position.

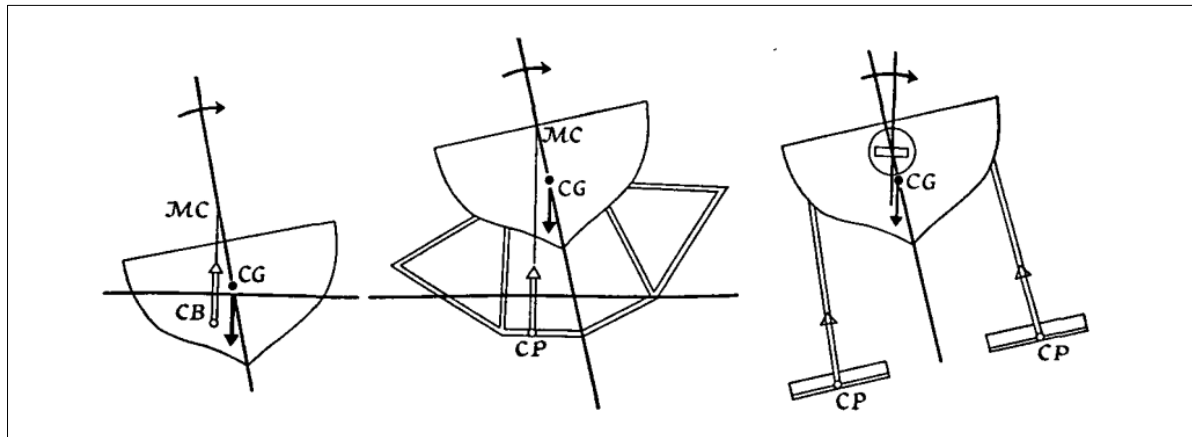


Figure 5: Free Body diagrams of standard, surface piercing and fully submerged foils [7]

The WaveFlyer [4] utilised this methodology with its central, fully submerged mast. Gen 2 looks to improve upon this and correct the instability issues observed by riders of the Gen 1 craft [8], the selection of a dual front mast assembly impacts how these systems operate and the design of the front foil assembly must make allowances for the sensors and servos that make up these systems.

Dual Mast Arrangement

Dual-mast hydrofoil arrangements are uncommon in the small-craft literature, which is dominated by single-mast designs. The case for one on the Hydroski follows from the control problem described above. A fully submerged foil has no inherent roll-restoring moment, so roll stability must be generated by control systems responding to the hull's position. A dual mast makes this control more effective.

Firstly, through stiffness; a single central mast reacts a roll moment by bending about its weak axis. For a moment applied at the foil, the rotation of a cantilever is

$$\theta = \frac{ML_m}{EI}$$

Equation 2: Rotation of a single mast under roll moment

giving a roll stiffness of;

$$k_{single} = EI/L_m$$

Equation 3: Roll stiffness of a single central mast

A pair of masts reacts the same moment as a couple. Each mast carries an axial force $F = M/s$, one in tension and one in compression. The resulting roll stiffness is:

$$k_{dual} = EAs^2/2L_m$$

Equation 4: Roll stiffness of a mast pair

The rider-reported instability of the Generation 1 WaveFlyer [8], which used a single central mast, gives practical reason to pursue a stiffer platform.



Figure 6: WaveFlyer foiling [20]

Secondly; a roll-restoring moment from control surfaces requires a difference in lift between the two sides of the craft. With a servo in each mast sheath, the front foil can independently drive an aileron on each side. This gives the front foil roll authority in addition to heave and pitch control.

Ripken's towing-tank study at the St. Anthony Falls Hydraulic Laboratory [9] supports placing masts at the ends of the wing. It compared a mast mounted at the foil extremity with one at the foil centre, two of its findings bear on the Hydroski:

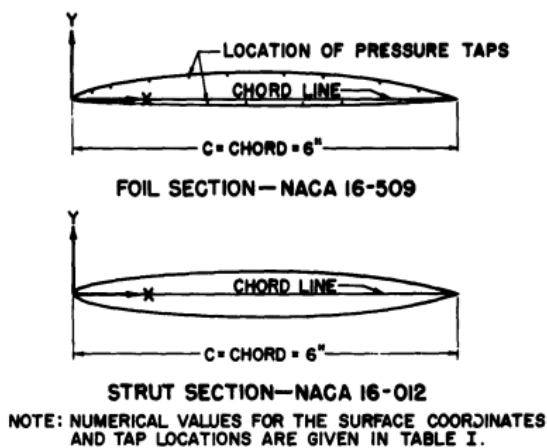


Fig. 2 - Pressure Tap Locations for the Test Sections

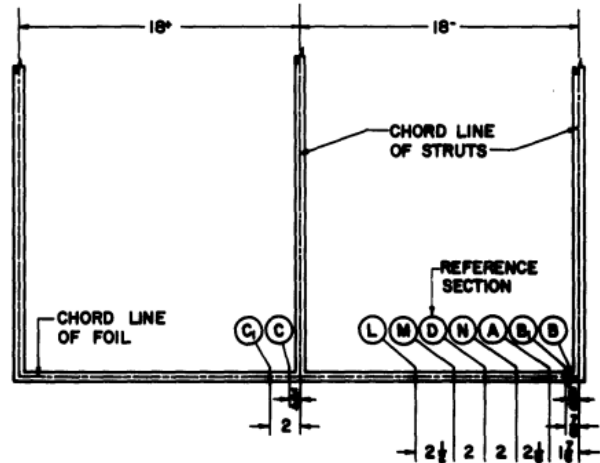


Fig. 3 - Placement of the Pressure Tap Lines in the Hydrofoil Assembly (Assembly Viewed from Leading Edge)

Figure 7: Ripken Testing Configuration [9]

The local minimum pressure on the foil surface was less negative beside the end-mounted mast across the attack-angle range tested, with and without fillets. Cavitation inception is set by the most negative pressure coefficient, so the end-mounted arrangement is the less cavitation-prone of the two at equivalent loading.

A mast produces major force interference over roughly two-thirds of a chord outward from its junction. A centre strut places this band on both sides of mid-span, where the lift distribution is highest. End struts confine it to the inboard side of each junction, leaving mid-span comparatively undisturbed.

These benefits come at a cost. Doubling the mast count doubles the appendage drag and adds a second junction. The net drag compared with a single mast depends on whether the reduced interference at each junction outweighs the added strut area.

Hull Attachment

A foiling personal watercraft does not experience a single, steady design load, each take-off and touch-down imposes a load reversal into the hull attachment. This produces both low-frequency bending reversals, from rider weight transfer, manoeuvring, and wave encounter, and high-frequency impulsive loads, from slamming. Slamming is identified in bolted-joint literature as the most damaging to bearing-type connections [10].

Hascoët and Jacques [11] show that for bodies whose vibratory response time exceeds the impact duration, slamming induced fatigue can govern sizing more conservatively than ultimate strength checks, they identify water-foils specifically as a body that may benefit from this treatment.

The Spark hull is made from Polytec, a composite that exhibits substantial creep under sustained compressive load, this causes preload relaxation in bolted joints. For a direct through-bolt configuration the bolt holes carry the full shear in bearing because friction grip is unreliable, even if oversized the bolts cannot be relied upon to retain the clamping force needed to develop friction.

Composite material is also intrinsically unsuited to point-bearing loads under any matrix system. A review by Darrel Nicholson [12] concluded that fibreglass does not deal well with point-loading, and that tapered or stepped backing plates are required to spread it. Although this work is on thermoset GRP, the same principle applies to GF-PP given Polytec's lower through-thickness stiffness.

Wingtip geometry

The tip of a foil is where the pressure difference between the two foil surfaces must equalise, and the manner in which it does so determines both the drag penalty and the position of the shed vortex. Tip geometry alters the effective behaviour of the whole lifting surface.

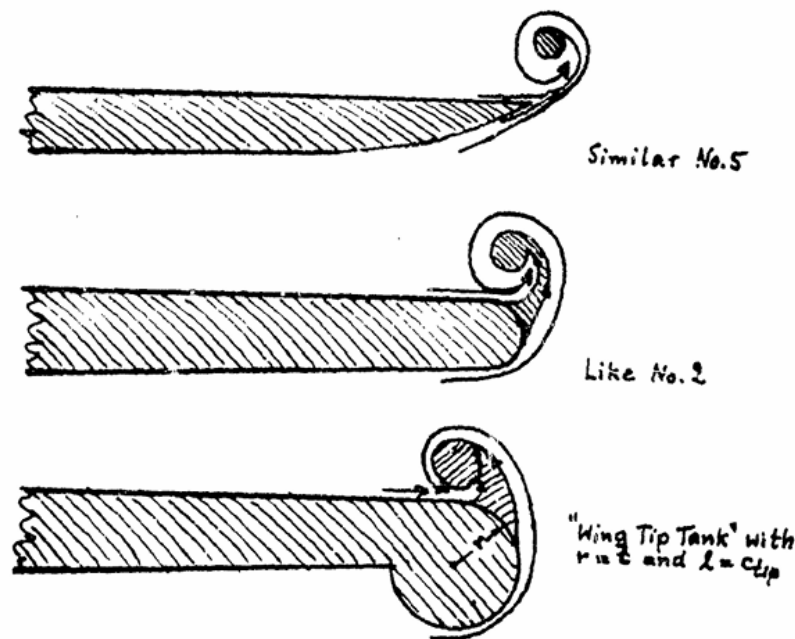


Figure 8: Wingtip geometries tested by Hoerner [13]

The most direct experimental treatment is Hoerner's study for the US Air Force [13] which tested a wing fitted with several different tips and measured the resulting lift-to-drag behaviour.

Two findings are relevant here; first, the effective span of a wing does not necessarily coincide with its geometric span, because the position at which the tip vortices form depends on the shape of the tips. Second, a portion of parasite drag originates at the tips, and its magnitude depends on tip shape.

On a blunt or rounded tip, flow remains attached as it wraps from the pressure side around to the suction side, so the vortex forms inboard of the geometric extremity. The effective span is reduced and the induced drag increases accordingly. On a tip with a sharp side edge, separation is fixed at that edge, the vortex forms at the extremity, and the effective span approaches or exceeds the geometric span.

Hoerner's optimum tip shape has a sharp side edge, a corner at the trailing edge, and an upper surface extending approximately straight to the end, the lower surface angling up to meet it. This is a thin, tapered tip with a defined edge, not a faired or rounded one.

Application to the Generation 1 WaveFlyer



Figure 9: Rear foil of Generation 1 WaveFlyer

The Generation 1 tip is a third case, and a worse one. It is a thick aerofoil block terminating in a square face cut normal to the span. The added thickness contributes no circulation, generating parasite drag and wetted area without producing lift. It was likely designed this way to accommodate servos for the ailerons mounted within the wingtips, but the result combines the induced drag penalty of a poorly positioned vortex with a base drag penalty that neither a rounded nor a sharp-edged tip incurs.

The square termination also carries a handling consequence. When a foil rolls, each section moves vertically, and the further outboard it sits the faster it moves. That vertical motion changes the local angle of attack increasing it on the descending side and reducing it on the ascending side, so the foil generates more lift where it is going down and less where it is going up. The resulting moment opposes the roll and is known as roll damping. Its magnitude depends on the square of the distance from the centreline, because an outboard section experiences both a larger change in angle of attack and a longer moment arm. Lift-generating area at the extreme span is therefore the most effective area there is at resisting roll.

By holding the section at full thickness and full chord out to the cut face, the Generation 1 tip places lift precisely where it damps roll most strongly, and the craft is correspondingly reluctant to roll.

TPU in a saltwater environment

TPU is a thermoplastic elastomer that has high flexibility and elasticity, as well as abrasion and chemical resistance. It is used on the Hydroski in both hull attachment and wingtip design.

A paper by Choi and Kim [14] explores the degradation of TPU in a saltwater environment. Finding that over a span of 20 years simulated through an accelerated lifetime test, there was roughly a 50% decrease in tensile strength of the TPU parts.

1.3 Project Objectives

This project tests the hypothesis that a hydrofoil system retrofitted to an existing production hull can generate enough lift for sustained and stable foiling.

Purpose-built recreational foiling craft such as Candela's C-8 achieve this with bespoke hulls, at around AU\$540,000. The Generation 1 WaveFlyer showed that a converted personal watercraft (PWC) could foil, but its riders reported roll instability. No documented method yet exists for fitting a retractable foil system to a production PWC hull.

To test the hypothesis, the following objectives were set for the Gen 2 Hydroski:

1. Design, build and install a retractable, dual-mast front foil system on a Sea-Doo Spark hull, attached without cutting into the hull's internal walls or penetrating its outer shell.
2. Show by calculation that the hull attachment will not slip under acceleration and sustained foiling loads, and confirm that it remains rigid during deployment, retraction and water testing.
3. Allow the foil to retract fully clear of the water and bow, so that the craft can be carried on a conventional jet-ski trailer, launched from a standard boat ramp, and deployed and retracted by a single rider.
4. Actuate the front wing aileron through its full range from servos housed above the waterline.
5. Develop a replaceable rear foil wingtip that actuates with the rear aileron and has lower drag and roll damping.
6. Complete the build within a budget of AU\$14,000.
7. Demonstrate sustained, stable foiling in water testing.

Meeting these objectives would advance the state of the art, providing a method for converting a production PWC into a foiling craft, from capturing the hull geometry to attaching to it without altering its internal structure. It would demonstrate a dual-mast front foil as a stiff platform for active roll control, an arrangement that is uncommon on small craft.

2 Concept Design for Front Foil System



Figure 10: CAD render - Hydroski in deployed position



Figure 11: CAD render - Hydroski in retracted position

2.1 Design Overview

Before structural sizing and further design elements could be considered, a base concept design had to be established.

The proposed design (Figure 10 / Figure 11) incorporates dual masts with one continuous wing connecting them, control linkages to actuate the two ailerons on the front foil wing must also be designed and incorporated into the design.

The entire front foil assembly is held on the hull by aluminium clamps that wrap over the lip of the hull and clamp together with 5 M12 bolts per side, these clamps support an aluminium bushing housing and a sheath that holds the mast. The sheath pivots about the bushing, which is offset from the line of the mast, this was done to allow clearance of the front of the hull whilst keeping the masts at the desired location relative to the centre of mass.

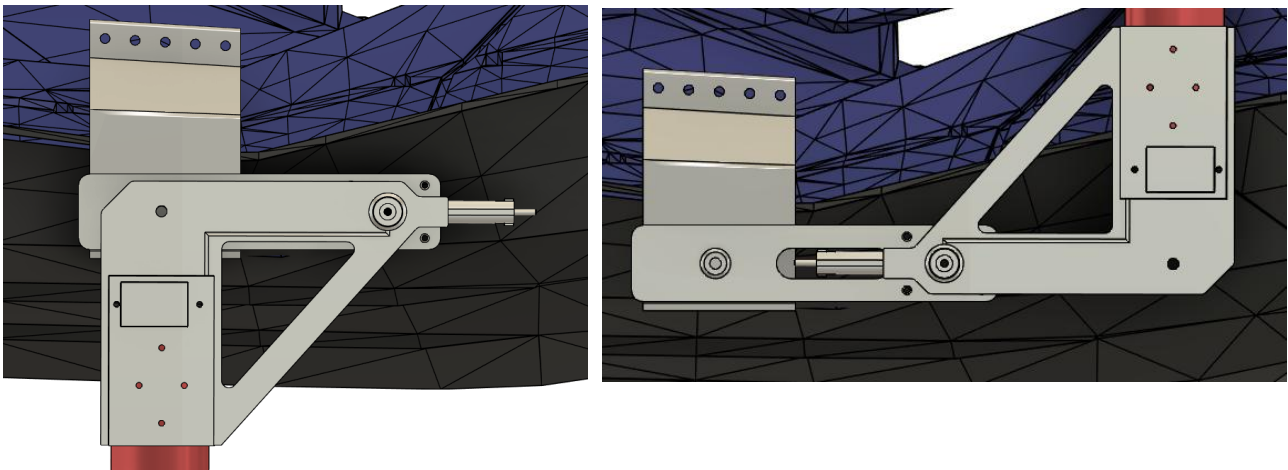


Figure 12: CAD render - Front foil rotation mechanism

A servo housing is located within the mast sheath; this servo drives the control rod that actuates the aileron of the crafts primary wing. A compact linear conversion method was developed for this purpose.

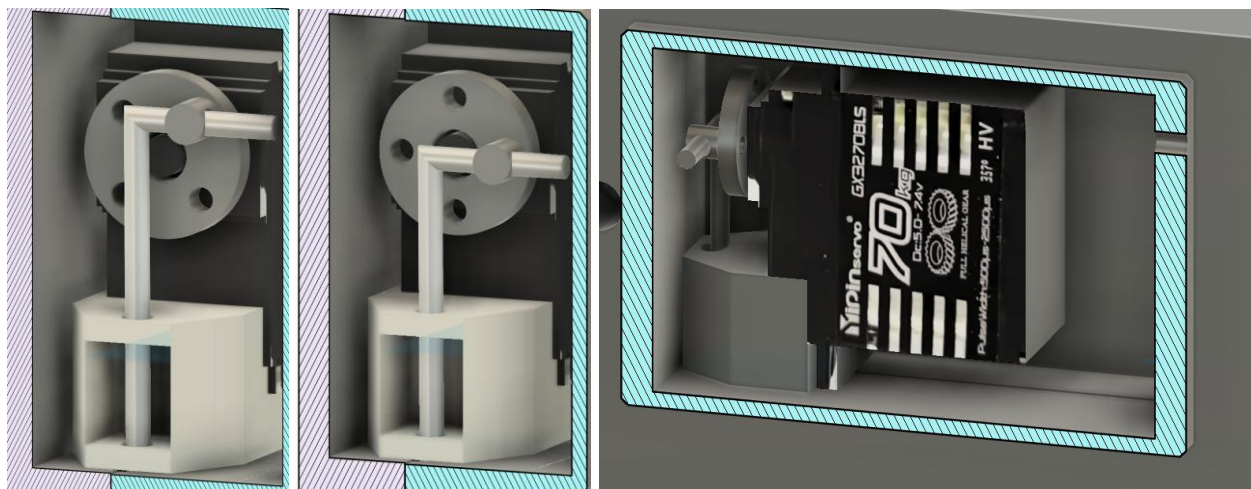


Figure 13: CAD render - Concept control rod arrangement

It involves a round servo horn and push rod linkage that rotates relative to the horn whilst allowing the rod to slip, this arrangement provides linear motion of the control rod that will run the length of the mast and actuate the aileron. A 3D printed rod housing with an internal brass bushing, supports the rod as it enters the top hole of the mast, this particular arrangement was selected for its simplicity, low cost, interchangeability and compactness whilst not relying on gear or rack and pinion systems that will likely jam or skip in the extremely bumpy and volatile operating environment.

