Foil Board Aerodynamic Objects Case Study

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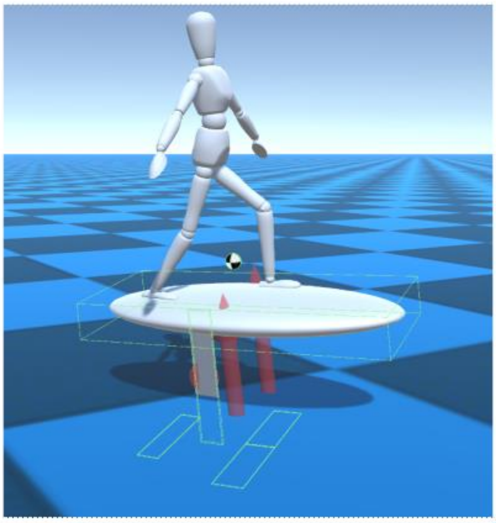


Introduction

A FoilBoard is essentially a surfboard mounted on top of an underwater glider. The glider has a main wing and a tail (front foil and rear foil). The main wing generates lift to support the weight of the board and rider, and the tail sets the trim (balance angle of attack) of the main wing. The rider controls the board by weight shift. Lateral shift causes the board to turn, longitudinal shift alters the trim angle of attack and subsequently allows control of ride height. When used to surf on waves, the board is propelled forward by the action of gravity. On flat water, the board can be propelled by pumping, in which hydrodynamic thrust from the foils is obtained by cyclic up and down motion of the rider, or by some kind of aerodynamic device like a fixed sail, hand held wing or kite. Alternatively thrust can be provided by a dedicated underwater propulsion unit.

The main benefit of using under water foils for weight support as opposed to a combination of buoyancy and hydrodynamic lift is that the drag from using foils is typically an order of magnitude smaller that the drag from a surface board for the same amount of lift. This means that much greater speeds can obtained for the same level of propulsive force (whether from gravity, pump action or electric motor), or alternatively much less force is needed for a given riding speed. The principal source of drag reduction is the elimination of wave drag from use of fully submerged foils. Furthermore, the profile drag of under foils can be greatly reduced compared to a surface hull using well understood principles of foil design. Lastly the use of relatively high aspect ratio foils means that the induced drag (drag due to production of lift) can be significantly reduced compared to the equivalent drag from planing low aspect ratio surface hulls.

There are several challenges in using submerged foils for weight support, mostly related to the need for much greater rider skill levels to maintain control. Firstly, board height above the water surface must be actively controlled by the rider by continuous micro adjustment of the fore and aft position of the centre of mass (CoM). Secondly, whilst the use of high aspect ratio foils increases hydrodynamic efficiency, these foils may stall relatively abruptly leading to sudden loss of lift and abrupt loss of fore and aft balance. Care must be taken to avoid surfacing the foils, which again would lead to a very sudden loss of lift and loss of control. Lastly, the significant vertical distance between the overall centre of mass rider and the hydrodynamic lifting surfaces means that there is significant lateral relative movement of the hydrodynamic surfaces due to rotation about the centre of mass. Depending on the dynamics of a particular manoeuvre this can lead to static instability and subsequent loss of control.

