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Development of a Full Scale Moth Hydrofoil Control System Test Rig

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Abstract. The design, construction and evaluation of a test platform to test the International Moth class in real world conditions was undertaken with the aim to investigate the effects of altering the value of the proportional control coefficient on flight modes to provide data for further numerical simulations. Through consultation with industry, technical experts and reviews of literature, a design was produced that allowed foils to be tested over a range of velocities, foil configurations and control systems that would be free to move in pitch and heave, however constrained in roll, yaw, sway and surge. The rig with the degrees of freedom can be seen below in Figure 1.

Improvement of an existing electronic ride control system (ERCS) allowed the test moth to be able to fly at a range of depth to chord ratios along with the capability to change the respective flight modes with varying amplitudes. Ultimately, it was concluded that in a real-world environment the differences in drag between the range of values tested resulted in no serious measurable performance gains despite significant motion variations. However, it was apparent that small relationships formed and that it is essential for more research to be conducted in order to validate the data.

The rig developed provides an easily accessible method for testing control algorithms in a real-world environment without the need for complex sailing configurations. The rig also allows cheap ways of tuning a system that is ripe for full on-water implementation.

Keywords: International Moth, Platforming, Contouring, Hydrofoil, Electronic ride control system, PID

1 INTRODUCTION

This project aims to provide validation data for numerical simulations with an investigation into the differences between two flight modes of an international moth. Platforming is when a vessel flies flat in respect to the waves and is often used during short wave lengths to minimise vertical accelerations. A sailor may opt to use a platforming flight mode when they are after a smooth flight when there is low apparent riskof ventilation or broaching. Contouring is when a vessel follows the profile of the wave and a sailor will choose this flight mode in sea states with longer wave lengths and greater wave heights in order to avoid ventilation and broaching of foils [1]. Numerical prediction of these modes of flight requires significant dynamic simulation and a range of physical phenomena. Such numerical simulation was progressed by Price [2], but requires significant validation data to calibrate the underlying physical models.

The International moth class is the fastest one person dinghy in the world and is restricted by the following [3]:

Maximum length: 3.355 m
Maximum beam: 2.250 m
Maximum sail area: 8.25 m^2

The current ride height control system used on a moth is a mechanical push rod system, driven by a wand situated at the foremost position on the vessel. When the boat is stationary the wand is almost horizontal, which pushes the tab on the frontfoil completely down, creating maximum lift. As the boat accelerates and begins to fly, the wand rotates to a vertical which reduces the tab angle of the foil, reducing the lift and increasing the speed.

For this project, an electronic ride control system (ERCS) is developed. Whilst the current mechanical system is sufficient, an ERCS offers the possibility to manipulate the test rig to simulate a wide variety of scenarios. The ERCS replaces the wand with an ultrasonic sensor. The ultrasonic sensor sends its inputs into the flight computer which determines the tabangle. The flight computer then filters the measurements that are recorded from the sensors, meaning that the input signal is dampened making the moth platform the wave profile, the input signal can then be amplified making themoth contour the wave profile.

A test rig that mimics an international moth was designed and constructed to work with the AMC's Davis Cat [4]. This test rig allows for the moth to be able to move in heave and pitch, yet be constrained in roll, surge, sway and yaw. From this, a drag measurement can be recorded and a range of different platform and contour scenarios can be tested in order to find the optimum flight mode of an international moth.

2 PRESENT RESEARCH INTO DYNAMIC VELOCITY PREDICTION AND CONTROL SYSTEMS

Moth control systems have largely remained untouched since the first time they began to foil. Every sailor that owns a moth will likely set up their boat in a different way, and once they begin sailing it can often be tricky to change settings, especially if the weather changes [5]. The very first discussion of a different control system was by Miller [6], during his time he mentioned the use of ultrasonic sensors but sadly the technology and durability of the sensors was not on the same level as today's standards, so their use was disregarded [6]. As time progressed, few individuals researched into the potential of using a different control method to fly a moth.

Flying a moth higher is more efficient, the drag of the strut is reduced [7], but also more risky as the likelihood of ventilation is increased [8]. Beaver and Zseleczky [7] were some of the first to do full size studies on a moth as a complete package. Their tests all concluded that the control system needs to be able to fly high with a reduced likelihood of crashing [7].

For a new control system to be implemented successfully it is a key design parameter that it has the ability to fly the moth as high as possible [7] without the ability for the foils to ventilate [8] and the sailor to crash, along with this it is essential that the sailor has the ability to tune the system whilst sailing [5]. To test such control systems experimental programs are restricted to full sailing programs [9] or numerically based simulations [10]. There has been some comment on developing semi-controlled environment experiments from the 2013 America's Cup Campaign of ETNZ [11], but the application of results to dynamic simulation has not been made.