2.2 Design of a hull attachment system

The proposed hull attachment design is a pair of aluminium clamps, designed to fit the contour of the hull, fastened with 5 M12 bolts, to hold the front foil system in place during use.

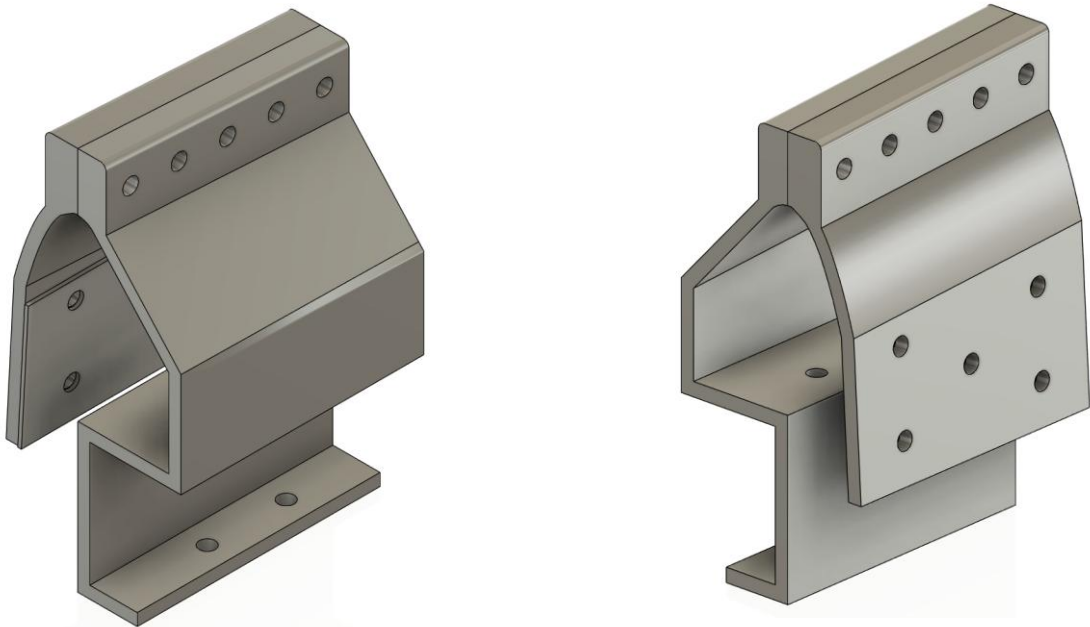


Figure 14: CAD render - Aluminium hull clamp

An additional security measure has also been planned if slipping of the clamp along the hull wall during foiling is observed (Figure 15). Bolts penetrate the first internal wall of the hull only significantly reducing the likelihood of water ingress compared to penetrations of the exterior hull shell.

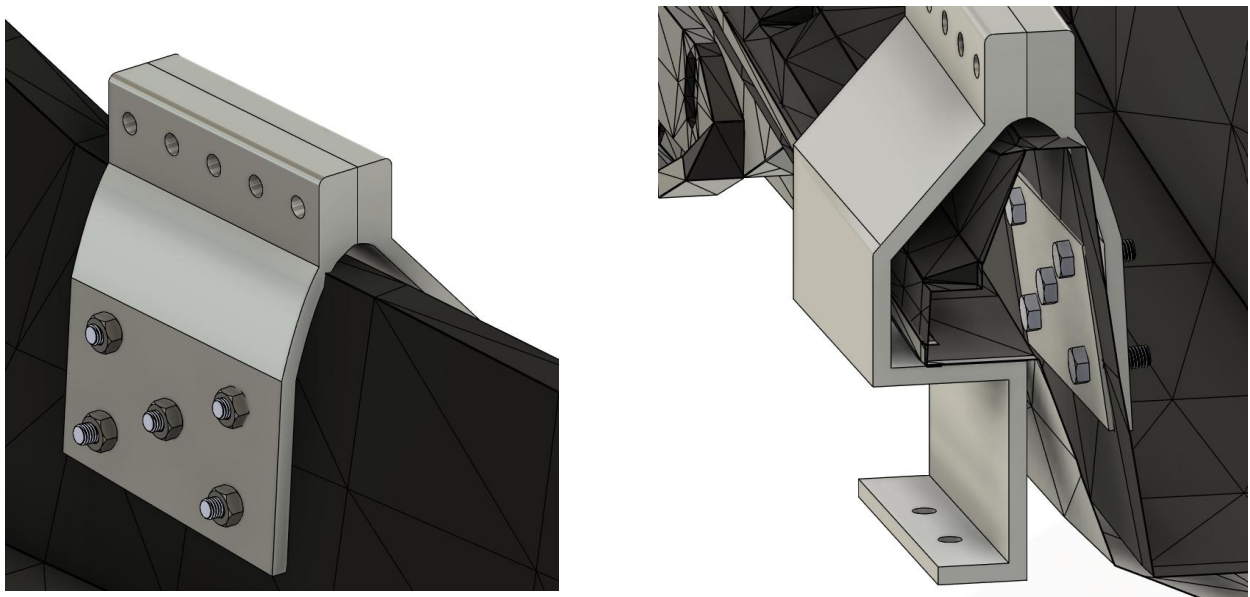


Figure 15: CAD render - Supplementary hull attachment method

2.3 Hull Clamp Calculations

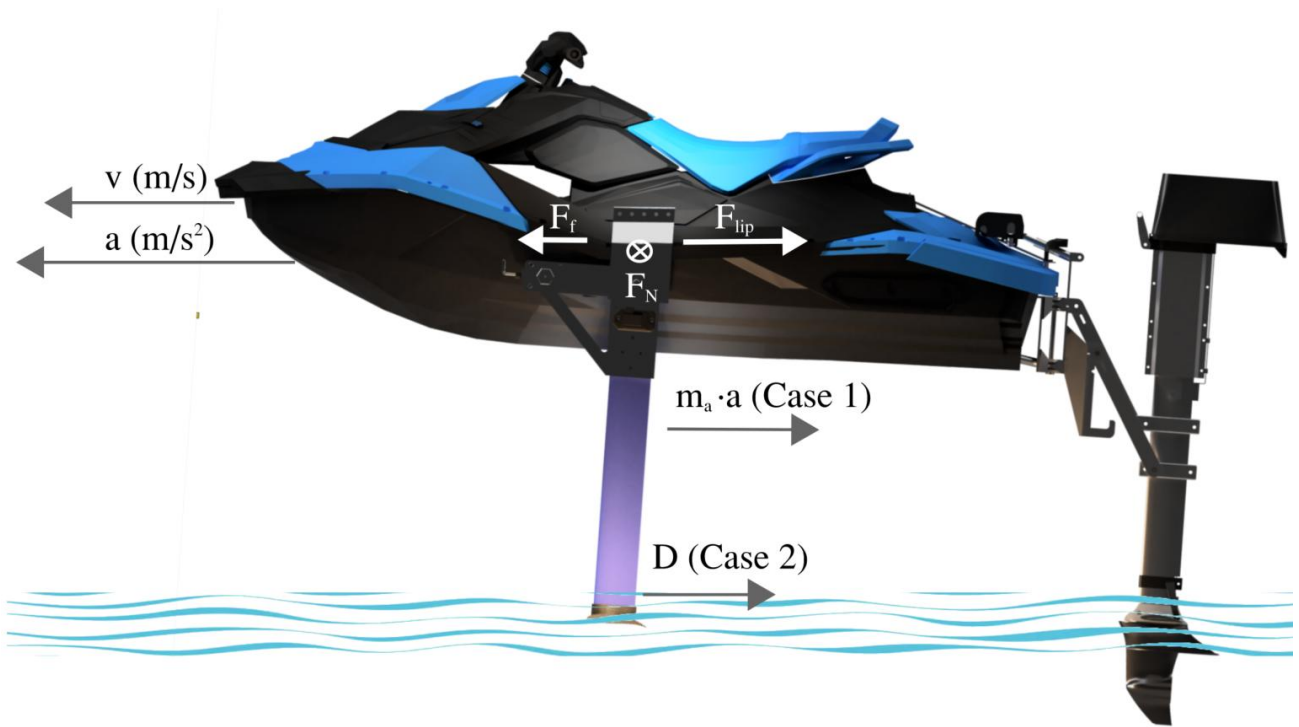


Figure 16: FBD displaying clamp slip along hull wall

The clamps hold the front foil on the hull by friction, so the governing question for the attachment is whether loads in operation could slide a clamp along the hull lip. Two load cases were checked independently (Figure 16) and the force each produces was compared with the grip the clamp can develop.

Load cases

The front assembly mass is 43.1 kg, made up of two mast sub-assemblies of about 18.6 kg each plus the 6 kg wing. Component masses are listed in APPENDIX B: Hull Clamp Calculations. Both loads push the assembly along the lip and are shared equally between the two clamps.

In a sudden acceleration, the clamps must accelerate the front foil assembly with the hull, so each clamp carries half the assembly's inertia:

$$F_{lip} = \frac{1}{2} \cdot m_a \cdot a$$

Equation 5: Clamp force under a sudden acceleration

In sustained level foiling there is no acceleration, and each clamp carries half the front foil drag:

$$F_{lip} = \frac{1}{2} \cdot D$$

Equation 6: Clamp force during sustained foiling

Drag was estimated at each speed from the lift needed for the front foil to carry the full 400 kg. This is a conservative assumption, since in practice the rear foil shares the load. The estimate combines four parts; profile drag, induced drag, mast drag and spray drag.

Accelerations of 2.5 to 5 m/s² and speeds of 20 to 100 km/h were considered. Both upper limits exceed what the craft is expected to reach.

Clamp grip

The five M12 bolts on each side pass through the top flanges of the inner and outer clamp. When the bolts are tightened, the flanges close metal-to-metal, so further torque does not increase the grip on the lip. The grip instead comes from the 5 mm TPU pad (Figure 25), which is compressed between the closed clamp and the lip.

The lip is sandwiched between the inner and outer clamp, so friction acts on both of its faces. The clamping force needed to prevent slip is therefore:

$$N_{req} = F_{lip} / (\mu_{TPU} \cdot n_s)$$

Equation 7: Clamping force required to prevent slip

No friction coefficient has been measured for wet TPU on Polytec, so a worst-case value of $\mu_{TPU} = 0.2$ was assumed.

The clamping force the pad can supply was estimated from its compression, treating the pad as linear elastic:

$$N_{ach} = E_p \cdot (\delta/t_p) \cdot \eta \cdot A_c$$

Equation 8: Estimated clamping force available

Results:

Load case	Range	Max force along lip per clamp	Clamping force needed	Factor of safety
1 - Sudden acceleration	2.5 to 5 m/s ²	108 N	269 N	57
2 - Sustained foiling	20 to 100 km/h	664 N	1,660 N	9.2
Combined	5 m/s ² at 100 km/h	772 N	1,930 N	7.9

Table 1: Calculation results for clamp slip

The pad is estimated to supply about 15 kN of clamping force per clamp, giving a factor of safety of 7.9 in the worst combined case.

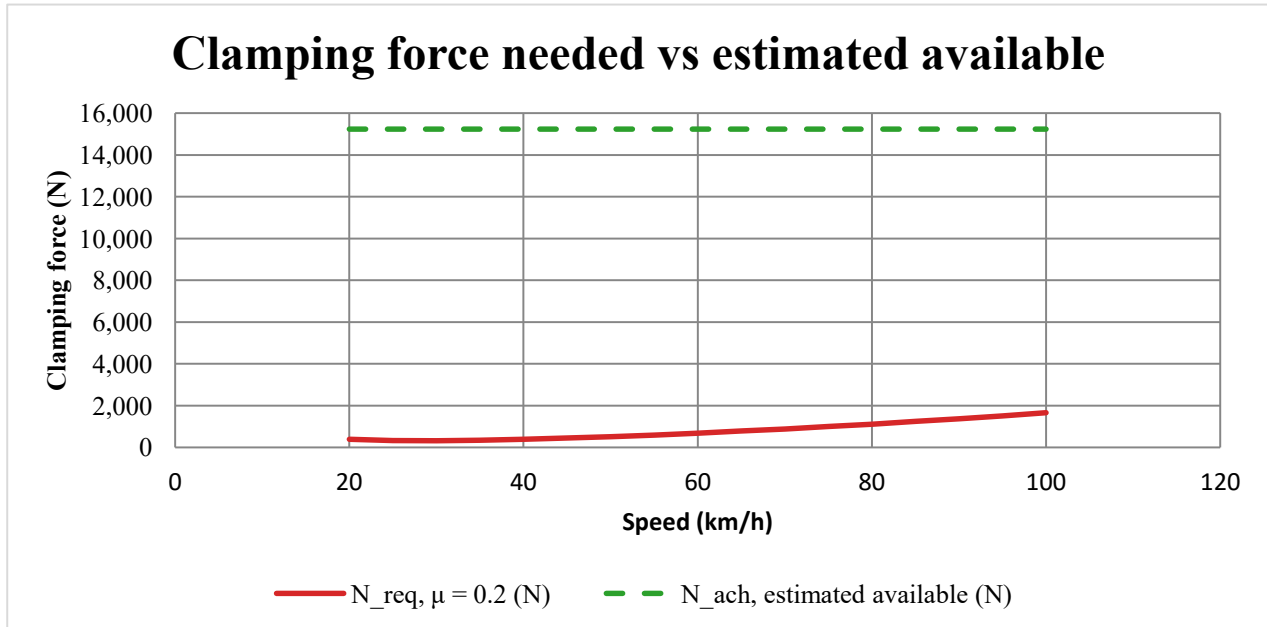


Figure 17: Graph from hull clamp calculations (Appendix B)

Because this depends on an assumed pad compression, the more robust result is the reverse calculation: holding the worst case requires only 0.06 mm of pad compression, about 1% strain. Compression visible by eye is well beyond this, so the clamp is expected to hold with a margin.

These results rest on several assumptions:

- *Stress relaxation*: TPU relaxes under constant squeeze, so the grip will reduce over time.
- *Friction Coefficient*: based on a conservative assumption, not directly measured.
- *Load Sharing*: The hull is assumed level, and the load is assumed to be shared equally between the clamps.
- *Loads not covered*. The check does not include the vertical lift reaction, the moment from drag acting below the clamp, or wave impacts.

The full calculations across the specified ranges are given in Appendix B: Hull Clamp Calculations

2.4 Prototyping

3D Printing was used to create 1:1 prototypes of designed components to see how well they interfaced with the complex hull geometry, initial prototypes however displayed significant discrepancies, suggesting the hull OBJ file sourced from Sea-Doo was not a perfect representation

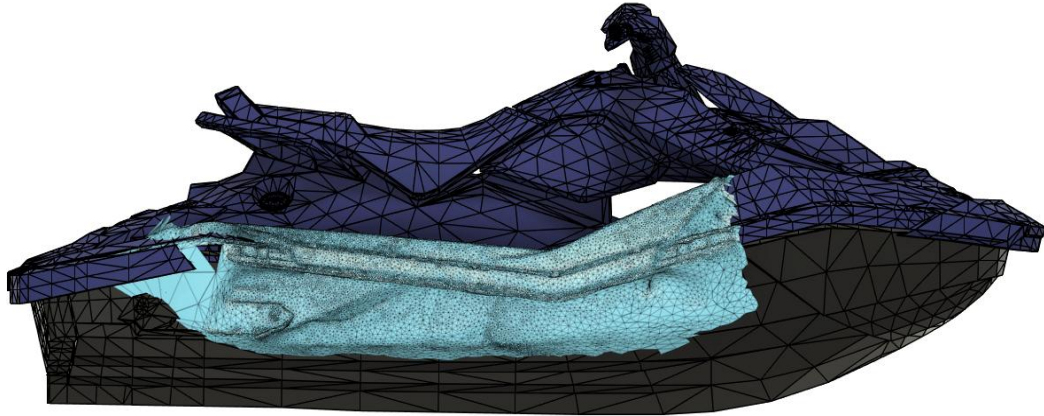


Figure 18: Imported Spark Hull OBJ file with overlaid 3D scan section

To remedy this a 3D scan of the hull was created using free software available on modern smartphones. The result was improved dimensional accuracy and a 1500% increase in mesh density

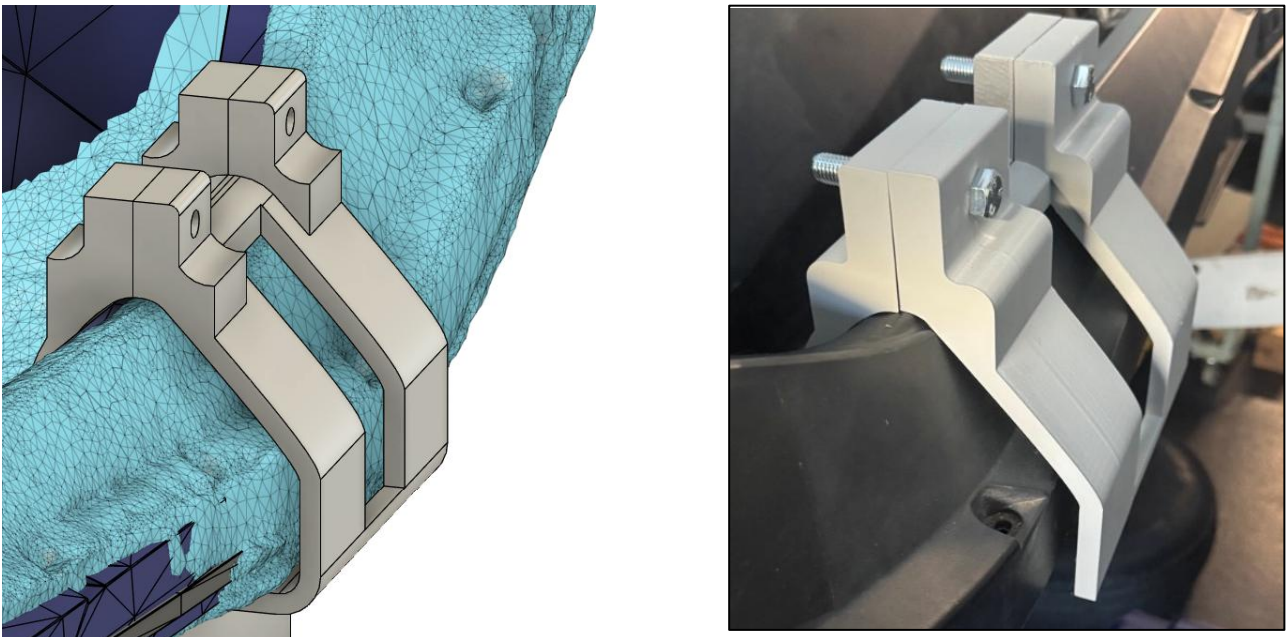


Figure 19: Preliminary clamp model and 3D printed prototype

Prototypes created after the development of this scan interfaced with the hull far better allowing 1:1 models to be 3D printed and fit with the hull.