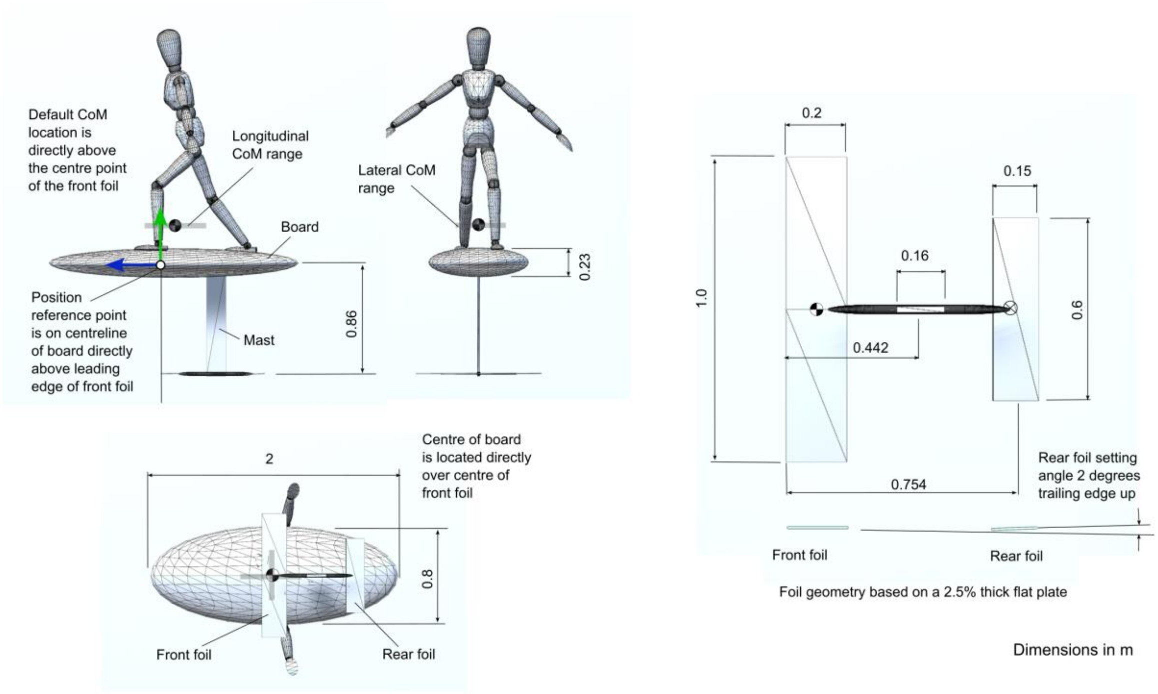


Figure 1 General arrangement of a generic FoilBoard with key dimensions

A general arrangement drawing of a generic FoilBoard is shown in Figure 1 General arrangement of a generic FoilBoard with key dimensions The sizing and detailed geometry of commercially available FoilBoard setups varies depending on intended use case. Larger wing area allows weight support at lower speed, however, to achieve high efficiency at high speeds a smaller wing area should be used. The size of the tail compared to the wing and its distance aft affects longitudinal stability and the ability to trim over a wide range of speeds. The tailplane will typically be set a nose down attitude relative the wing to help achieve longitudinal trim at an acceptable level of stability. The mast provides structural attachment of the foils to the board and acts as a vertical fin which contributes to directional stability.

The CoM of the board and rider will typically be located directly above the wing. Under ideal cruising conditions, the lift from the wing acts directly up through the COM, and the load on the tail is close to zero. In practice, there will typically be some load on the tail to fully trim out moments.

For trainer level boards, the buoyancy of the board will typically be sufficient for full weight support at zero forward speed. Higher performance boards, depending on application, may require hydrodynamic lift in addition to buoyancy for weight support. To achieve full weight support on foils, a board will typically start by planing then progressively transfer load to the foils to the point where the board is lifted out of the water.

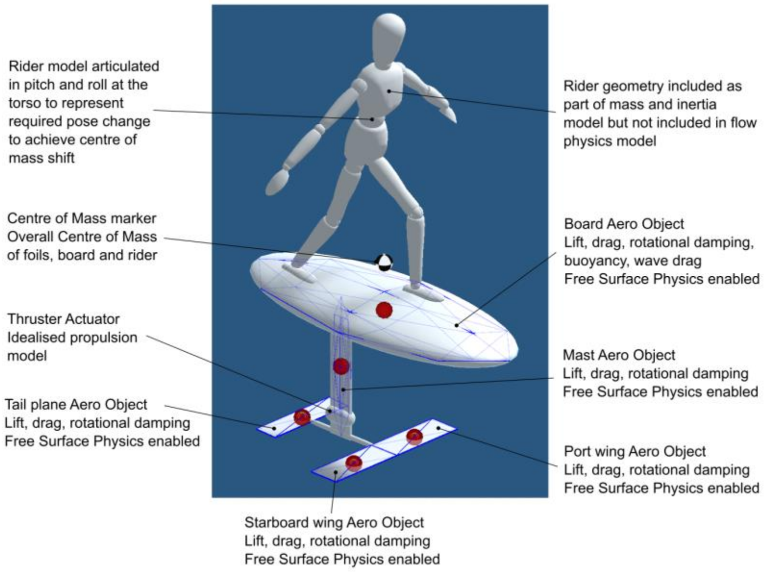


Figure 2 FoilBoard modelling for hydrostatics and dynamics, propulsion and rider pose