Model scale testing of moth foils and other T foils have been conducted by Binns, Brandner [12], Beaver and Zseleczky [7] and Day, Cocard [13] all of which conducted testing in a controlled environment such as a towing tank. However, there are no cases of full-size testing of a complete moth system. Nevertheless, it has become apparent that a rig to test an International moth without physically sailing would be beneficial to understand certain sailing phenoniums.

Figure 1: Test rig degrees of freedom. Red arrows display the vertical heave motions of the rig, the green horizontal arrows show the motion that aft carriage is capable of which allows for pitching motions. The two blue arrows demonstrate the rotation around that axis which also allows for pitch.

Figure 2: Test rig attached to Davis cat beam on Lake Trevallyn

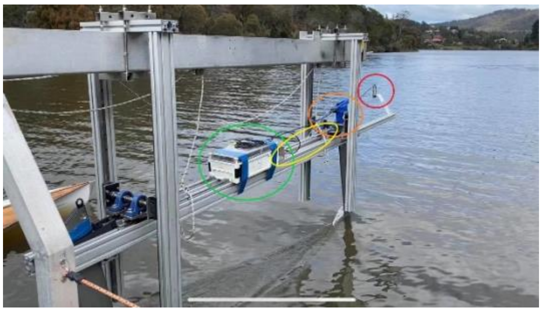

Figure 3: Test rig components, red circle is the ultrasonic sensor, orange is the servo mount, yellow is the loadcell and green is the control bo**x**

3 METHODOLOGY

3.1 Test rig

The design of the test rig was inspired by a moth sailing dinghy. The test rig needed to be compact in design, whilst also offering the flexibility to change foil configurations. The rig was designed to have the follow degrees of freedom, it is free to pitch and heave but constrained in roll, surge, yaw and sway. The test rig went through 5 design iterations and the rig in use with the degrees of freedom can be seen below in Figure 2.

The rig consists of two main parts, the static structure and the dynamic structure. The static piece consists of 4 vertical sections front and rear, which are attached to the horizontal beam of the Davis cat which can be seen above in Figure 2. These vertical pieces have slider rails which allow for the heaving motions which can be seen by the red arrows in Figure 2.

The dynamic structure consists of two large slotted aluminium profile sections, slider rails fwd and aft, the load cell, flight computer and the foils. The aft slider rails are 500mm long and the carriages on those rails are free to move to allow for pitch, this can be seen by the green arrows in Figure 1. The connection between the dynamic and static rig consists of two horizontal carriages that mount onto the rails, on top of these are two self-centring pillow block bearings which are connected by a horizontal rod. On either end of the rod are two more carriages which then connect onto the vertical static structure. Each foil is clamped in a 3D printed casing, each casing has mounting points so it can be mounted anywhere on the rig between the two pieces of extruded aluminium and the rake of the foil is adjustable. The load cell which is forward of the box in Figure 2 is connected by a rod to the carriages on the forward slider rails, this is used to measure the drag of the foils in the different flying modes. The test rig used two foils from a Waszp sailing dinghy and had a combined weight of 45kg. The test rig on the Davis cat can be seen in Figure 3 and the full technical drawings of the test rig can be viewed in the supporting documents.

Figure 3 shows the main items on the test rig, fwd in the red circle is the ultrasonic sensor. This sensor acts in the same way as the wand acts on a moth. Aft of the ultrasonic is the servo mount. Inside the orange circle is a 3D printed mount that houses the waterproof servo that drives the tab on the hydrofoil. The yellow oval aft of the servo mount is the load cell. The load cell is close to the control box and is slightly out of frame. The green circle is the control box, this box houses the raspberry pi along with the altitude and heading reference system (AHRS) sensor, loadcell amplifier, the batteries and other electrical items integral to operation of the system.

3.2 Electronic ride control system

The ERCS works by taking the inputs from two sensors, making sense of the data and then exporting the relevant response to the servo. The two sensors that are used on the test rig are an attitude and heading reference system (AHRS) sensor and an ultrasonic sensor. The AHRS sensor consist of a sensor that provides information on the 6 different motions of the vessel.

However, for this system, the AHRS will only provide information on the pitch. The ultrasonic sensor is a high frequency instrument that measures distances by using a transducer that sends an ultrasonic sound wave out, and then intercepts the sound wave that comes back once it has bounced of surface and interprets the objects proximity.