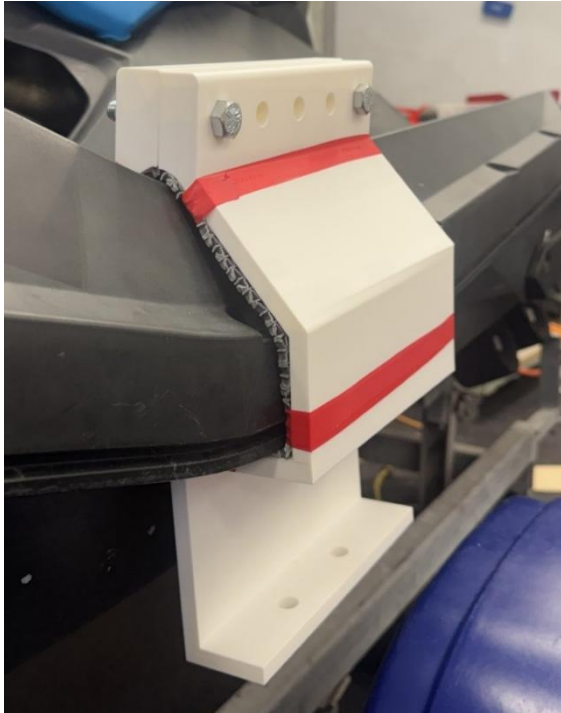


Figure 20: 3D printed prototype mounted on hull

Many iterations were taken to perfect the profile of the clamp, the above (Figure 20) was found to be an extremely tight and ideal fit when paired with a 5mm rubber interface pad. The 3D printed prototype could not be slid along the wall of the hull by hand; held in place by the applied friction and clamping force of 2 bolts alone.

3 Construction of Front Foil System

3.1 Hull Attachment System

The components depicted in section 2 were machined by external workshops. Received parts were inspected against prototypes and against each other to ensure everything fit. Initial test fits proved the connection to be as secure as the 3D printed prototypes had indicated.

The outer clamp was extremely rigid and resistant to bending about the horizontal plane in which forces from foiling will act. Each set of clamps has a mass of 4.39 kg about 1.1% of the 400kg system mass.



Figure 21: Complete front foil assembly mounted on hull

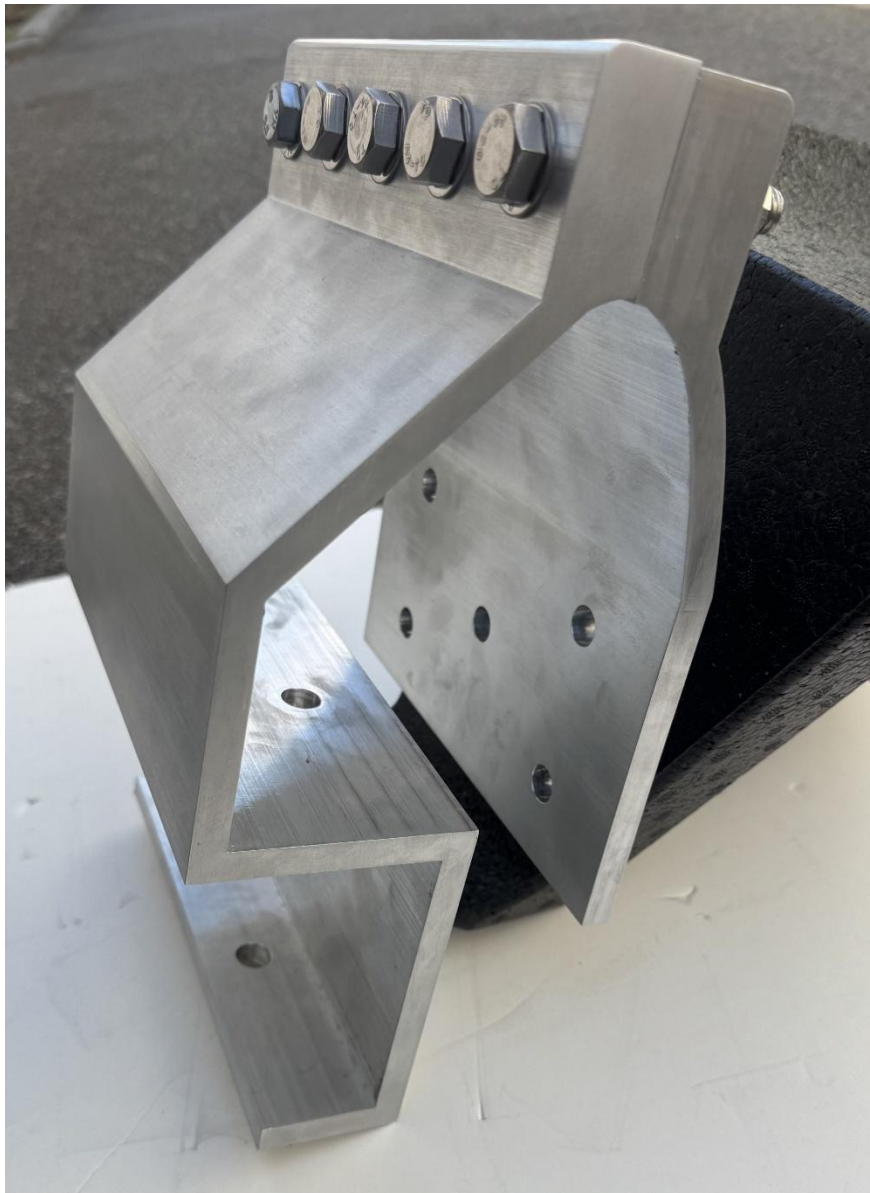


Figure 22: Aluminium hull clamps assembled

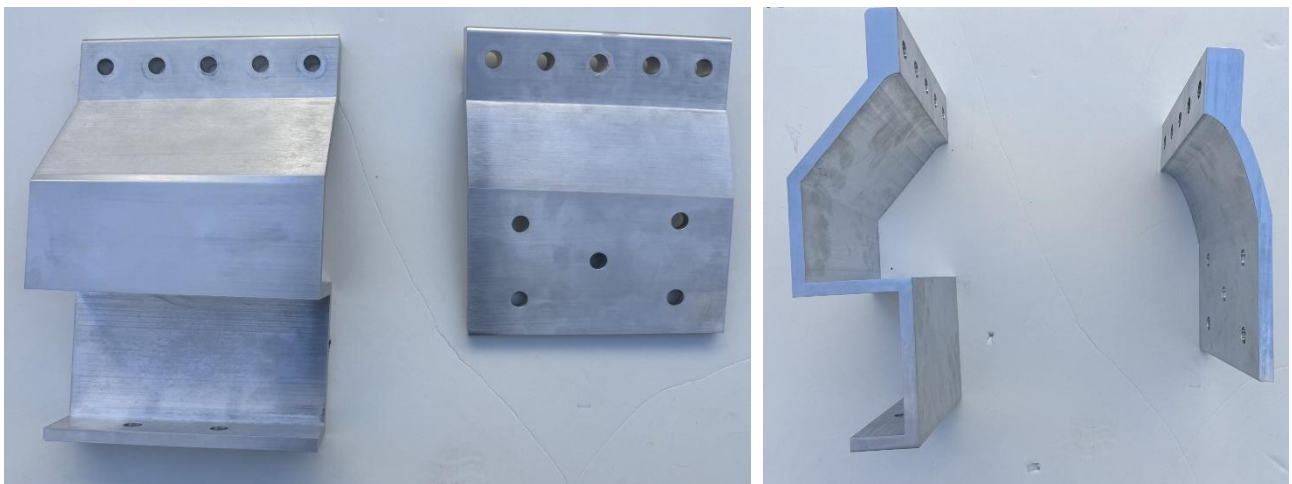


Figure 23: Outer and inner hull clamps



Figure 24: Hull clamp mounted with temporary rubber pad

Figure 24 shows the clamp mounted on the hull using the same temporary rubber interface used during prototyping (Figure 20). Whilst this was effective, it was imperfect structurally and aesthetically. There were areas where the thickness of the pad would benefit from an increase and others where the fit was already ideal. To achieve a perfect geometry of the interface pad using a flat sheet of rubber is extremely difficult, so an alternative was considered.

A TPU interface pad was modelled and 3D printed to perfectly fit the gaps in the hull and clamp connection. It was printed as one continuous piece that wraps around the hull lip, extending beyond the clamp walls on both sides to mitigate some minor scratching of the hull lip that was observed.

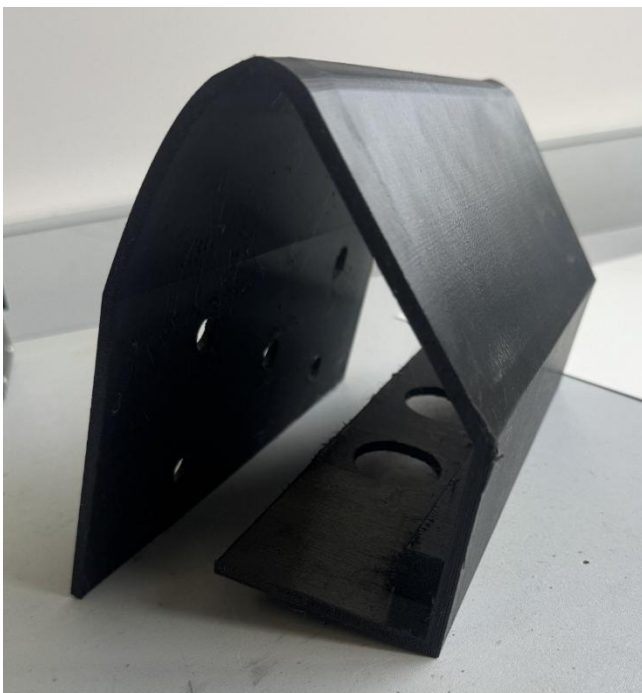


Figure 25: 3D printed TPU interface pad



Figure 26: TPU pad over hull lip and hull clamp over pad

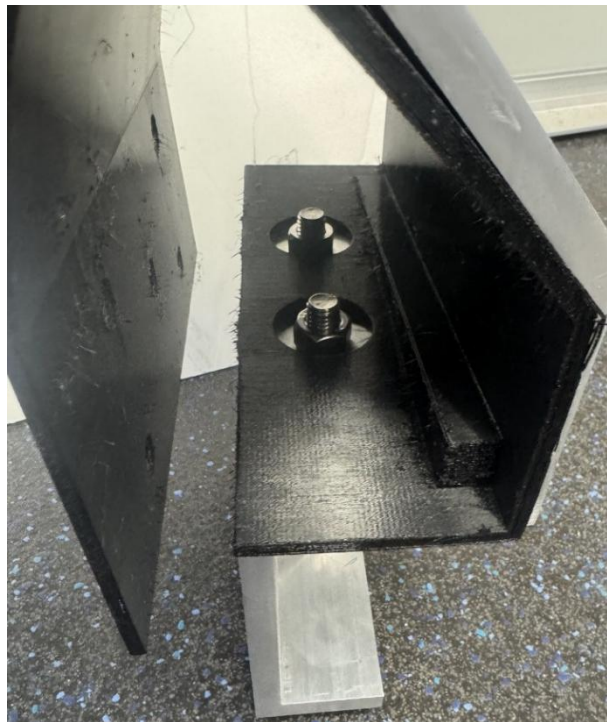


Figure 27: TPU pad; thickened section along hull lip and clearance for bolts

The primary gain from this approach was being able to add a thickened, tapered padding along the bottom of the hull lip to fit its sloping geometry (Figure 27)

95A grade TPU was used for this print. This sits at the higher end of the hardness scale for TPU which follows the Shore A durometer scale [15], used for indentation resistance of various plastics, this runs from 0-100. 95A TPU provided what is believed to be a sufficient balance between compressibility for a snug fit with the hull, and elasticity so this fit is maintained for many cycles of loading.

3.2 Wing Control System

The control rod arrangement was modified from the initial concept design (Figure 13) to suit other design changes. Bench testing of the fully assembled front foil system was performed to confirm control rod travel and cut the rods to length.

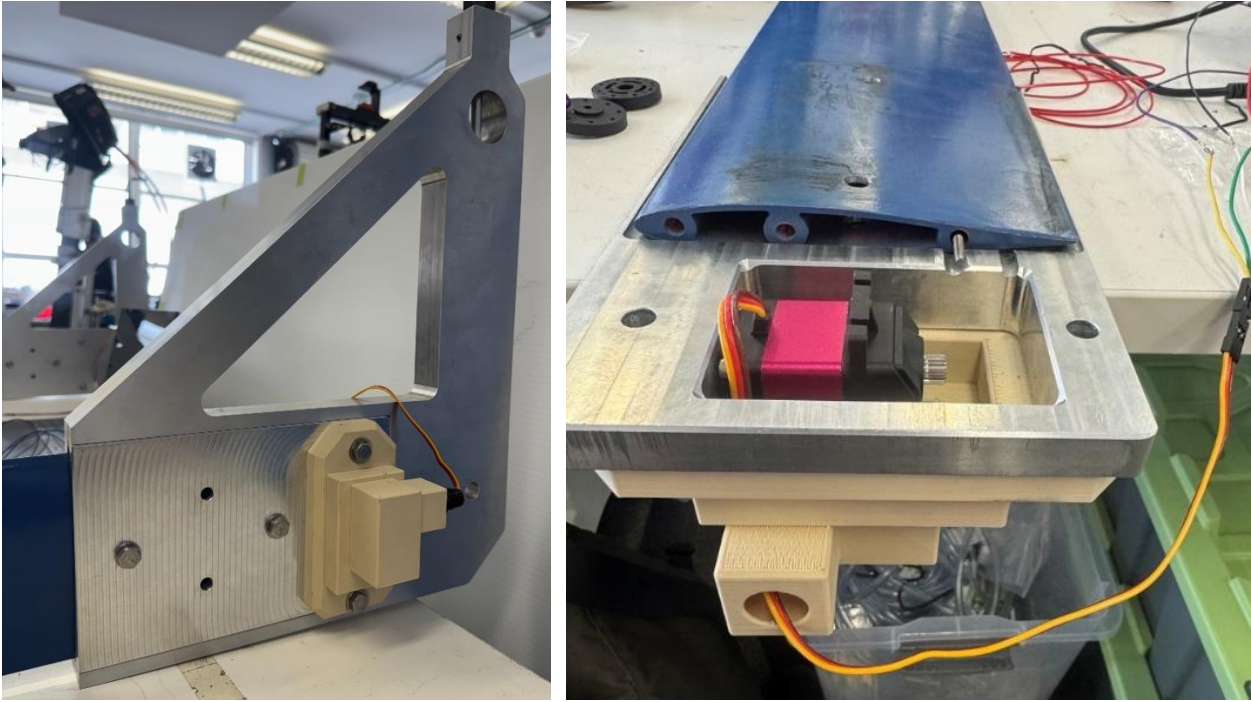


Figure 28: Servo housing within mast sheath

Threaded M3 tie rod ends (Figure 29) were used at both the servo and wing ends. Full actuation of the aileron was measured as 20mm of linear travel, so a servo arm length and sweep that could achieve this had to be established.

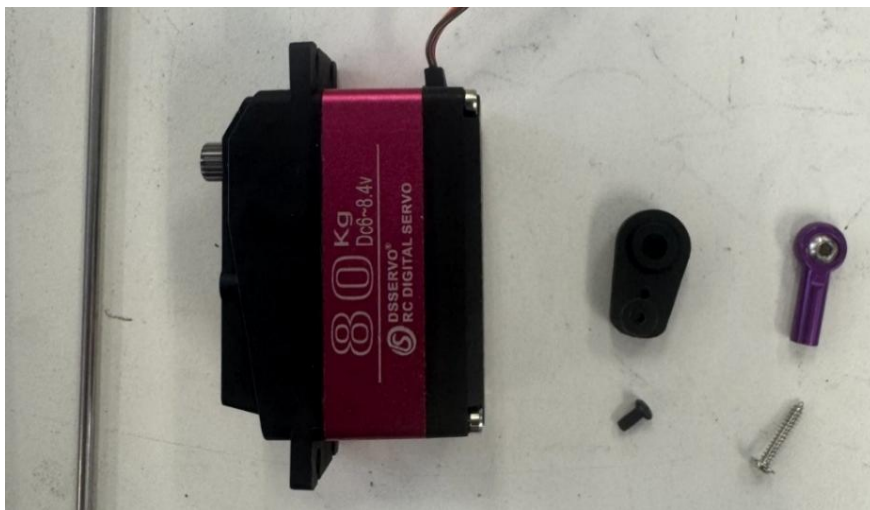


Figure 29: Components for control rod mechanism

First the full possible range of motion of the servo arm within the enclosure was established; it was found that a sweep of 95° was possible from 50° above horizontal on one side to 35° on the other.

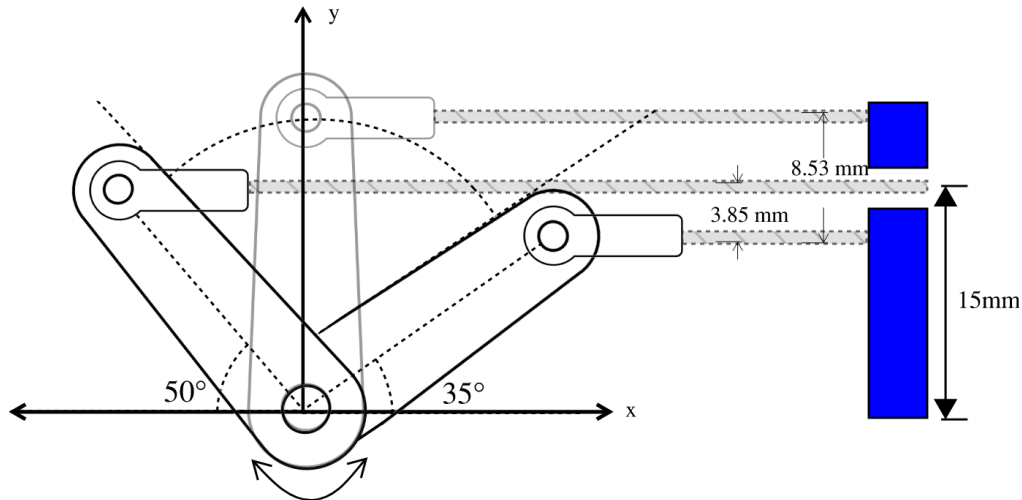


Figure 30: Control rod configuration for 20mm arm (N.T.S)

The supplied 20mm arm gives 29.2mm of travel over the full sweep. However, within the enclosure limits, any sweep that delivers the required 20mm must pass through vertical, where the rod end sits 5.0 mm above the mast hole. Bench testing with this arm showed satisfactory actuation, but also a small, noticeable deflection of the rod within the mast. After the servo had reached the end of its rotation, the aileron could be pulled slightly further as the rod straightened. This deflection should be limited where possible.