FoilBoard modelling in Aerodynamic Objects

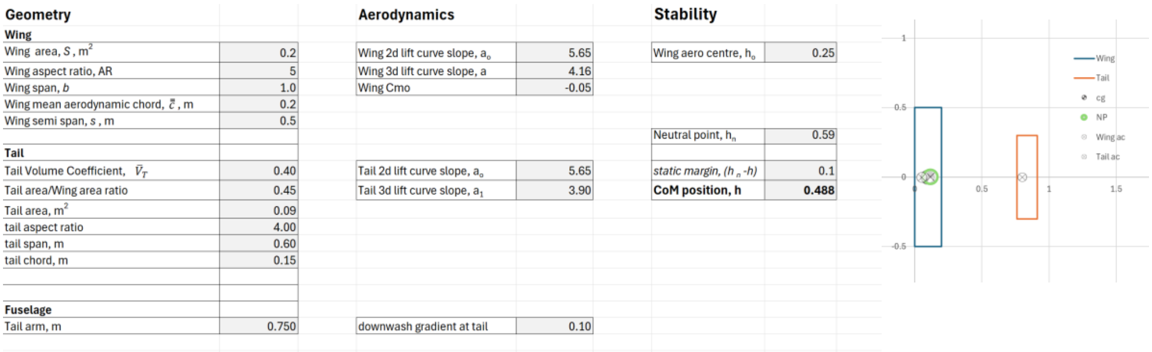
The Aerodynamic Object components used to model the FoilBoard, and rider are shown in Figure 2. The blue outlines represent the geometry used by the model on each object. Buoyancy is provided by a buoyancy model attached to the board object; buoyancy of other objects is not included. The board model is also distinct in that it is the only component for which a wave drag model is included. For reasons of economy, wave drag is not included in the other components where contribution is small. A Free Surface Physics component is attached to all hydrodynamic objects. This provides methods for handling flow physics on objects immersed in two different fluids (air and water) at the same time. The Thruster has a Flow Sensor component attached that changes thruster behaviour depending on the fluid in which it is immersed.

The mass and inertia properties of the board and rider is modelled using a single rigid body component. The centre of mass can be moved longitudinally and laterally at run time via user input or control system command. The rider pose adjusts according to the required centre of mass shift, however this done as animation rather than physical modelling. Furthermore, centre of mass motion is quasi static, in that forces required to accelerate the centre of mass are not included. These forces should be included if modelling of the dynamics of pumping propulsion is required.

Aerodynamic analysis

When geometry already exists, this can be used to successfully build models directly using Aerodynamic Objects. However, when undertaking design, or there is a requirement to better understand and existing geometry, it can be useful to undertake a low order analytical modelling approach. For this project, the essential hydrodynamics of the problem was abstracted as two rectangular wings with a longitudinal displacement. The theory for this configuration is well-established in-flight dynamics texts[1]. The key geometric and derived aerodynamic parameters are shown in Table 1, and the nomenclature of the surface geometric arrangement and relationship to the COM shown in Figure 3. The specific geometry defining tail setting angle is defined in Figure 4.