3.3 Robot Operating System (ROS)

The Robot Operating System (ROS) is a flexible framework for writing robot software. It is a collection of tools, libraries and conventions that aim to simplify the task of creating complex robust robot behaviour across a wide variety of robotic platforms [14]. This overview will not go into the full workings of ROS, however, will touch on a few important concepts for the ERCS. Two aspects of ROS that will be touched on are topics and nodes. Nodes are processes that perform computation whilst topics act as a system that can transport messages. Through topics, a node can either publish or subscribe to a topic.

Below in Figure 4 is a basic system schematic for the ECRS, all the items in green are physical hardware items, blue are nodes and red are the topics. The system works in the following way, at either sensor a node directly reads and interprets thedata that is being supplied. This node then publishes the data to a topic. The next node in the system runs a PID loop, this node gets its input by subscribing to the first topic. Each PID node also subscribes to a topic which tunes the PID based on an input, this can be seen at the bottom left corner of Figure 4. The P, I and D circles in the diagram are physical knobs that tune the system, the node *PID control* reads the physical knob settings and publishes that data back to the topic. Returningto the PID node, this node publishes its data to the next topic. Once this data gets to this topic the numbers are useable and for example might give a value such as 3 degrees for the state of the pitch. The node *flight control* puts all the inputs together and essentially decides how the system will react to that information it has received. Continuing with the example of a state of pitch of 3 degrees, the topic *servo angles* will subscribe to the *flight control* node as it wants to give informationto the servos, so when in subscribes to the *flight control* node it will return with physical values for the amount of tab required to either correct the pitch to 0 degrees or keep going to 10 degrees.

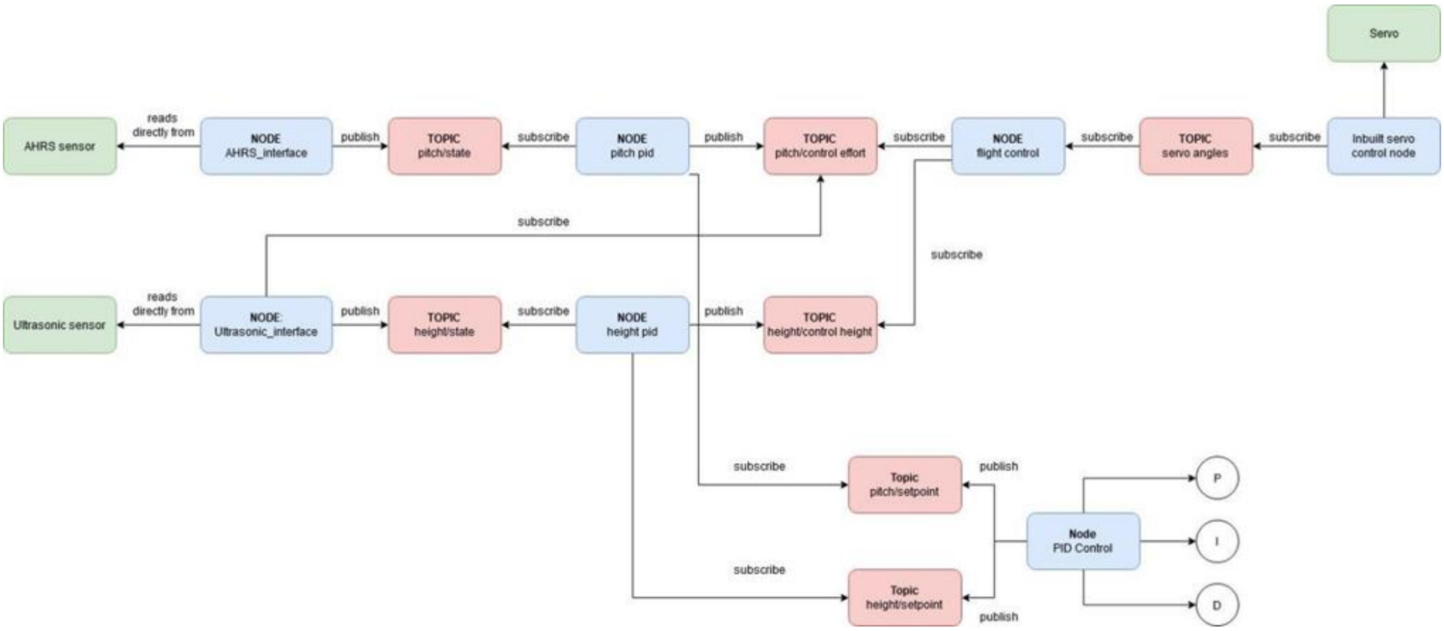

Figure 4: ROS system schematic

3.4 Testing Conditions

Due to the full-scale and the speed of the rig, a controlled environment like a model test basin or towing tank would not be appropriate, thus lake Trevallyn in Launceston was decided to be the most suitable option. The tests aimed to look at the differences in drag of different flying methods at different height to chord ratios. The height to chord ratio is the ratio between the distance to the free surface from the foil, to the chord of the foil, for this paper it was decided to test at a h/c of 1 and 2.. Below in Table 1 is a summary of the runs.