A 15mm arm was therefore adopted, sized so that the rod aligns with the mast hole when the arm is vertical. Its sweep was limited to 50° and 46° above the horizontal, which gives the required travel:

$$15 \cdot (\cos 50^\circ + \cos 46^\circ) = 20.1 \text{ mm}$$

The largest offset from the mast hole is then 4.2 mm, about 16% less than the best a 20mm arm can achieve while still providing 20mm of travel. Bench testing with the 15mm arm confirmed a reduction in rod deflection.

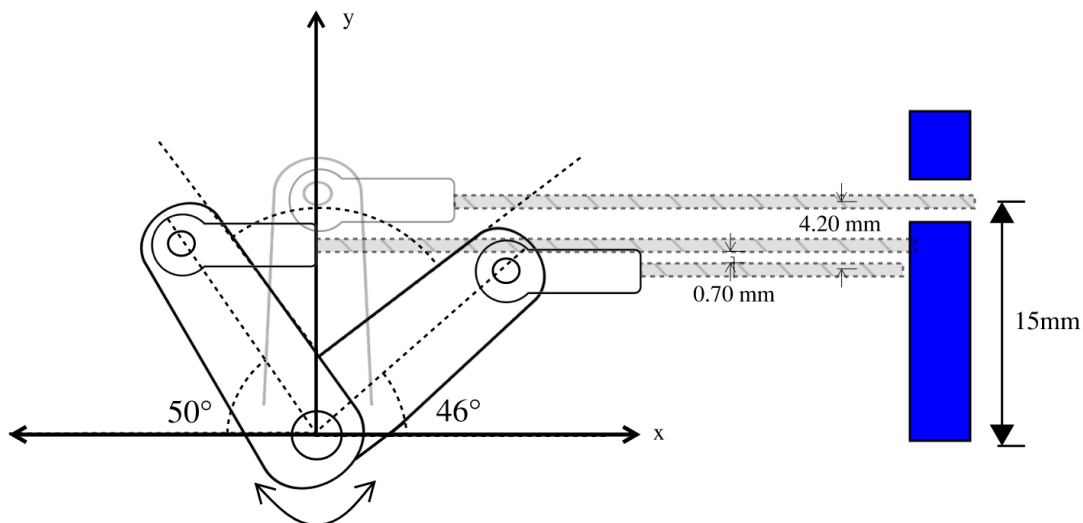


Figure 31: Control rod configuration for 15mm arm (N.T.S)

If more travel is needed in future, the 20mm arm can provide up to 29.2mm within the existing enclosure, and the 3D printed enclosure can be adapted if more than this is required.

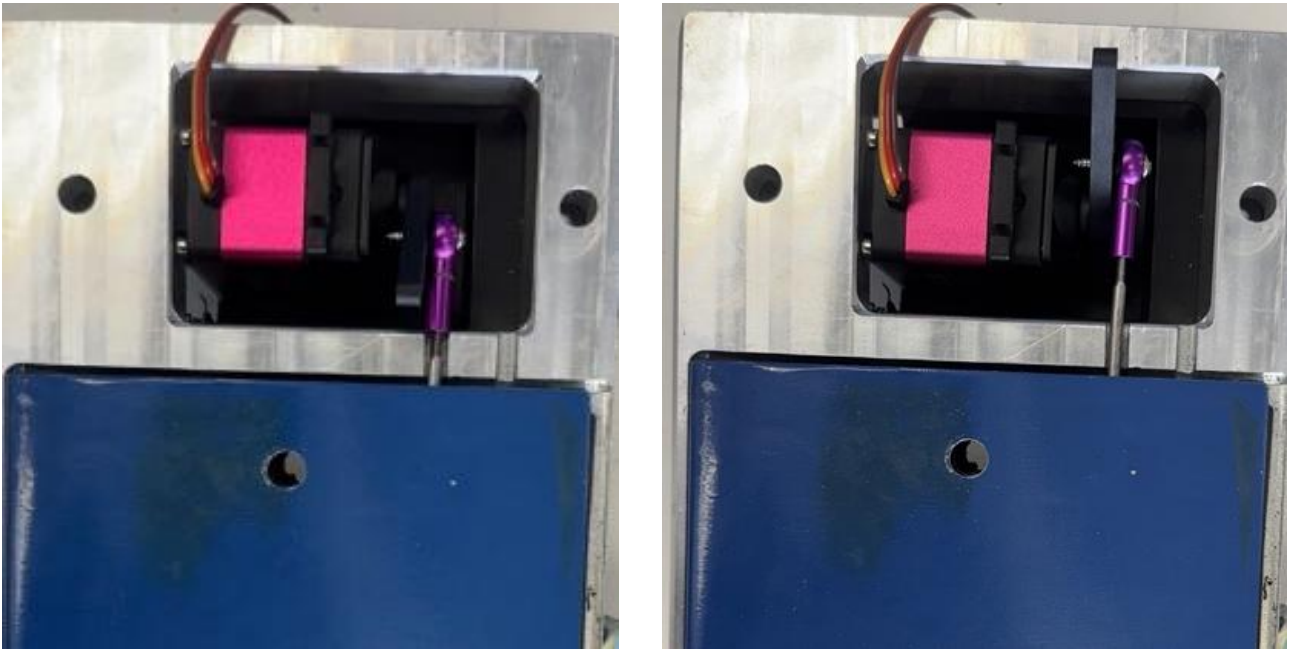


Figure 33: Control rod limits using 15mm arm

After confirmation the 15mm control arm fit within the enclosure, the entire front foil was assembled with servos tested together to size the control rods based on aileron position

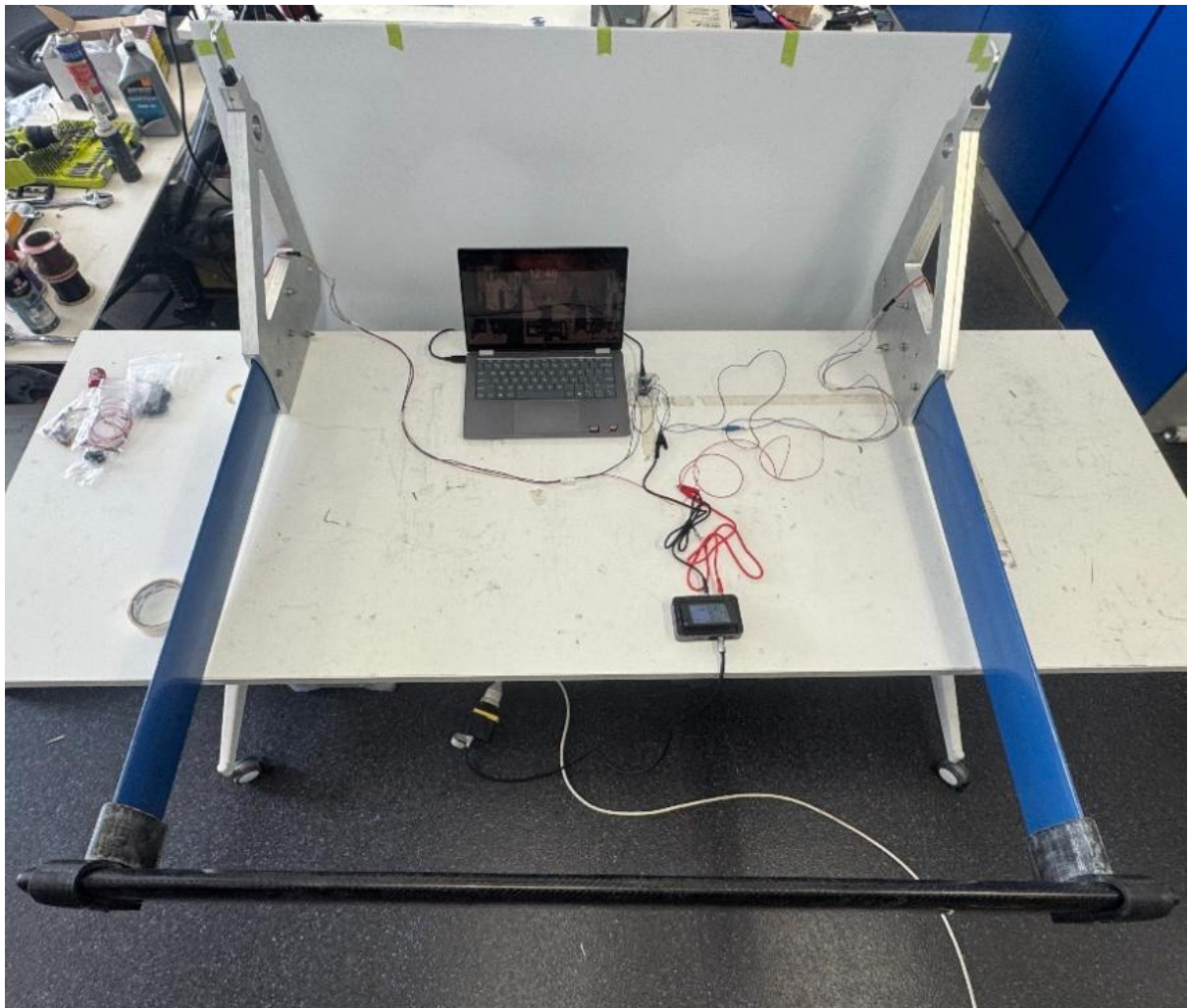


Figure 32: Bench testing setup for fully assembled front foil

3.3 Assembly of Front Foil System

(Figure 34 - Figure 37) shows the assembly process for the front foil, with explanations summarised below. Figure 32 shows the assembled front foil connected in the final step. Initial testing on this assembly is covered in *Results & Discussion*

Figure 34:

Place TPU pad over the lip of the hull, ensure the thicker side of the triangle printed along the corner is oriented toward the back of the craft

Figure 35

Connect base block to outer clamp with two M12 x 150 bolts and nylon lock nuts

Figure 36:

Connect inner and outer clamps over the lip of the hull, stagger tightening to distribute preload evenly over the clamp face

Figure 37

Slot the front wing assembly on to the pivot mechanism, securing with the threaded aluminium caps



Figure 34: Assembly Step 1

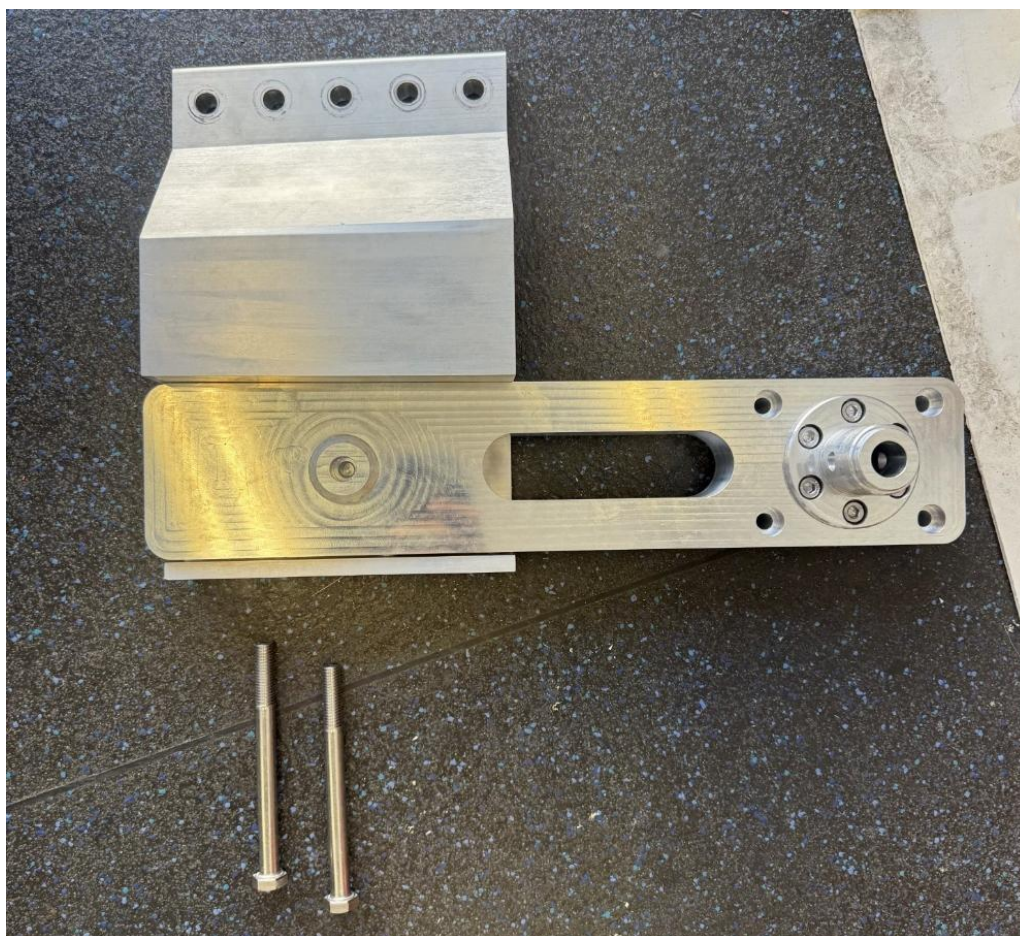


Figure 35: Assembly Step 2

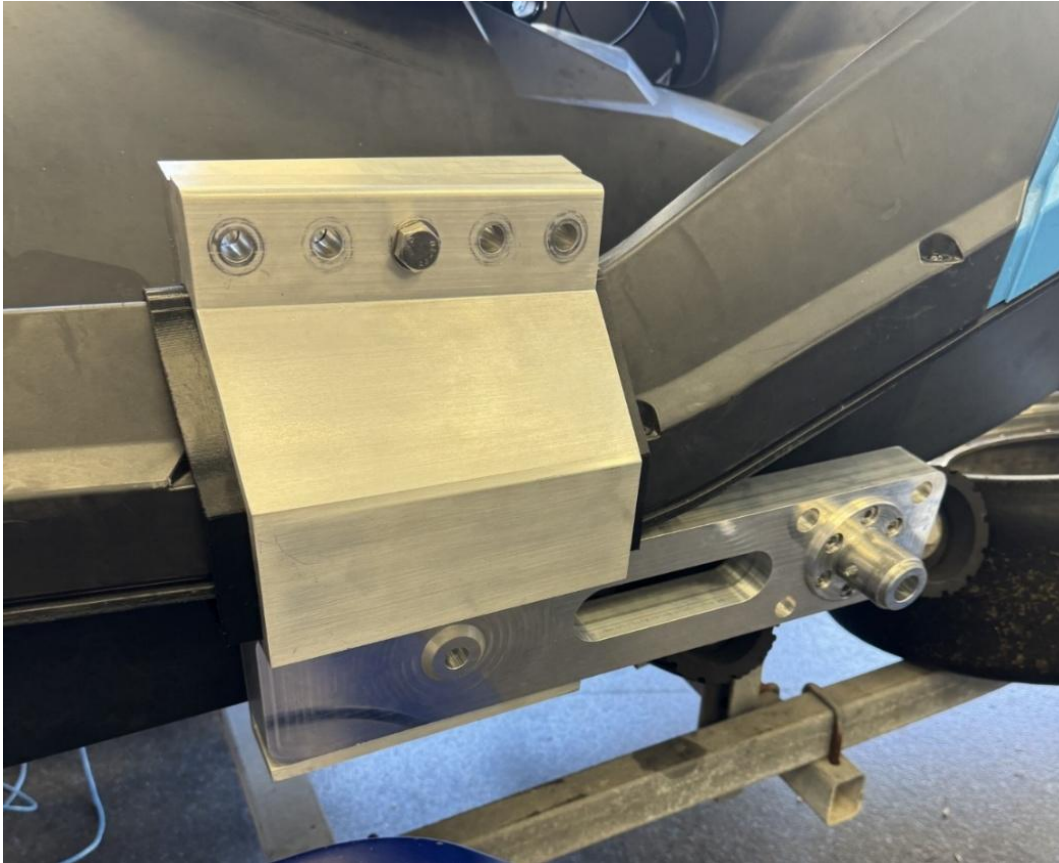


Figure 36: Assembly Step 3



Figure 37: Assembly Step 4

4 Design and Construction of a Hydrofoil Wingtip

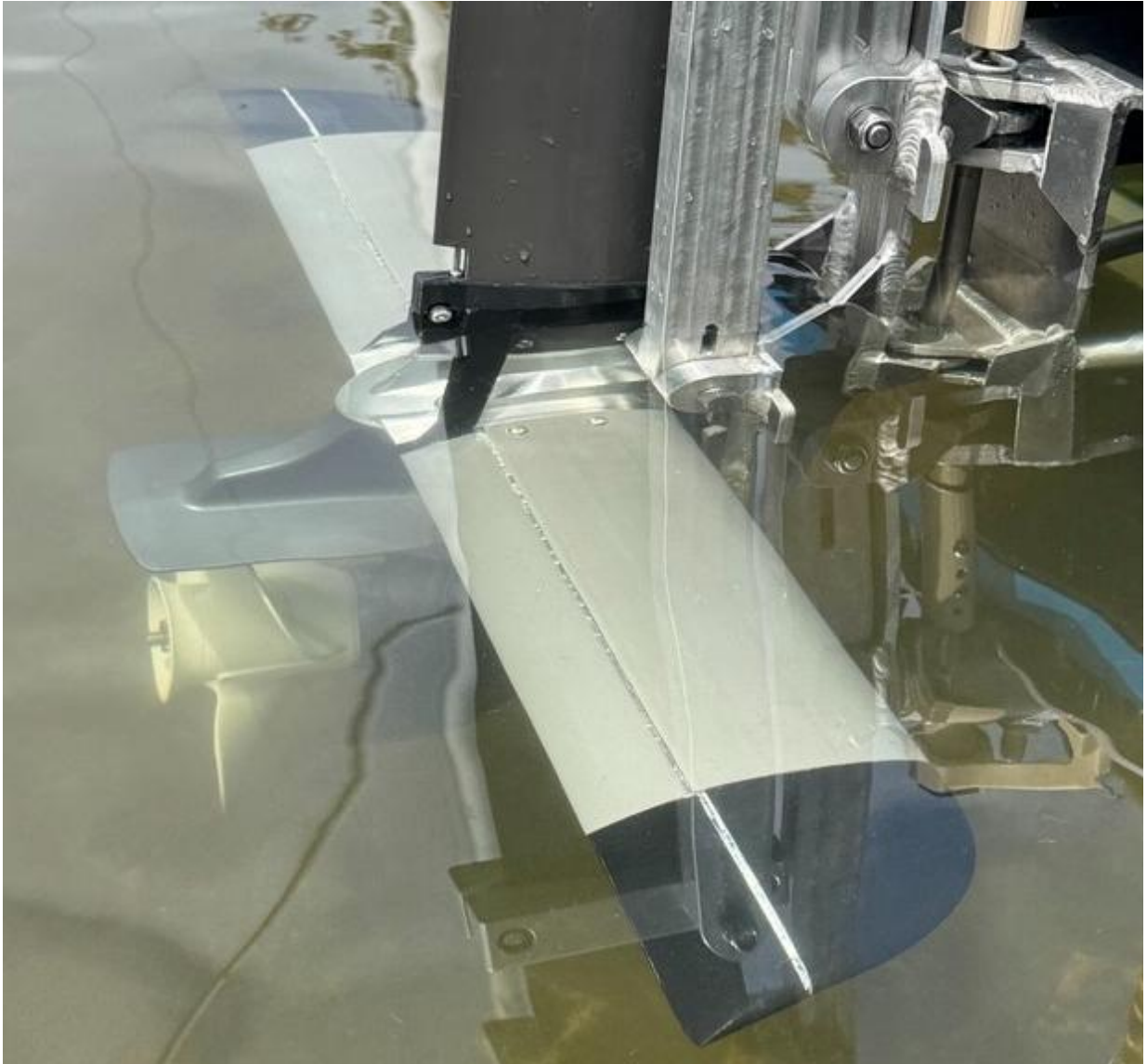


Figure 38: Rear foil during initial water testing

4.1 Requirements for the Hydroski

The geometry of a hydrofoil's wingtips has a large influence on its drag and on how readily the craft rolls. Improved agility is a key aim for the Hydroski, including the ability to perform sharp, banked turns "like a motorbike".