Table 1 Definition of Geometric, Aerodynamic and Stability parameters for a simple FoilBoard configuration



Geometry		**Aerodynamics**		**Stability**	
Wing					
Wing area, S, m^2	0.2	Wing 2d lift curve slope, a_o	5.65	Wing aero centre, h_o	0.25
Wing aspect ratio, AR	5	Wing 3d lift curve slope, a	4.16		
Wing span, b	1.0	Wing Cmo	-0.05		
Wing mean aerodynamic chord, $\bar{\bar{c}}$, m	0.2				
Wing semi span, s, m	0.5				
				Neutral point, h_n	0.59
Tail					
Tail Volume Coefficient, $\bar{V}_T$	0.40	Tail 2d lift curve slope, a_o	5.65	*static margin, (h_n-h)*	0.1
Tail area/Wing area ratio	0.45	Tail 3d lift curve slope, a_1	3.90	**CoM position, h**	**0.488**
Tail area, m^2	0.09				
tail aspect ratio	4.00				
tail span, m	0.60				
tail chord, m	0.15				
Fuselage					
Tail arm, m	0.750	downwash gradient at tail	0.10		

Link to FoilBoard spreadsheet

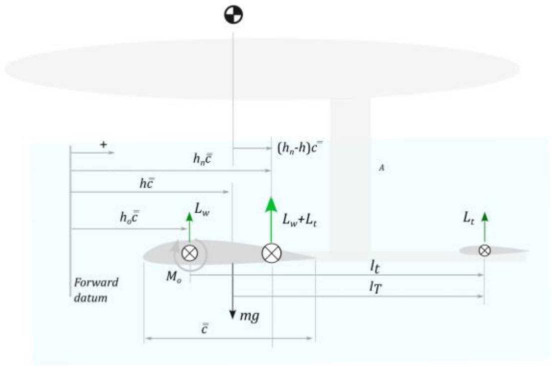


Figure 3 Definition of FoilBoard longitudinal geometry for stability and control analysis

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[1] E.g. see Flight Dynamic Principles, Mike Cook

Figure 4 Definition of tail setting angle. In practice, tail setting angle will be negative (leading edge down)

$$C_m = C_{mo} + C_{Lw}(h - h_o) - \bar{V}_T \left(C_{Lw} \frac{a_1}{a} \left(1 - \frac{d\epsilon}{d\alpha} \right) + a_1 \eta_t \right). \qquad \textit{EQ 1}$$

Taking moments about the CoM for the configuration shown in Figure 3, the equation EQ 1 is obtained. There are three contributions to the moment: First, the couple produced by the wing, C_{mo}, second, the contribution of the wing lift acting at a moment arm to the CoM, $C_{Lw}(h - h_o)$, and third, the contribution of the tail, $\bar{V}_T \left(C_{Lw} \frac{a_1}{a} \left(1 - \frac{d\epsilon}{d\alpha} \right) + a_1 \eta_t \right)$. The tail contribution depends on its size and position relative to the wing, the downwash created by the wing and its setting angle relative the wing datum

Forces and moments are in coefficient form defined by $C_{Lw} = \frac{L_w}{qS}$, and $C_m = \frac{M}{qS\bar{\bar{c}}}$, with $q = \frac{1}{2}\rho V^2$ and other parameters defined in Table 1.

EQ 1 can be rearrange give the tailplane setting required to give a given trim lift coefficient for a given CoM position, EQ 2,

$$\eta_t = \frac{1}{\bar{V}_T a_1} \left(C_{mo} + C_{Lw}(h - h_o) \right) - \frac{C_{Lw}}{a} \left(1 - \frac{d\epsilon}{d\alpha} \right), \qquad \textit{EQ 2}$$

or rearranged to give the trim lift coefficient for a given tailplane setting angle and CoM position, EQ 3,

$$C_{Lw} = \frac{\bar{V}_T a_1 \eta_t - C_{mo}}{(h - h_o) - \bar{V}_T \frac{a_1}{a} \left(1 - \frac{d\epsilon}{d\alpha} \right)}. \qquad \textit{EQ 3}$$

The speed at which lift is equal to weight is proportional to the square root of the trim lift coefficient. According to EQ 3, with a fixed tail plane setting angle, a rider can control trim lift coefficient and hence their speed by adjusting CoM position.