Table 1: Test conditions summary

Run	h/c	Speed(m/s)	Mode
0	1	3.5	Small contouring
1	1	3.5	Platforming
2	1	3.3	Large contouring
3	2	3.6	Large contouring
4	2	3.9	Small contouring
5	2	3.3	Platforming

In order to distinguish between platforming and contouring, the proportional gain value on the PID controller was increased. Initial tests showed that a value of 0.06 will result in a platforming motion while a value of 0.2 will result in small contouring motions and finally 0.5 will return large contouring motions. Figure 5 demonstrates the differences in flight modes with a h/c ratio of 2.

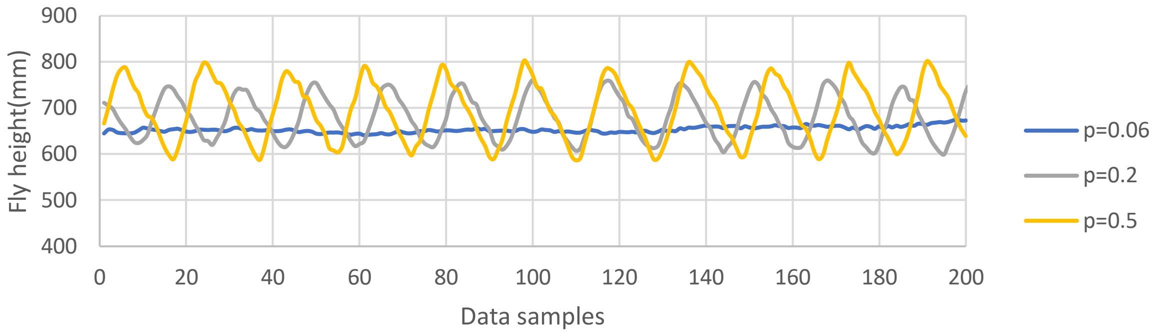

Figure 5: Variation in flying height modes with varied proportional controllers

4 RESULTS

Due to the speed not being constant during testing, it is important to discuss how this can affect the results. As expected with an increase of speed an increase of drag would be present, this can be highlight below in Figure 9.

From Figure 6, a very small difference in speed is observed, of which the increase does result in a marginal rise of drag but only by the magnitude of 3-4 N for proportional values of 0.06 and 0.2. Also, quite noticeable for these two values is that the deeper h/c ratio returns a smaller drag value. This is unexpected as less strut should result in a less drag as less resistance is present, however the increase might be due to loss in lift to drag ratio due to free surface proximity along with a greater wave making resistance. Nevertheless, this uncertainty highlights the need for further investigation. Below in Table 2 is the summary of the results from testing.

Table 2: Summary of results for all tested conditions

	h/c	P	I	D	speed (m/s)	Minimum drag (N)	Maximum drag (N)	Difference (N)	Average drag (N)	Mode
run1	1	0.06	0	0	3.47	22.88	41.85	18.97	32.20	Platforming
run5	2	0.06	0	0	3.33	24.10	43.72	19.62	29.97	Platforming
run6	1	0.2	0	0	3.19	22.02	42.21	20.19	35.23	Small contouring
run7	2	0.2	0	0	3.19	16.18	48.17	31.99	31.82	Small contouring
run2	1	0.5	0	0	3.33	6.86	65.25	58.40	31.20	Large contouring
run3	2	0.5	0	0	3.61	7.00	90.91	83.91	42.71	Large contouring