The rear foil tips must meet three requirements. Their trailing edge should actuate with the rest of the rear foil aileron without resisting its motion, they should add minimal drag, and they should attach non-permanently so they can be replaced as wing profiles are further developed. These requirements directed the research toward simple flat and tapered profiles.

The leading manufacturing solution for these wingtips is 3D printing, there were two main options considered, a mechanical hinge connection between separate main body and aileron components, or one continuous piece utilising the flexibility of TPU filament to allow for a single piece that could actuate with the rest of the rear foil.

4.2 Design process

First a profile to interlock with the existing rear foil had to be created, with high dimensional accuracy and tight tolerances for an interference fit. No offset was added to this sketch as it was hypothesised that the shrinkage the part experienced post 3D printing would be sufficient to allow assembly of the bodies with a tight interference fit.



Figure 39: Rear foil wing cross section and CAD render of profile

The main body of the tip was then designed, flat and tapered (Figure 40).

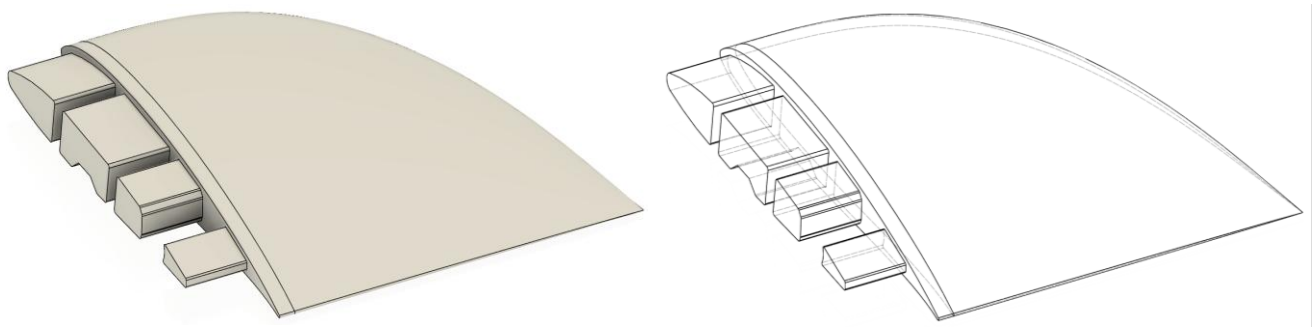


Figure 40: CAD render of tapered wingtip profile

Two main concepts for this design were considered and are covered in the following sections;

- 4.3 Flexible TPU wingtip
- 4.4 Mechanical Linkage wingtip

Concept and initial testing:

A conventional pin hinge requires a hinge line groove on its upper and lower surfaces. The boundary layer separates at the lip of the groove, recirculates within the cavity and reattaches downstream, a pressure drag contribution.

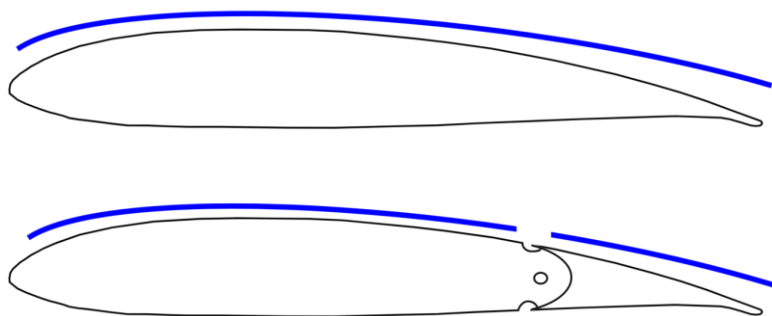


Figure 41: Diagram showing boundary layer discontinuity for a hinged wingtip

The groove carries a further consequence specific to a hydrofoil. It forms a continuous low-pressure channel running spanwise along the suction surface, so air entrained at one end during a tip breach has a connected path along which to spread, and the sharp lips provide sites at which this can begin.

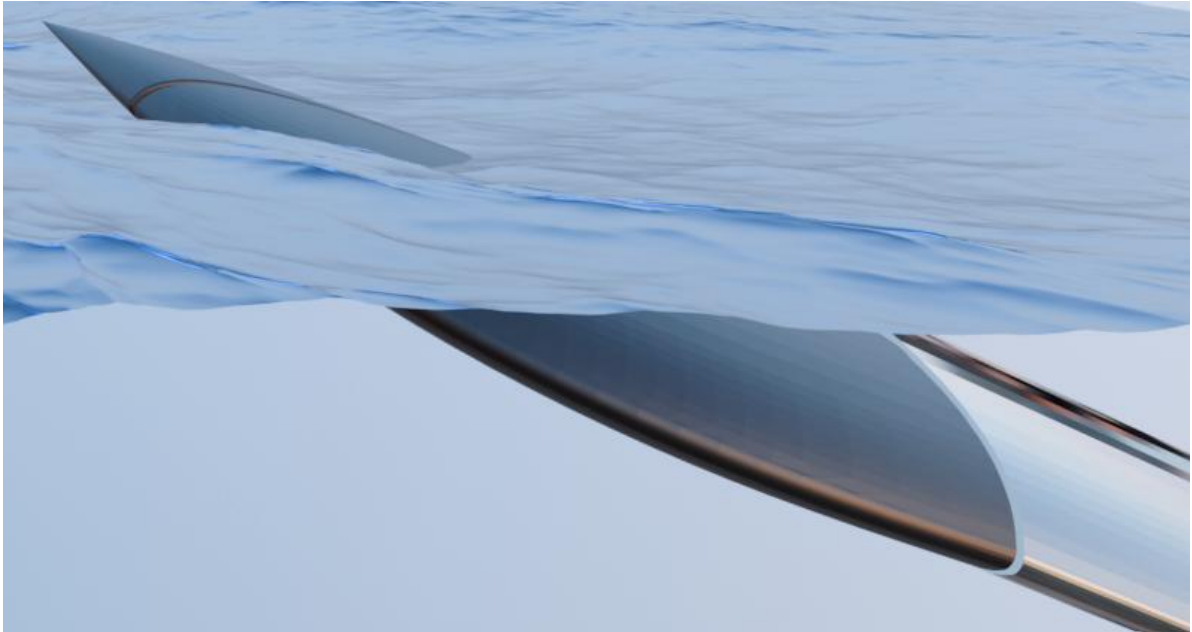


Figure 42: Simulated wingtip breach, exposing groove to the free surface

A continuous elastomeric surface eliminates these issues. The surface stays unbroken, so the boundary layer is not interrupted, no cavity drag is generated, no spanwise channel exists for air to propagate along, and the deflection is carried by distributed strain within the material rather than by a discontinuity in the wetted surface. This became the main driver in the design of a 3D printed flexible TPU wingtip

4.3 Flexible TPU wingtip

The flexibility of a TPU print can be tuned through its infill density and pattern. Rather than printing the whole tip in TPU, a multi-material print was used, so the part stays rigid where it needs to be and flexes only at the hinge.

PETG was selected as the rigid material for its ease of printing during prototyping. The main challenge with this approach is slicing the print to achieve good layer adhesion at the TPU/PETG interfaces.

Test Print 1

The feasibility of this design was assessed through Test Print 1, a rectangular print with a band of TPU in the middle. To maximise the layer adhesion at the multi-material interfaces, “Beam interlocking” was used; for a given number of layers below or above the multi-material interface the printer will cross-hatch layers of the two filament types, creating a strong bond that runs deeper in the print than the typical single layer interface.

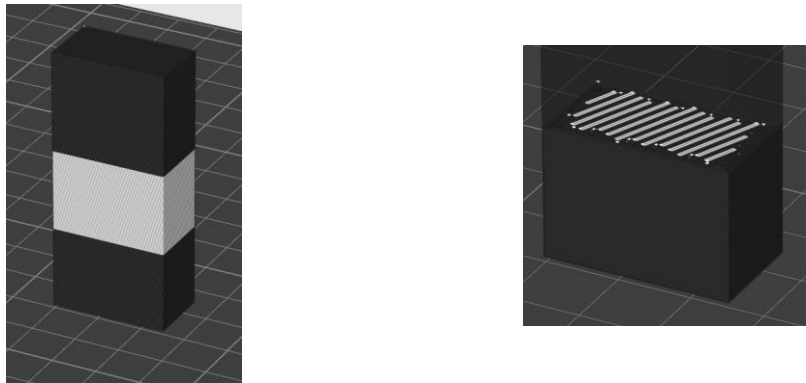


Figure 43: Slicer preview – Test print 1 body and beam interlocking

The test was promising, with deflection of the object achieved and an extremely high tensile strength of the bond between TPU and PETG layers observed, separation of the two materials was only slightly visible around the edges where the beam interlock did not reach.

However; the bend point of the TPU section was inconsistent between cycles and created a sharp crease, as the side walls bulged out to compensate for the bend. These sharp creases led to the development of cracks along layer lines after putting the test piece through 200 cycles of stress.

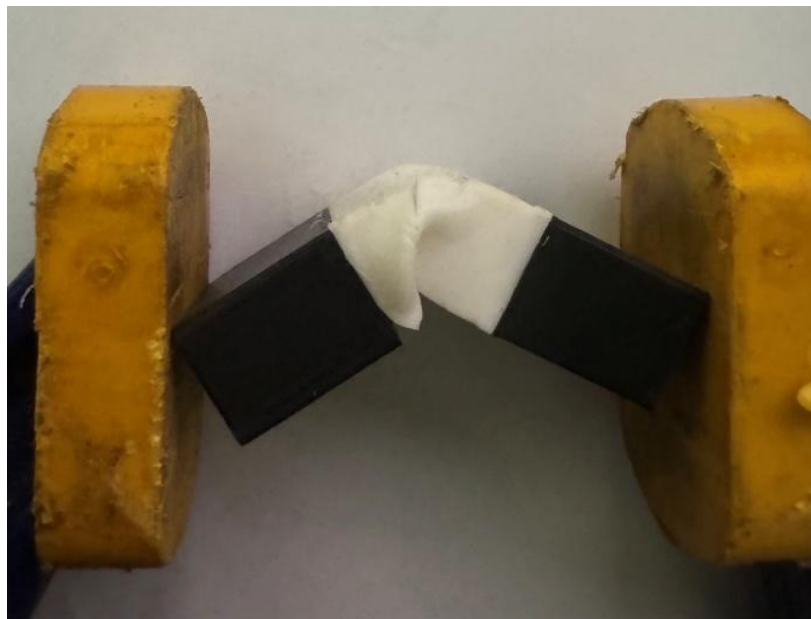


Figure 44: Test print 1 flexure test

Test Print 2

The second test piece addressed these issues, whilst also being shaped as the profile of the wingtip to better reflect the purpose.

The removal of the side wall meant the surface didn't have to contort and crease whilst actuating, removing the likelihood of crack initiation. Additionally, a relief groove was added to top and bottom surfaces to control the line about which actuation would occur.

This test piece performed well with controlled uniform actuation about the relief groove, and no contortion of the material resulting in cracks. The method was extended to a full-sized model.



Figure 45: Test print 2 flexure test

Prototype 1

The original profile was modified to include a relief groove, whilst this groove negates some of the benefit discussed in 4.2 *Design process*, the groove is only 0.8mm deep and is believed to still provide a net positive effect during breaching

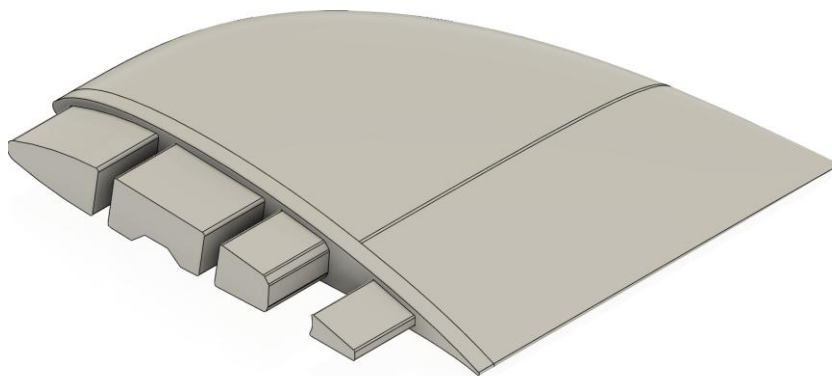


Figure 46: CAD render – TPU wingtip profile

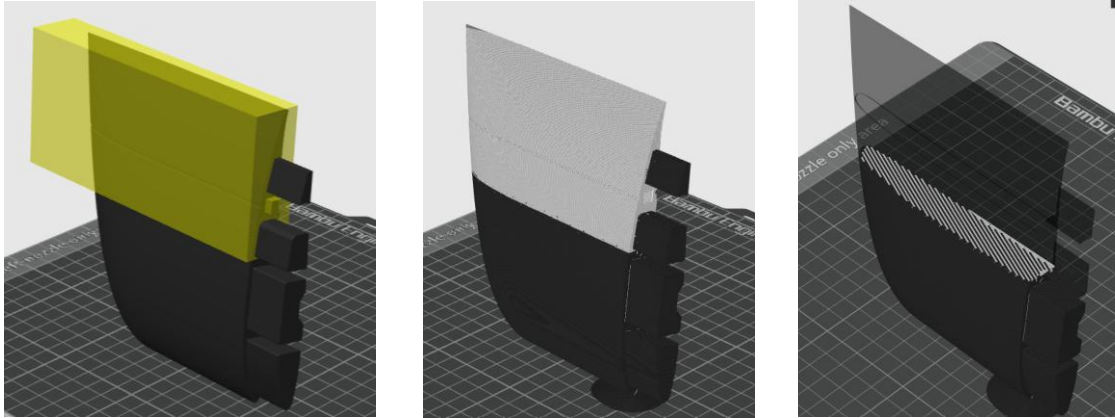


Figure 48: Slicer preview- TPU wing prototype 1

Two modifiers were added to the slicer for the 3D printing of this part, the larger to set the bounds of the TPU section and the smaller to hollow out the section underneath the groove and remove the side wall.

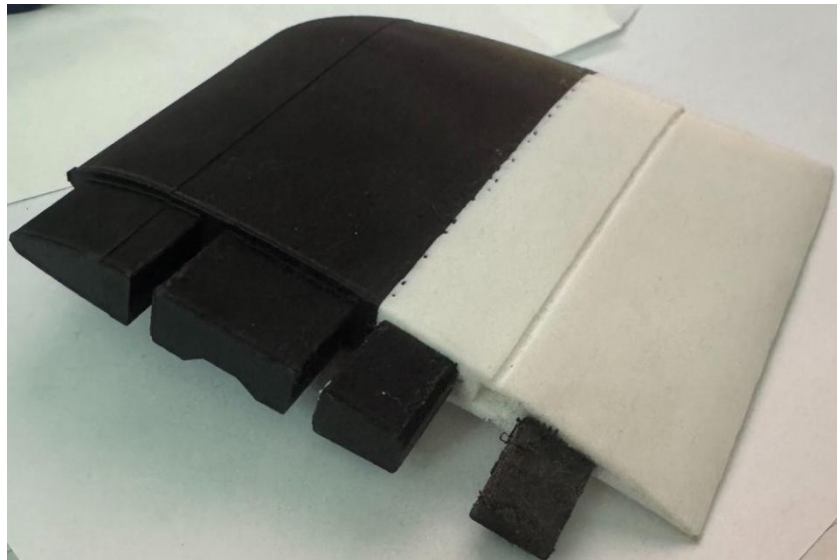


Figure 47: TPU wingtip prototype 1

Prototype 1 showed promising results, with easy deflection of the wingtip aileron through the $\pm 20^\circ$ range required of the rear wing and no separation visible at the multi-material interfaces.

The embrittlement of TPU after prolonged exposure to saltwater was tested to address the findings of Choi and Kim previously cited [14]

Wingtip prototype 1 was submerged in a bucket of Swan River water for 1000 hours to see how this submergence affected the flexibility and layer adhesion of the part.