Using the data in Table 1, the output of EQ 3 in terms of trimmed lift coefficient for a range of CoM locations and for three different tailplane setting angles is shown in Figure 5 FoilBoard trim lift coefficient curves as a function of CoM position for different tail plane setting angles. Cmo=-0.05, neutral point is at h=0.58. CoM position h measured positive aft relative to wing leading edge. For the present configuration, the CoM location for neutral stability (the neutral point) is 0.58 $\bar{\bar{c}}$ aft of the leading edge of the wing (just past halfway back along the wing root chord). This point represents an aft most limit of where the CoM can lie in order for the board to be stable in pitch. In practice there has to be a margin on this (called the static margin), which would be at least 0.1.

The data in Figure 5 show that for a small tail setting angle of -2 degrees, CoM shift over the available range is ineffective in altering the trim lift coeffient. With increasing setting angle a useful range of trim lift coefficients can be obtained, noting however that the board becomes increasingly sensitive as the CoM is moved back, and less sensitive as the CoM is moved forward. This characteristic would have to be felt and learned by a rider in order to maintain good control. Also, the wing in practice will have a maximum attainable lift coefficient after which it will stall. This represents a horizontal upper limit in Figure 5 that needs avoiding by an appropriate margin, as stall of either wing or tail would lead to abrupt loss of moment balance that would require rapid correction by the rider.

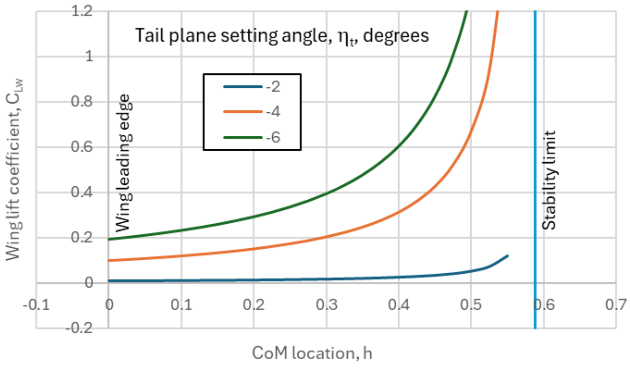
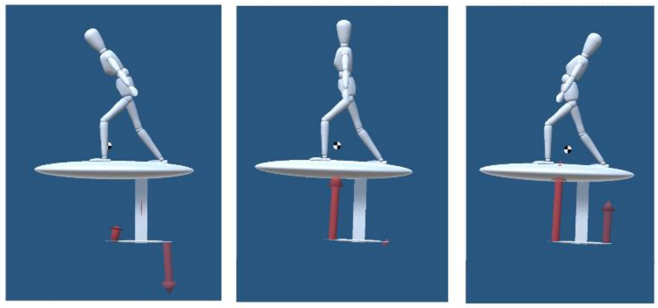


Figure 5 FoilBoard trim lift coefficient curves as a function of CoM position for different tail plane setting angles. Cmo=-0.05, neutral point is at h=0.58. CoM position h measured positive aft relative to wing leading edge.



a) Forward trim b) Centre trim c) Aft trim

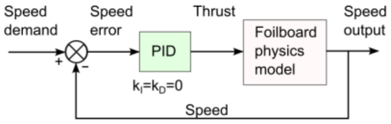
Figure 6 Net hydrodynamic forces on FoilBoard wing and tailplane for different CoM trim states. In the forward trim state, the net lift on the board is negative (downwards)

An illustration of the relative forces on the wing and tailplane for different CoM positions is shown in Figure 6. With a forward CoM, the up load on the wing is small and there is a large download on the tail to balance the moments. With an aft CoM, the load on the wing is increases, and the tail has an upload to balance the moments. With a mid CoM approximately over the top of the aerodynamic centre of the wing, the required load from the tail is approximately zero. This condition provides the minimum trim drag and represents the ideal operating point for the board.

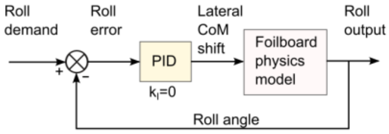
Closed loop control

To model the behaviour of a moderately experienced rider, closed loop control is applied to speed demand, roll demand and ride height, Figure 7. The control used is classical PID, which has tuneable gains for Proportional, Integral and Differential action on the error between demand and measured values of the controlled parameter. AerodynamicObjects includes a PID controller class for this purpose. The speed and roll angle controllers contain a single loop, whereas the height controller has an inner control loop on pitch angle and an outer loop on height. For the speed controller adequate performance can be obtained using just proportional control (integral and differential gains set to zero). The roll angle and pitch angle controllers both include an additional differential term to provide additional damping. Lastly, the ride height control includes all three terms, with the integral term required to adequately remove the steady state error in height.

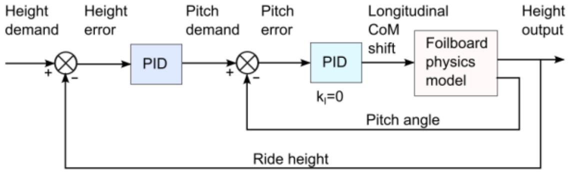
Controllers for the present model were tuned manually using an incremental approach. First up, the speed control loop was tuned on the basis it was the simplest and achieving a constant speed during experiments is critical to tuning the other controllers. Next the pitch and roll controllers were tuned at zero ride height. This allowed correct signs and approximate magnitudes of gains to found. Next, the height controller was tuned using the existing tuning of the pitch control loop. Once the board could be stabilised at a given ride height, the pitch and roll controllers were retuned for foiling flight.



a) Speed control loop



b) Roll (bank) angle control loop



c) Ride height control loop (outer) with pitch control loop (inner)

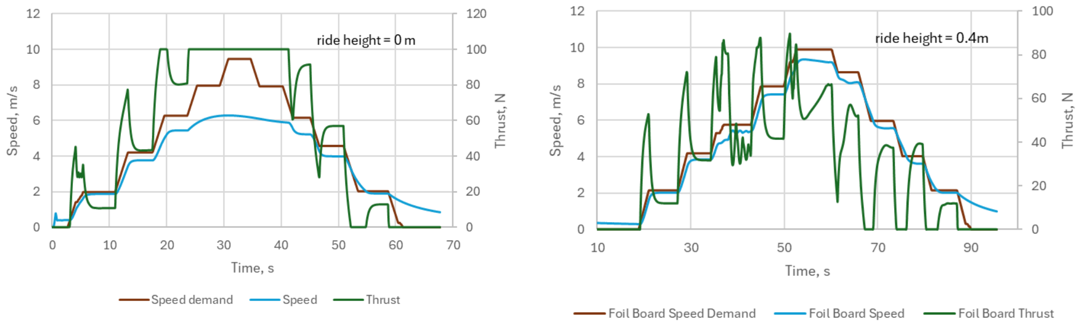
Figure 7 Closed loop controllers for FoilBoard Speed, Roll Angle and Ride Height

Results

The response of the FoilBoard to user inputs for a variety of experimental cases is shown in Figure 8, Figure 9 and Figure 10. Evaluation of speed control at zero ride height (board on the surface) and 0.4 m (foiling flight) is shown in Figure 8. For non-foiling flight, the drag is high and with a maximum thrust limit of 100 N, the maximum speed reached is around 6 m/s. With the board out of the water (foiling flight), a speed of around 9 m/s can be reached with a thrust of around 60 N. An approximate analysis from these numbers suggests that for this experiment the drag coefficient in foiling mode is approximately a factor of 4 less than in no foiling mode. Note that the spikes in thrust are due to the speed controller managing acceleration between speed set points.

Evaluation of FoilBoard height control is shown in Figure 9. At a speed of 4 m/s, the FoilBoard is unable to achieving foiling flight, even with maximum pitch input. The inference here is that the wing is unable to generate a lift force greater than weight at this speed. This limit is set by a combination of the limit on achievable maximum lift coefficient of the wing and the limit on maximum trimmable angle of attack at this speed with the given limit on aft CoM travel. At a speed of 6 m/s the board can comfortably achieve foiling flight, and reasonably precise control can be obtained, albeit with some damped oscillation following a change in set point.