It was observed that the effects of saltwater on TPU are a more serious design consideration than initially anticipated with shearing along the TPU layer lines after a few movements of the aileron (Figure 49).



Figure 49: TPU wingtip prototype 1 failure

Prototype 2:

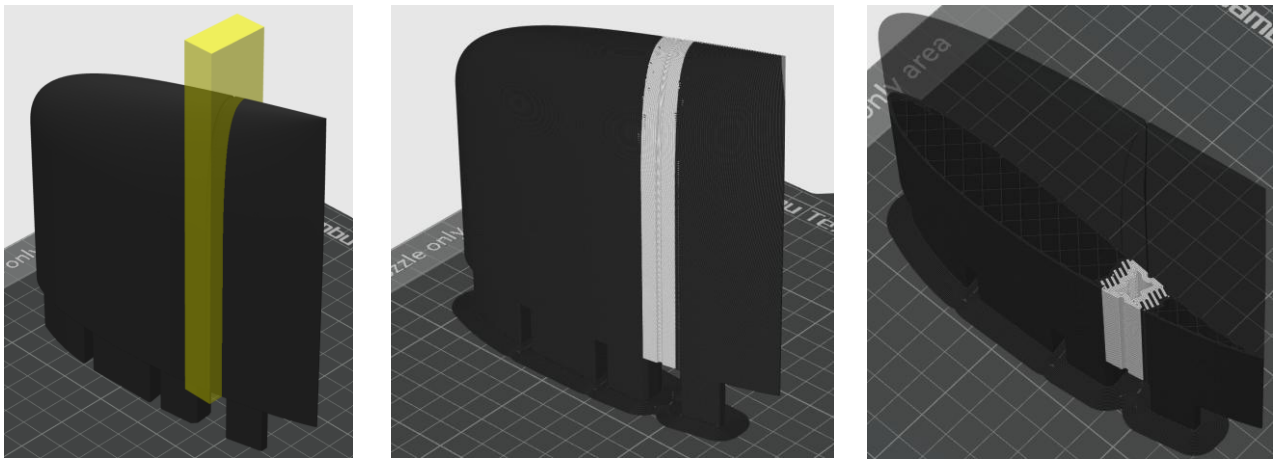


Figure 50: Slicer preview – TPU wingtip prototype 2

In the second prototype, to address the layer adhesion issues following saltwater submersion of prototype 1, the wing was reoriented, so the TPU layer lines were no longer aligned with the plane of bending

After attaching with the rear foil and flexing the aileron, the TPU joint worked well, it was put through hundreds of cycles and flexed along the groove. However, the inherent resistance of the elastomer TPU placed additional strain on the servo responsible for actuating the wing, whilst this servo is oversized and capable of overcoming this, it is still an un-needed force that is difficult to quantify in water and as the joint wears over time.

On a more positive note, the bond between PETG and TPU layers was strong, with no edge separation visible indicating the changes made to beam interlocking parameters had benefited the design.

The primary concern identified from prototype 2 was the alignment with the foil wing. The trailing edge does not perfectly align with the foil, particularly on upward tilting. This discontinuity negates any hydrodynamic gain from the rest of the continuous skin of the profile (Figure 52)



Figure 52: TPU wing prototype 2 aileron movement



Figure 51: TPU wing prototype 2 assembled with rear foil

The flexible TPU wingtip showed promise. The multi-material process produced a strong TPU-PETG bond, and the relief groove gave controlled bending without creasing. Reorienting the print layers in Prototype 2 also resolved the layer shearing seen in Prototype 1, with no sign of the same failure after 400 hours of soaking in saltwater.

However, it was not suited to this craft. Prototype 2's trailing edge did not stay aligned with the foil when deflected upward, which removed the hydrodynamic benefit the continuous skin was intended to provide. The stiffness of the elastomer also added a load on the servo that could not easily be quantified. Given these problems, development of the TPU tip stopped after Prototype 2 and attention turned to the mechanical linkage design, which delivered promising results and is described in the following section. The TPU approach still has merit for applications that do not need to match an existing surface, as discussed in *5.2 Contribution to the State of the Art*

4.4 Mechanical Linkage wingtip

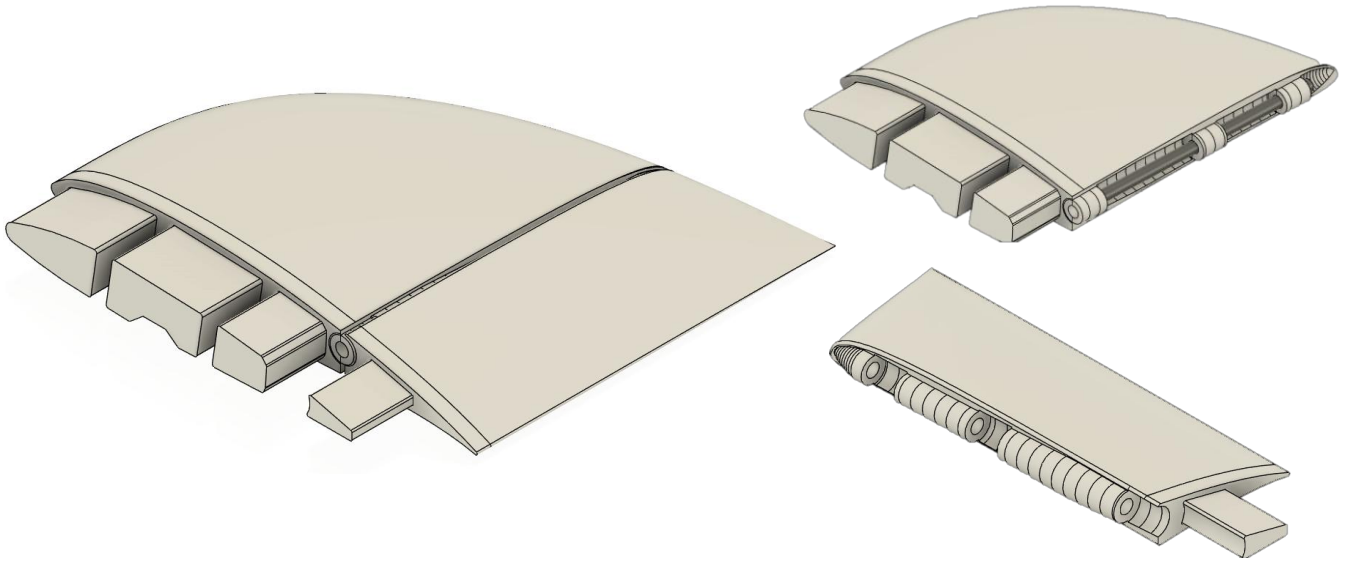


Figure 53: CAD render -Components of mechanical linkage wingtip

The mechanical linkage wingtip was designed using the same original profile Figure 40, split into two bodies and a slender steel rod connecting them.

The rod used was of 2mm diameter, the hinge holes in the aileron are 1.5mm before any shrinkage; it was hypothesised that these two bodies could be held together by the friction fit between the aileron and rod without any adhesive necessary.

The existing limits of the rear foil aileron were $\pm 20^\circ$ from the horizontal, so the wingtip aileron was designed to match, the design has a groove above and below the hinge point actuated, despite best efforts to minimise it, this groove displays the properties described in 4.3 that will worsen the effects of breaching.

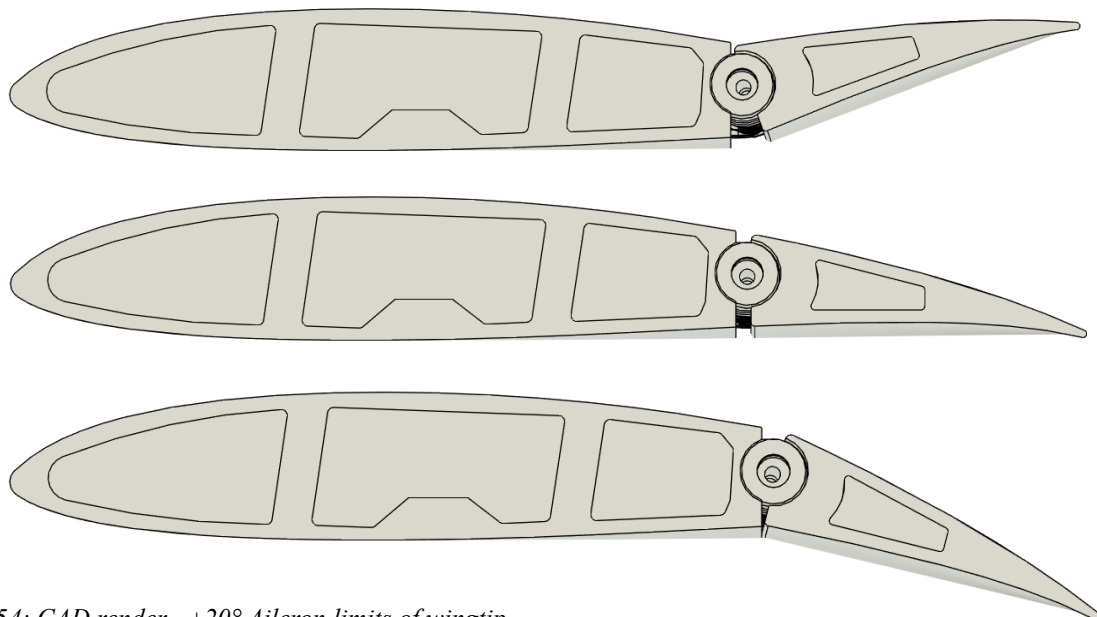


Figure 54: CAD render - $\pm 20^\circ$ Aileron limits of wingtip

Now that the 3D printing of the part was not constrained by the orientations required for TPU flexibility and strength, the part could be reoriented on the print bed for maximum strength, Figure 55 shows the best determined print orientation for strength of the hinge attachment points and of the wingtip tenons



Figure 55: Recommended print orientation for wingtip

Assembling the wingtip

A small steel rod should be marked at 2 lengths, (Figure 57), the first mark indicates the depth to which the rod should be installed and the second the length at which the rod should be cut to allow the drill sufficient clearance to drive the rod to the required depth.

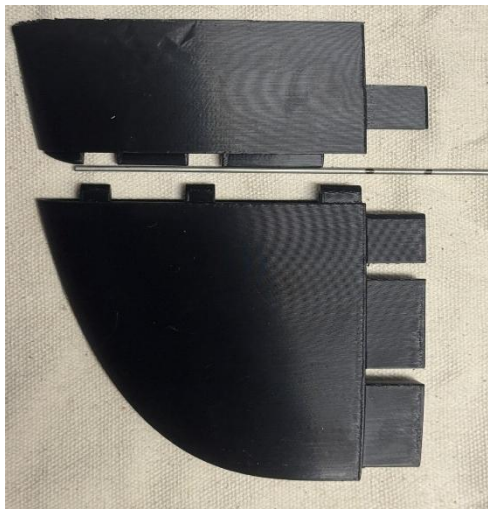


Figure 56: Wingtip components



Figure 57: Rod in drill arrangement

After cutting the rod at the second marking, install the rod on a drill (Figure 56) and align the two printed bodies, insert the rod and run the drill on the lowest speed setting, applying gentle pressure as the rod works down the hinge joint, lightly deforming the material of the aileron, securing the two bodies together.

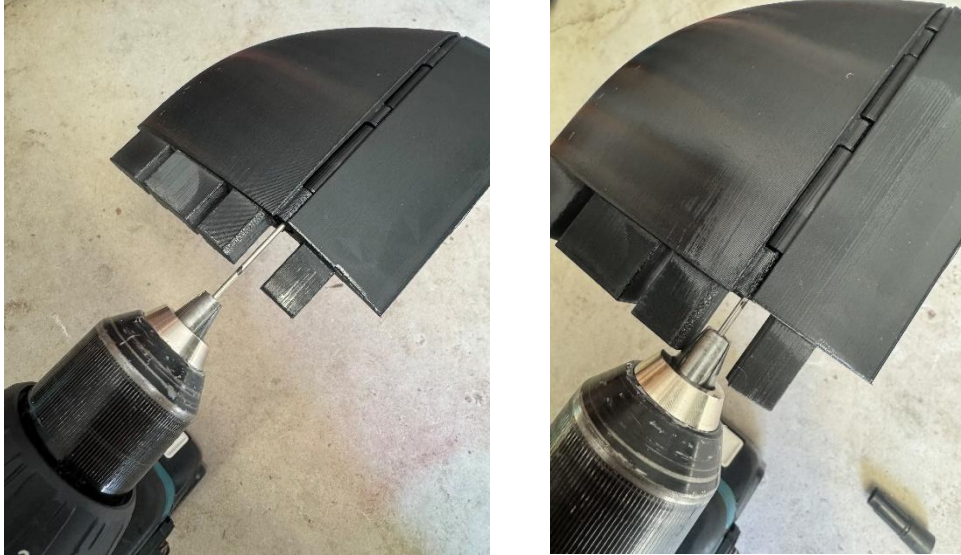


Figure 58: Drilling of hinge rod in to wingtip

A gloss clear coat was also applied, this provides the tips with a more favourable surface finish and improved UV protection.

The wingtips are then pressed into the rear foil wing, the fit is extremely tight so gentle pressure should be applied as the tenons are slowly pressed inward. No adhesive was applied, the theory being that between the tight interference fit and the swelling the part would experience as it took on water, enough friction would be generated to hold the tip in the wing.

The tenons were covered up during the clear coat application to maximise this swelling effect.

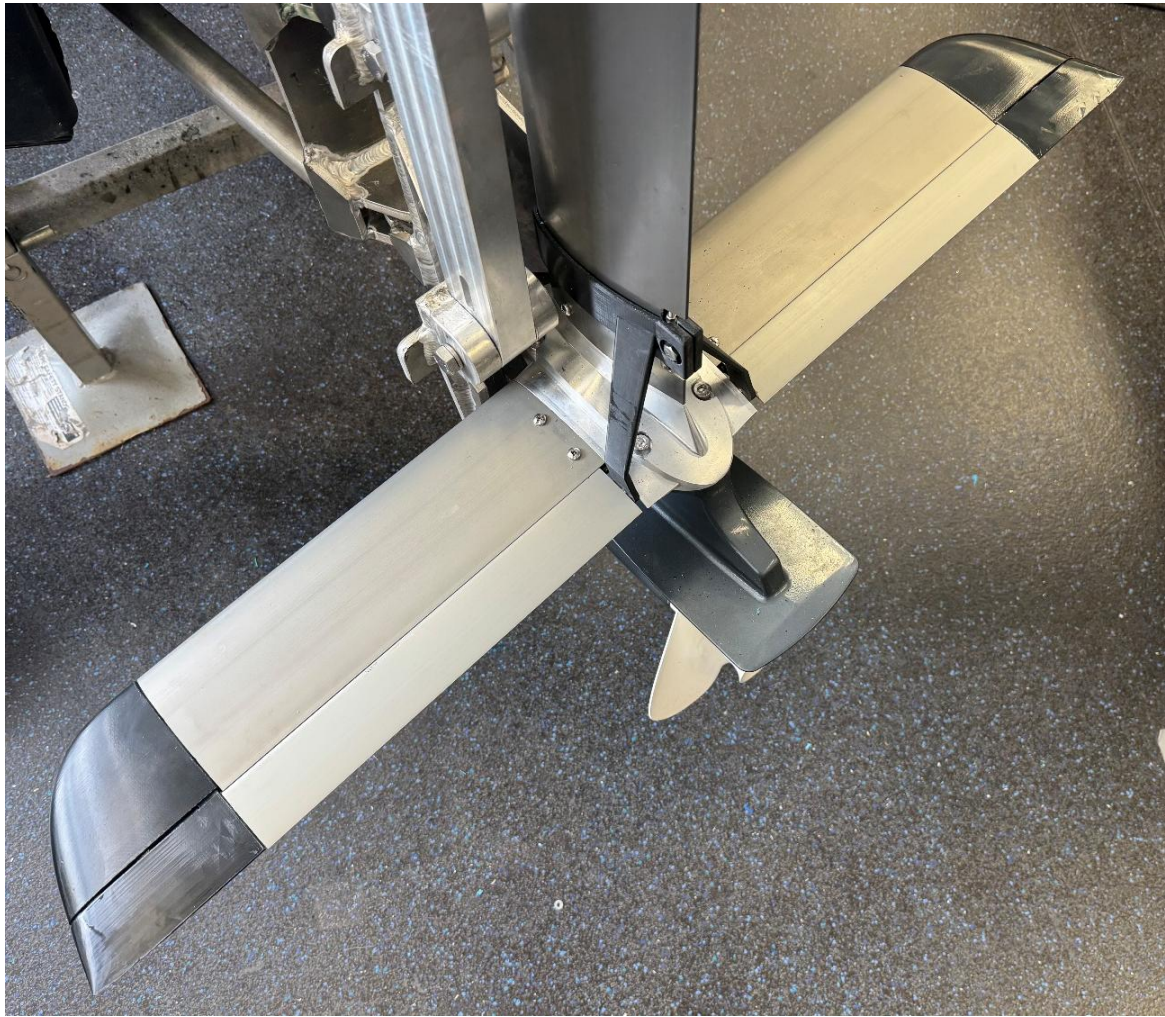


Figure 59: Rear foil with wingtips

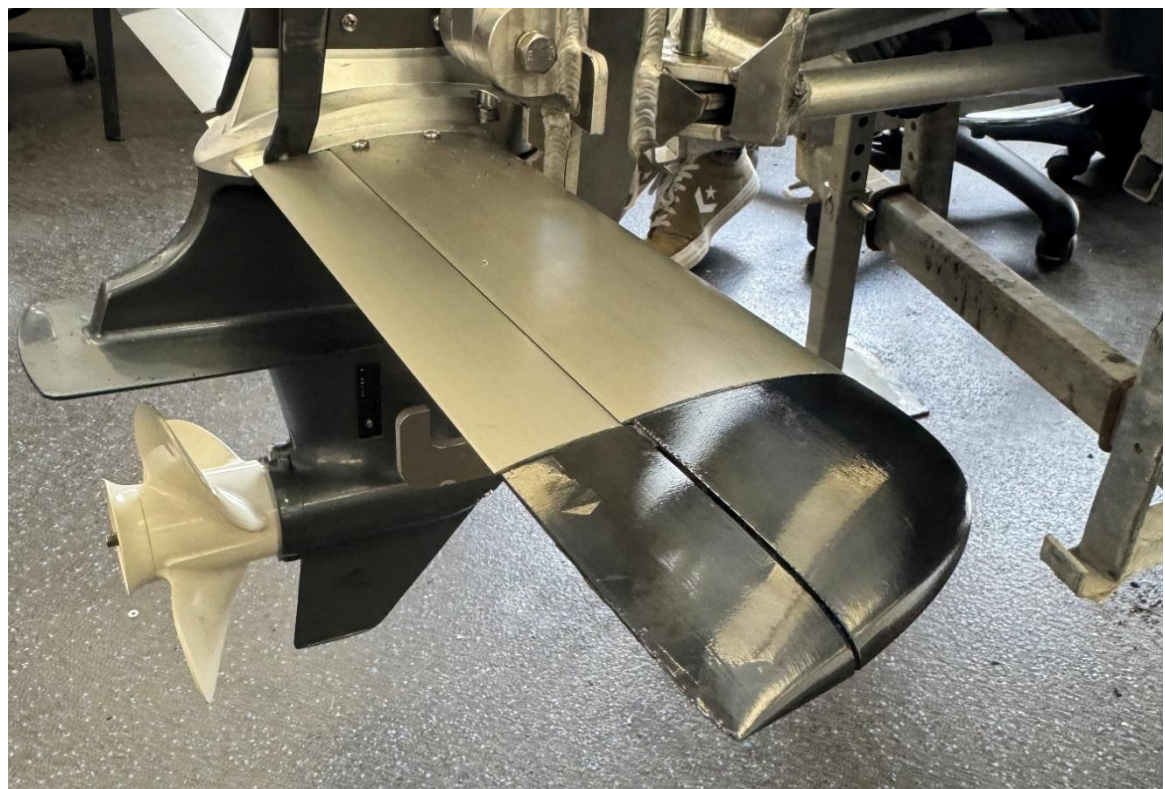


Figure 60: Completed hydrofoil wingtip

5 Results & Discussion



Figure 62: Initial water testing - Hydroski in deployed position



Figure 61: Initial water testing – Hydroski in retracted position

5.1 Initial Testing and Observations

Initial water testing of the craft (Figure 62/Figure 61), was the first time the front foil mechanism could be fully deployed and retracted, the mechanism cleared the front of the hull, and the hull attachment remained rigid throughout rotation and rocking of the craft

A full water testing arrangement was delayed by electrical and software issues; so data surrounding the ability of this craft to generate hydrodynamic lift, and analysis of the strength of the hull attachment during this lift, is currently limited.