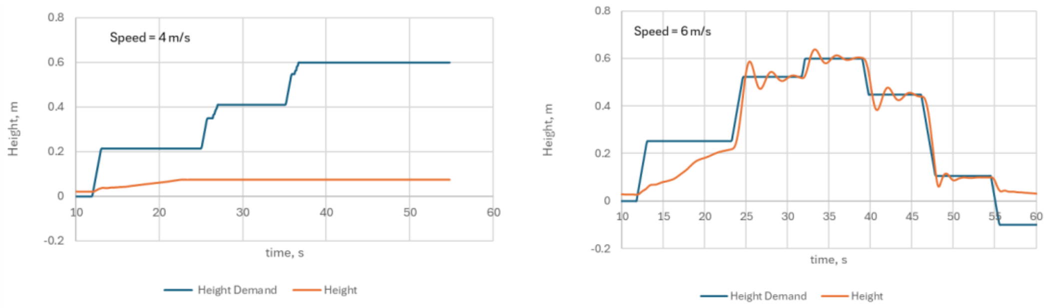
Evaluation of roll control is shown in Figure 10. With a ride height of 0 (board on the surface), the roll control authority is less and the roll damping higher than when the board is foiling, as might be expected. Roll control generally couples in to ride height control and at large roll angles (or during rapid changes in roll demand angle) there may be significant variations in ride height. Furthermore, rapid changes in roll can lead to large angles of sideslip, which may cause the board to tip over if not corrected sufficiently fast by the roll controller. The issue is most significant at high ride heights were only a small part of the mast (fin) is submerged, and hence directional stability is at its lowest.



a) Ride height 0 m

b) Ride height 0.4 m

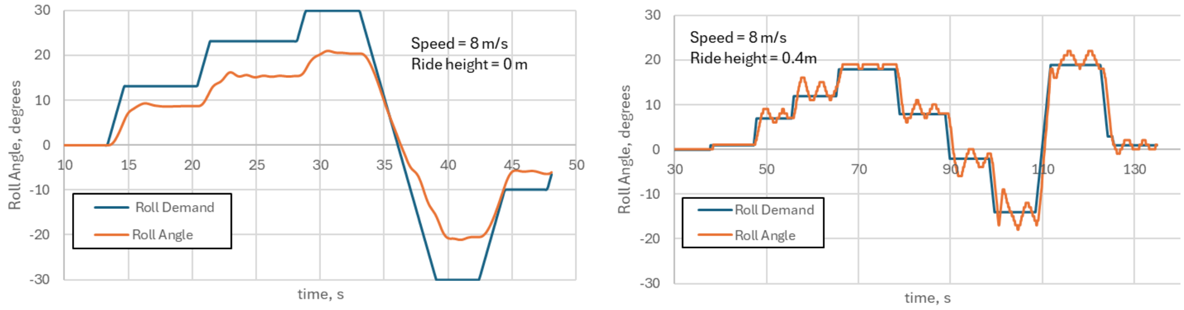
Figure 8 FoilBoard speed control at different ride heights



a) Speed 4 m/s

b) Speed 6 m/s

Figure 9 FoilBoard height control at different speeds



a) Ride height zero

b) Ride height 0.4m

Figure 10 FoilBoard roll control at different ride heights

Conclusions

A FoilBoard and rider has been successfully modelled in the Unity real-time environment using the Aerodynamic Objects tool for hydrostatics and hydrodynamics. The AO Free Surface Physics component is used to handle behaviours where objects are immersed in two different fluids. This provides a simple but effective model for forces due to fluid motion on semi-submerged bodies.

A trim and stability analysis using well known principles from the discipline of flight dynamics demonstrates the relationship between rider longitudinal position and trim speed (trim wing lift coefficient). A fundamental characteristic of a weight shift control system is confirmed in that aft CoM movement to increase trim lift coefficient also decreases stability, leading to increased pitch sensitivity at higher lift coefficients (low speed or high normal acceleration) and decreased sensitivity at low lift coefficients (high speed).

A control system has been implemented based on CoM shift by the rider. Closed loop control is successfully demonstrated for speed, ride height and roll angle.

Further work

1. Mass modelled rider
2. Optimisation of foil areas and tail sizing
3. Verification of height control in waves
4. Include wave drag on board
5. Propulsion via pumping (dynamic CoM shifting including reactions to acceleration)