So whilst the initial hypothesis that “a hydrofoil system retrofitted to an existing production hull can generate enough lift for sustained and stable foiling.” cannot be confirmed at this stage, all the groundwork for the confirmation of this hypothesis has been laid and initial signs are promising;

- The system can fit on a conventional trailer and be towed and deployed from a boat ramp without issue
- The front foil system can be deployed by a single rider
- Control rods sufficiently actuate the front wing ailerons from the top of the masts and cables are waterproof and clear of the rotational mechanism

The constructed design lays the groundwork for everything it set out to achieve, creating a one-of-a-kind hydro-foiling craft built around an existing PWC hull whilst coming in under the \$14,000 budget

5.2 Contribution to the State of the Art

The closest comparison to the Hydroski remains the Generation 1 WaveFlyer [4]. The Hydroski differs from this craft in ways intended to produce a more agile and responsive craft capable of sustained foiling. As the craft has not yet foiled, the contributions below are design outcomes, and their hydrodynamic benefits remain to be confirmed.

Retrofit to a production hull

The C-8 [2] shows what foiling can achieve, but at around AU\$540,000 it is out of reach for most recreational users. The Hydroski takes the opposite approach: it adds a foil system to a production Sea-Doo Spark hull, available for under AU\$10,000, within a project budget of AU\$14,000. The comparison is not like for like, as the C-8 is a finished commercial product and the Hydroski is a prototype. It does show, however, that a retrofit could bring foiling to the large existing fleet of production PWC at a fraction of the cost.

Dual Mast Arrangement

Single central masts dominate small foiling craft, and dual-mast arrangements are uncommon in the literature. A fully submerged foil has no inherent roll-restoring moment [7], so no mast arrangement



Figure 63: CAD render - Gen 1 WaveFlyer and Gen 2 Hydroski

can make the craft stable on its own. What a dual mast can do is make the active control that provides stability more effective. The Hydroski's arrangement does this in three ways.

The first is a stiff platform for control. Joined by the continuous wing below and the clamps above, the two masts react roll moments as a couple in tension and compression rather than by bending. This was motivated by rider-reported instability on the single-mast Generation 1 WaveFlyer [8].

The second is support at the outboard span. Because the masts hold the wing at its ends, twist and deflection are smallest where roll damping and aileron moment are generated, and largest at mid-span.

The third is roll authority on the front foil. A servo in each mast sheath drives its own aileron, so the front foil, which carries most of the craft's lift, can generate differential lift.

Ripken's results [9] add a hydrodynamic case for end-mounted masts. They produce a less negative minimum pressure on the foil, making cavitation less likely, and confine strut interference to the inboard side of each junction, leaving the highly loaded mid-span undisturbed. In exchange, the interference falls on the outboard span with a still unquantified effect.

The arrangement also enables the non-permanent hull attachment, as each mast loads the hull lip from outside the hull, a mounting point a single central mast lacks.

Together, these give the Hydroski a stiff, removable front foil with its own roll authority, retrofitted to a production hull, a combination not documented in the literature reviewed.

Its hydrodynamic benefits await testing.

Fully non-permanent front foil system

The front foil system clamps over the hull lip rather than attaching through the hull or to the baseplate. The entire front foil system can be removed and installed as a unit with no modification to the hull whilst adding only 8.8 kg.

The pivot is offset from the line of the mast to allow the foil to rotate fully clear of the water and over the bow while keeping the masts at the intended position relative to the centre of mass.

The craft can be carried on a conventional jet-ski trailer and launched from a boat ramp, and a single rider can deploy the foil.

Built for agility



Figure 64: WaveFlyer wingtip vs Hydroski wingtip

The Generation 1 rear foil tips were likely thickened to house the aileron servos. The result is a square-ended block that adds drag and strongly damps roll. On the Hydroski, aileron actuation on both foils sits out of the water.

With nothing to house at the tip, shaping can be purely for its hydrodynamic role. The thin, tapered tip developed in Section 4 is consistent with Hoerner's finding that a tip with a defined edge fixes the tip vortex at the extremity [13].

It is believed that the designed wingtips will closely follow this behaviour when applied to the Hydroski and produce a more agile craft.

A platform for further development

The Hydroski is part of a multi-year REV project, and much of its value lies in its adaptability. The front foil system is removable, and the wingtips are push-fit and replaceable. Files for all components have been supplied. Future students can therefore test alternative tip geometries, foil sections or control strategies without rebuilding the craft, and compare them directly against the current configuration. The craft is as much a test bed as a finished vessel.

Flexible TPU wingtip

Whilst the design of a flexible TPU wingtip was not the leading solution for this craft, it still has merit for other applications where coincidence with another body is not a limitation. This manufacturing method could have been applied to the works of Christopher Franz (2026) for development of an electric hydrofoil board [16], where the selection of a NACA 2412 wing profile was in part dictated by the need for a thicker profile to house mechanical linkage components



Figure 65: NACA 2412 profile with hinged aileron [16]

A TPU aileron could be used to remove this limitation and allow for the selection of the profile to be purely based off the hydrodynamic advantage whilst also reducing the wing breach issues discussed in 4.3 Flexible TPU wingtip.

5.3 Alternative Designs

In the selection of this final design, many alternative options were considered;

APPENDIX C: Alternative Front Foil Designs, shows a selection of initial concept designs for the front foil assembly that informed the final design

The main drawback of these initial concept designs was hull attachment where problems were identified concerning both waterproofing and secure connection to the hull that could withstand the cyclic loading the craft would experience.

Initial designs predominantly planned for a hull attachment with the existing steel chassis baseplate as it was believed that this would provide the most secure connection resistant to cyclic loading through providing a metal-to-metal connection and limiting direct load transmission through the Polytec hull.

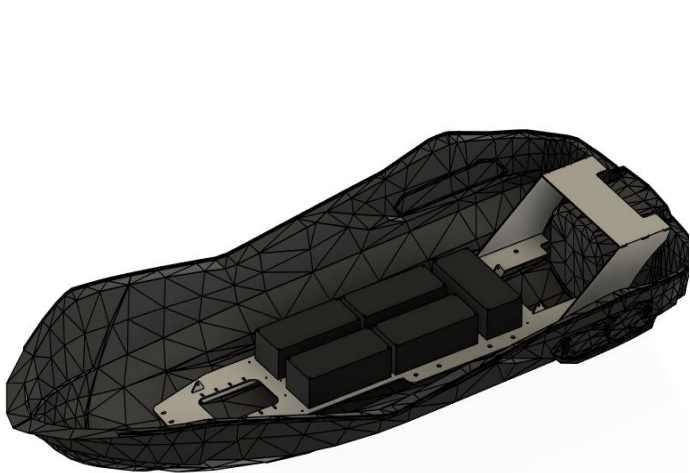


Figure 66: Hull base plate and batteries

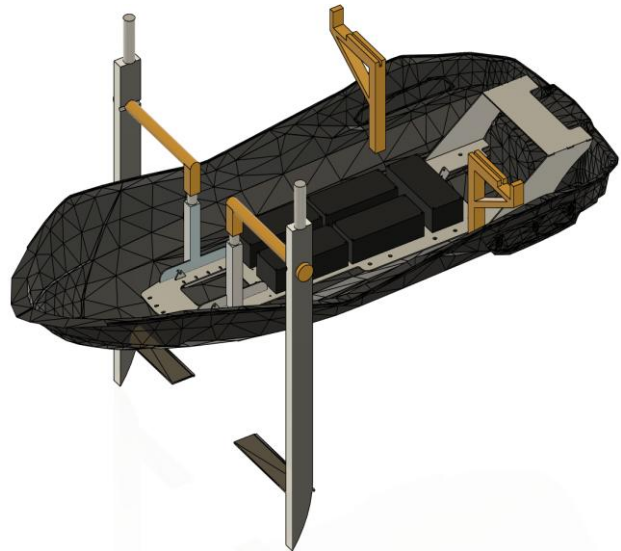


Figure 67: Concept design A attachment to baseplate

Despite the strength advantages this would have provided to the system, the resultant waterproofing complexity was seen to outweigh this. To connect to the baseplate, internal walls of the hull would need to be cut, and dynamic shaft seals would need to be placed at these points. Additionally, a waterproofing methodology for the 5 batteries pictured above (Figure 66) had not been established at this initial concept design stage

Exact sizes for the required enclosure and requirements of this enclosure, i.e. water cooling, pressure relief, were not known, locking in a front foil design that relied on a connection to the baseplate seemed likely to cause a clash later in the design process as other disciplines requirements were synchronously established

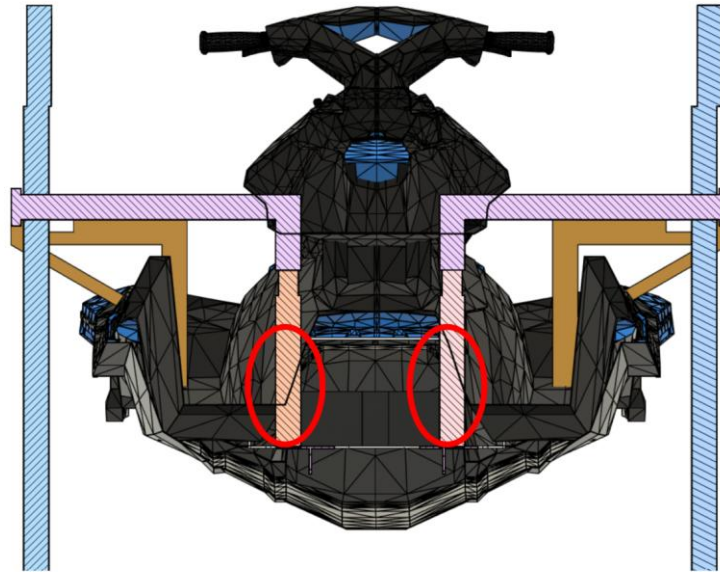


Figure 68: Concept design A section view showing attachment to base plate

5.4 Limitations and Remaining Issues

The constructed system meets its design requirements as far as they can be tested without foiling. However, several results rest on limited testing, and some choices made to keep the project moving were judgement calls rather than calculated outcomes. They are set out here so that future test results can be interpreted against them.

Untested hypothesis

The most significant limitation is that the central hypothesis, that a hydrofoil system retrofitted to an existing hull can generate sufficient lift for sustained and stable foiling, could not be tested. Full water testing was delayed by electrical and software issues outside the scope of this report, and no water testing has taken place since the initial deployment trials (5.1 Initial Testing and Observations)

Every load on the front foil system to date has come from handling, deployment, and rocking at rest. The design has been shown to fit, deploy, retract and actuate, but not to carry foiling loads.

None of the performance benefits that motivate the project, such as reduced drag and improved efficiency, have been quantified on this craft.

Hull attachment

The secondary retention measure planned in 2.2 was not fitted, as the clamp proved extremely solid on installation and in initial water testing. The literature review identified creep in the Polytec hull relaxing the pad's grip on the lip, and slamming loads as two risks to this joint that should be monitored over its lifespan should it be implemented. The judgement to not install this second measure is reasonable for the loads seen so far. It was, however, made under loads well below those expected in foiling.

Usability and control

Two smaller limitations were found in the front foil system. First, retraction by a single rider is difficult and currently requires the craft to be parked beside a jetty. This limits where the craft can be recovered and falls short of the aim that the system be easily deployed and retracted by the average user. Second, the aileron linkage showed a small amount of free play at the end of servo travel, caused by control rod deflection within the mast. The 15mm servo arm reduced this deflection but did not remove it. As it was observed on the bench with no load on the aileron, its effect on aileron position under hydrodynamic load is not known and long-term effects on the rod are yet to be seen.

Wingtip

Improvement in roll response due to wingtip design has not yet been quantified for this craft. Similarly, the arguments against the hinge groove in Section 4.2 are qualitative, so the cost of the groove introduced by the mechanical tip is not known.

The TPU soak test is the clearest example of literature not transferring to a printed part given Choi and Kim's finding [14] of a 50% loss in tensile strength over 20 simulated years of submersion.

After 1000 hours in Swan River water, however, Prototype 1 sheared along its layer lines within a few movements. This is a failure mode specific to printed parts, and one the literature review had not accounted for. Reorienting the layers in Prototype 2 so they no longer aligned with the plane of bending addressed this, and Prototype 2 showed no sign of the same failure after 400 hours of soaking. That result is encouraging but not directly comparable. The soak was cut short by time constraints, and because Prototype 1 was only inspected at 1000 hours, it is not known whether its failure had begun by 400 hours.

The flexible tip was ultimately not adopted for reasons unrelated to saltwater. Its trailing edge did not align with the foil when deflected upward, which removed the hydrodynamic benefit of the continuous skin.

6 Conclusions & Future Work

6.1 Conclusion

This project set out to design and build a retractable front foil system for a production Sea-Doo Spark hull that can be trailered and launched from a standard boat ramp, and a rear foil wingtip that would make the craft more responsive in roll than the Generation 1 WaveFlyer [4].

The front foil system has been designed, manufactured and installed. It attaches without any modification of the hull required, it deploys and retracts clear of the bow, with control rods actuating the front wing ailerons from the top of the mast.

The project was completed under its \$14,000 budget.

However, the central hypothesis could not yet be tested. Electrical and software delays meant the craft has not foiled, and the hull attachment has not carried foiling loads. Single-rider retraction currently needs a jetty, so objective 3 is only partly met. On the rear foil, a replaceable mechanical linkage wingtip was fitted; its effect on roll response is still to be measured

6.2 Future Work

Water testing.

The electrical and software issues should be resolved and water testing completed in stages: low-speed running with the foils deployed, then take-off, then sustained foiling. Take-off speed, ride height and power draw at foiling speed should be logged, as these directly test the reduced drag and improved efficiency that motivate the project, and allow comparison with the WaveFlyer.

Hull attachment.

This is the least verified part of the front foil system, and its failure is the most costly, so it should be monitored from the first session. Witness marks across the clamp and hull lip will show any slip, and the hull lip under the TPU pad should be inspected for indentation or cracking.

Aileron control under load.

Bench testing showed free play at the end of servo travel caused by control rod deflection within the mast, reduced but not eliminated by the 15mm arm. Under hydrodynamic load this may mean the aileron position is different to commanded. Aileron angle should be measured against servo position with a load applied on the bench, then in the water. If the difference matters for roll control, a stiffer rod or an additional guide within the mast are the simplest fixes.

Wingtip performance analysis.

Computational fluid dynamics (CFD) of the tip with and without the hinge groove would show how much the groove costs in drag, and whether the trade made in adopting the mechanical tip is significant, providing further insight into the value of producing a continuous elastic wingtip.

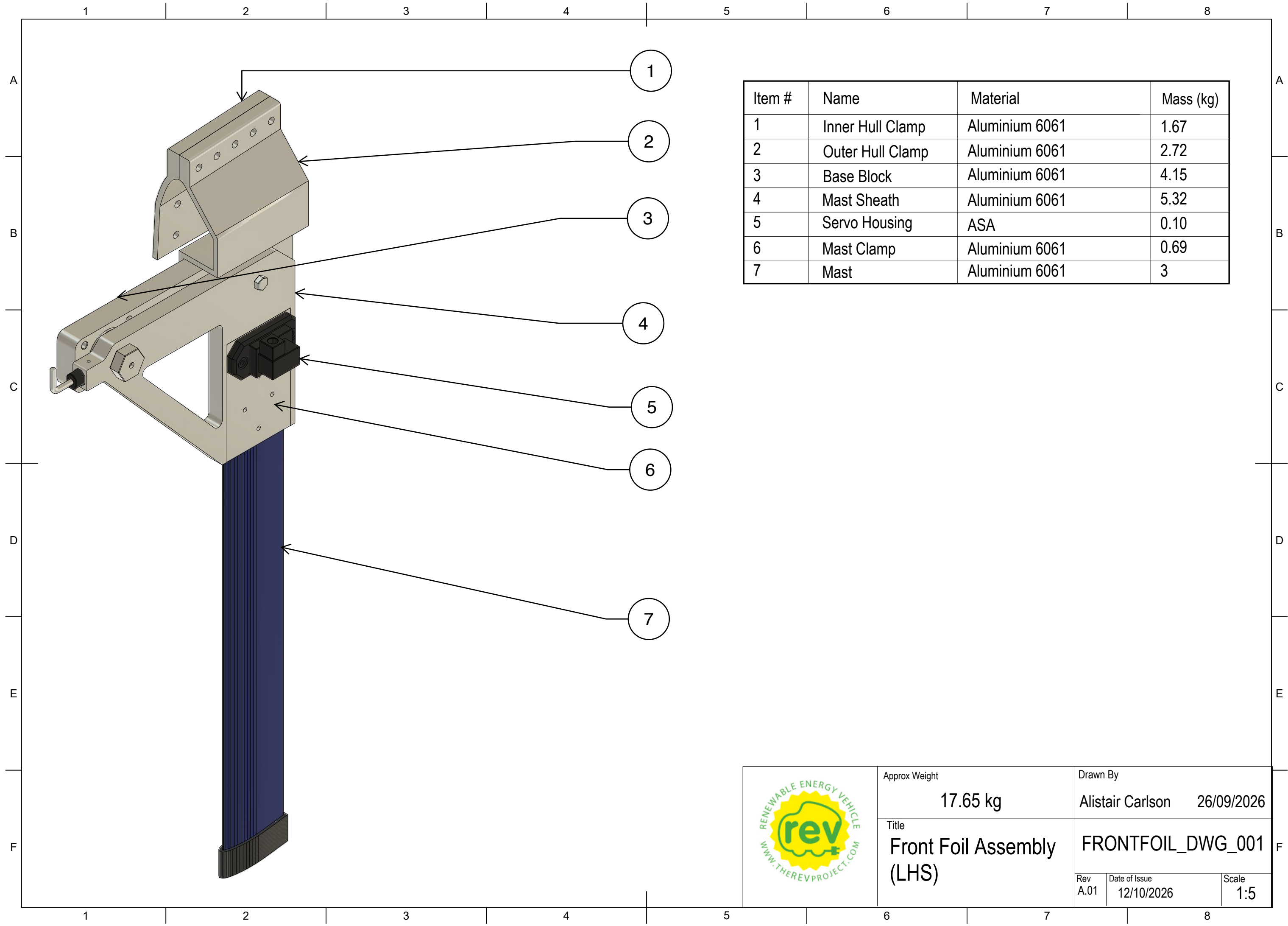
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APPENDIX A: Front Foil Assembly Schematic



	Approx Weight	17.65 kg		Drawn By	
	Title	Front Foil Assembly (LHS)		Alistair Carlson 26/09/2026	
	Rev	Date of Issue	Scale		
A.01	12/10/2026	1:5			

APPENDIX B: Hull Clamp Calculations

Hydroski Gen 2 - Front foil hull clamp: calculations

CASE 1 - Sudden acceleration of the craft.

CASE 2 - Sustained level foiling.

1. Inputs - geometry

Parameter	Symbol	Value	Unit	Source / note
Total system mass	m	400	kg	Front foil assumed to carry all lift
Gravitational acceleration	g	9.81	m/s²	
Wing planform area	S	0.26	m²	
Wing span	b	1.2	m	
Wing maximum thickness	t_w	0.0293	m	
Span efficiency factor	e	0.9	-	ASSUMED
Number of masts	n_m	2	-	
Mast chord	c_m	0.1307	m	
Mast maximum thickness	t_m	0.0225	m	
Immersed mast length when foiling	h	0.30	m	ASSUMED - one wing chord below the surface
Spray drag coefficient per strut	C_Ds	0.24	-	ASSUMED
Seawater density	ρ	1025	kg/m³	Typical seawater.
Seawater kinematic viscosity	ν	1.19E-06	m²/s	ITTC 7.5-02-01-03, seawater at 15 °C

2. Inputs - mass carried through the clamps

Parameter	Symbol	Value	Unit	Source / note
Outer clamp (per side)		2.72	kg	
Inner clamp (per side)		1.67	kg	
Base block (per side)		4.15	kg	
Mast sheath (per side)		5.32	kg	
Mast clamp (per side)		0.69	kg	
Mast (per side)		3	kg	
Servo, control rod, fasteners (per side)		1	kg	Allowance
Front wing (whole wing)	m_w	6	kg	

3. Inputs - clamp grip

Parameter	Symbol	Value	Unit	Source / note
Friction faces per clamp	n_s	2	-	TPU pad grips the inner and outer faces of the hull lip.
Friction coefficient (worst case)	μ	0.20	-	ASSUMED. Lowest value of the plausible range for wet TPU on Polytec
Clamp contact area per friction face	A	39,061	mm²	Measured.
TPU pad modulus	E_p	7.8	MPa	[21]
Pad thickness under the clamp	t_p	5.0	mm	Confirmed.
Pad compression when the clamp is closed	δ	0.50	mm	Measured
Effective contact fraction	η	50%	-	Allowance for an uneven fit.

4. Derived values

Quantity	Symbol	Value	Unit	Formula / note
Front foil lift	L_f	3,924	N	$L_f = m \cdot g$
Wing mean chord	c_w	0.2167	m	$c = S / b$
Wing thickness-to-chord ratio	t/c	0.135	-	$t/c = t_w / c$
Pad compressive strain	ε	10.0%	-	$\epsilon = \delta / t_p$
Pad contact pressure (estimate)	p_ach	0.780	MPa	$p = E_p \cdot \epsilon$
Clamping force available per clamp (estimate)	N_ach	15,234	N	$N_{ach} = p \cdot \eta \cdot A$
Mass carried through clamps	m_a	43.1	kg	

5. Case 1 - sudden acceleration of the craft

a (m/s²)	F along lip per clamp (N)	N_req, μ = 0.2 (N)	Factor of safety (N_ach / N_req)
2.5	53.9	135	113.1
3.0	64.7	162	94.3
3.5	75.4	189	80.8
4.0	86.2	216	70.7
4.5	97.0	242	62.8
5.0	107.8	269	56.6

6. Case 2 - sustained level foiling

V (km/h)	V (m/s)	q (Pa)	C_L	Re wing	C_f wing	C_D wing	D wing (N)	Re mast	C_f mast	D masts (N)	D spray (N)	D total (N)	F along lip per clamp (N)	N_req, μ = 0.2 (N)	Factor of safety (N_ach / N_req)	N_ach, estimated available (N)
20	5.56	15,818	0.954	1.01E+06	0.00468	0.07020	288.7	6.10E+05	0.00523	18.1	3.8	310.7	155.4	388	39.2	15,234
25	6.94	24,715	0.611	1.26E+06	0.00446	0.03532	226.9	7.63E+05	0.00498	26.9	6.0	259.9	129.9	325	46.9	15,234
30	8.33	35,590	0.424	1.52E+06	0.00429	0.02256	208.7	9.15E+05	0.00478	37.3	8.6	254.6	127.3	318	47.9	15,234
35	9.72	48,442	0.312	1.77E+06	0.00416	0.01693	213.2	1.07E+06	0.00462	49.1	11.8	274.0	137.0	343	44.5	15,234
40	11.11	63,272	0.239	2.02E+06	0.00404	0.01407	231.5	1.22E+06	0.00449	62.3	15.4	309.2	154.6	386	39.4	15,234
45	12.50	80,078	0.188	2.28E+06	0.00395	0.01246	259.5	1.37E+06	0.00438	76.9	19.5	355.8	177.9	445	34.2	15,234
50	13.89	98,862	0.153	2.53E+06	0.00387	0.01147	294.9	1.53E+06	0.00429	92.8	24.0	411.8	205.9	515	29.6	15,234
55	15.28	119,623	0.126	2.78E+06	0.00380	0.01082	336.4	1.68E+06	0.00420	110.1	29.1	475.6	237.8	595	25.6	15,234
60	16.67	142,361	0.106	3.03E+06	0.00373	0.01035	383.2	1.83E+06	0.00413	128.8	34.6	546.6	273.3	683	22.3	15,234
65	18.06	167,077	0.090	3.29E+06	0.00368	0.01001	434.8	1.98E+06	0.00406	148.7	40.6	624.1	312.0	780	19.5	15,234
70	19.44	193,769	0.078	3.54E+06	0.00362	0.00974	490.8	2.14E+06	0.00400	169.9	47.1	707.8	353.9	885	17.2	15,234
75	20.83	222,439	0.068	3.79E+06	0.00358	0.00953	551.0	2.29E+06	0.00395	192.3	54.1	797.3	398.7	997	15.3	15,234
80	22.22	253,086	0.060	4.05E+06	0.00353	0.00935	615.1	2.44E+06	0.00390	216.0	61.5	892.6	446.3	1,116	13.7	15,234
85	23.61	285,711	0.053	4.30E+06	0.00349	0.00920	683.1	2.59E+06	0.00385	241.0	69.4	993.5	496.7	1,242	12.3	15,234
90	25.00	320,313	0.047	4.55E+06	0.00346	0.00906	754.8	2.75E+06	0.00381	267.2	77.8	1099.8	549.9	1,375	11.1	15,234
95	26.39	356,891	0.042	4.80E+06	0.00342	0.00895	830.1	2.90E+06	0.00377	294.6	86.7	1211.4	605.7	1,514	10.1	15,234
100	27.78	395,448	0.038	5.06E+06	0.00339	0.00884	909.1	3.05E+06	0.00373	323.1	96.1	1328.3	664.1	1,660	9.2	15,234

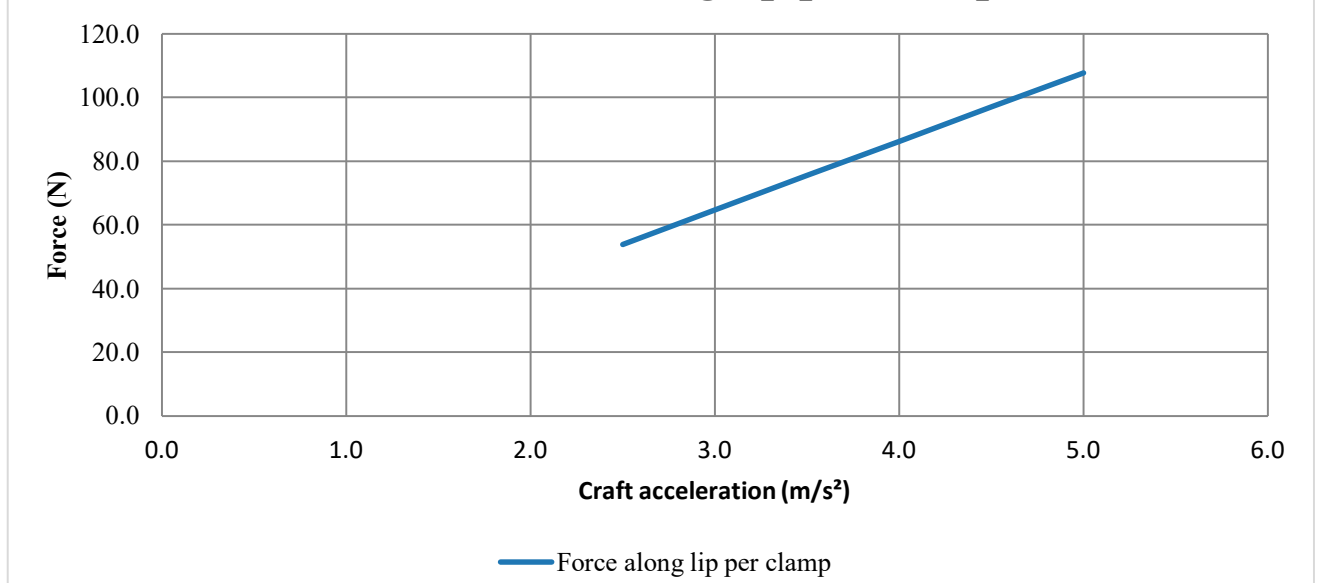
7. Results summary

Result	Value	Unit	Note
Max force along lip per clamp, acceleration case	108	N	
Max force along lip per clamp, sustained foiling case	664	N	
Combined (both cases maximum)	772	N	
Clamping force available per clamp (estimate)	15,234	N	
Clamping force needed per clamp, combined case	1,930	N	$N_{req} = F_{comb} / (\mu \cdot n_s)$
Contact pressure available (estimate)	780.0	kPa	
Contact pressure needed	98.8	kPa	$p_{req} = N_{req} / (\eta \cdot A)$
Factor of safety against slip, combined case (estimate)	7.9	-	$FS = N_{ach} / N_{req}$

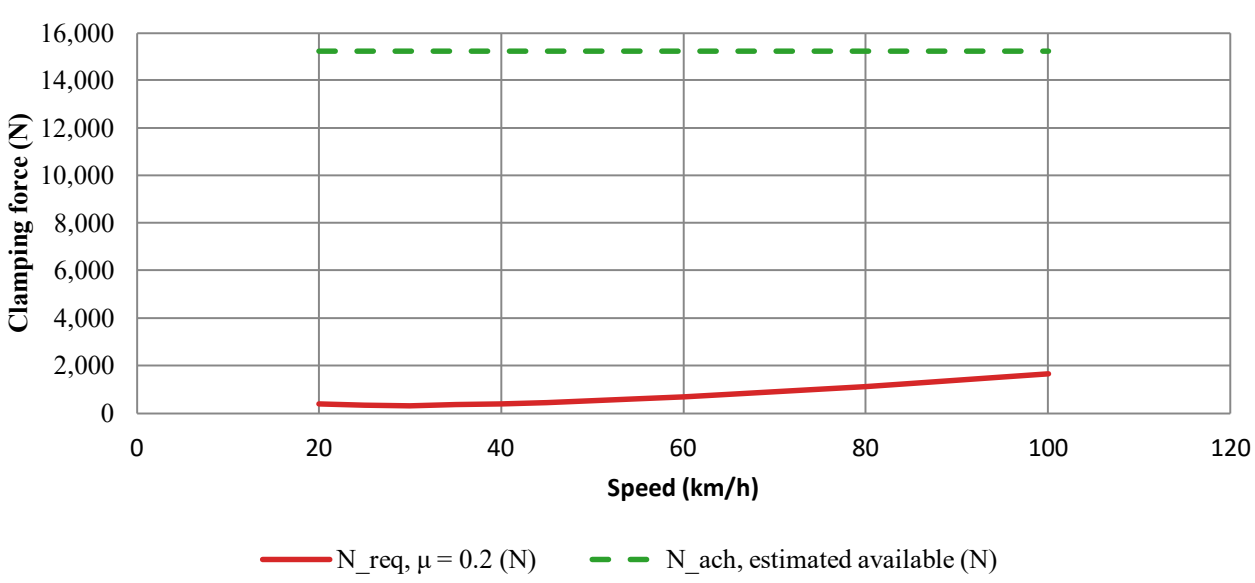
8. Assumptions and exclusions

- The clamp resists slip along the lip by friction on the inner and outer faces of the lip. The clamping force it must apply is $N_{req} = F_{lip} / (\mu \cdot n_s)$.
- Available clamping force is estimated from the pad compression: $p = \frac{E}{l} \delta$ and $N_{ach} = p \cdot \eta \cdot A$. This is an estimate, not a measurement: the pad compression and contact fraction are assumed. It is likely conservative in one respect, since a pad confined inside a closed clamp is stiffer in compression than the tensile modulus suggests, and optimistic in another, since TPU relaxes over time under constant squeeze, which lowers the pressure.
- Creep in the Polytec lip or the TPU pad would reduce the pad squeeze without changing bolt torque, so torque checks will not detect loss of grip.
- Assumed: load shared equally between the two clamps; hull level (no trim); front foil carries all lift. The vertical lift reaction and the drag moment are assumed not to reduce the grip.
- Excluded: vertical lift reaction, pitching moment from drag acting below the clamp, wave impact and slamming, free-surface effects on foil drag.

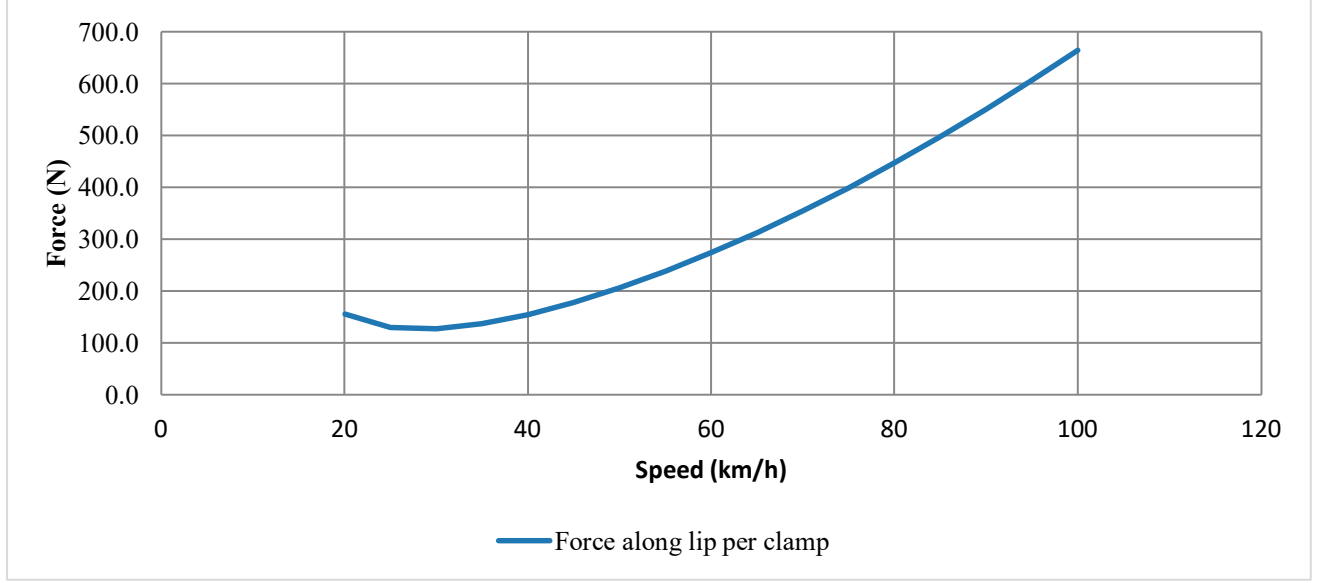
Case 1: Force along lip per clamp



Clamping force needed vs estimated available



Case 2: Force along lip per clamp



APPENDIX C: Alternative Front Foil Designs



Concept Design A:

- Disjoint wings
- Dual-mast arrangement
- Independent Revolute Masts



Concept Design B:

- Hinged dual masts with T-wing formation



Concept Design C:

- Sliding rails bolted through hull exterior
- Masts can be positioned along the length of the ski, allowing movement for storage and for tuning front masts to ideal operating position.