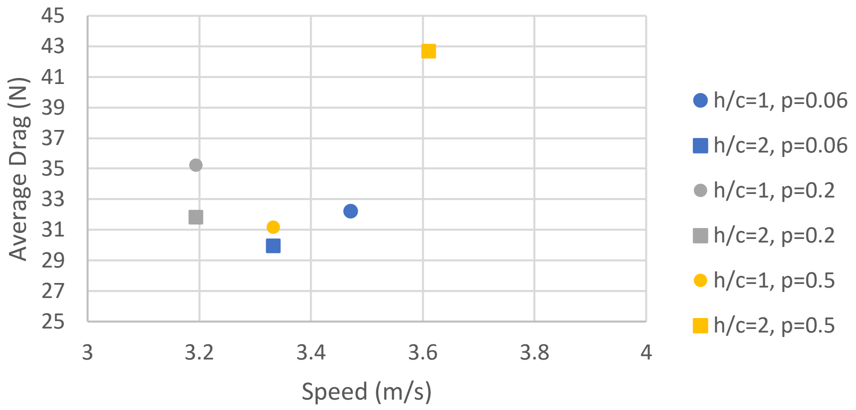

Figure 6: Variation in drag with respect to variation in speed

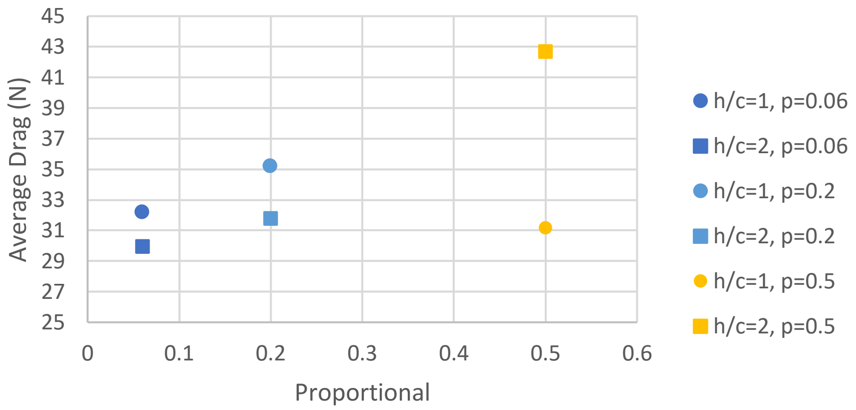

Figure 7: Variation in average drag with respect to variation to proportional gain

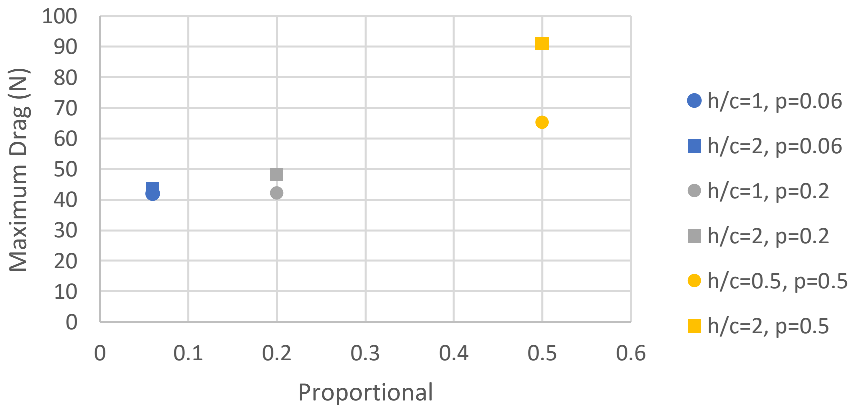

Figure 8: Variation in maximum drag with respect to variation in proportional gain

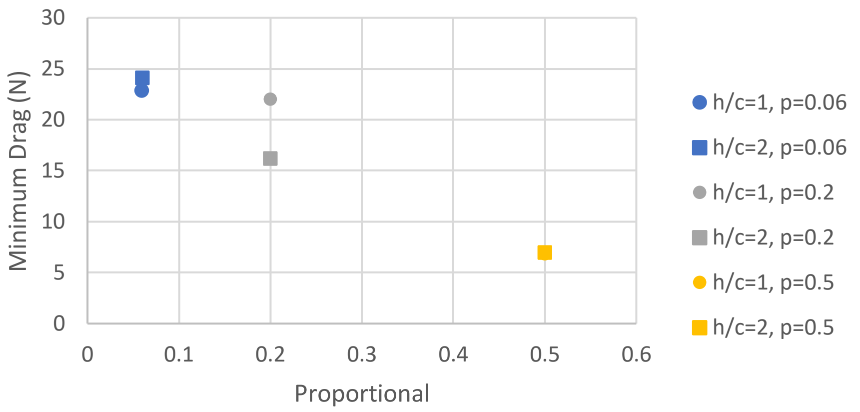

Figure 9: Variation in minimum drag with respect to variation in proportional gain

4.1 P = 0.06

As seen in Figure 5, a proportional value of 0.06 gives a platforming flying mode. In this mode it would be expected that the minimum and maximum values for drag would be very similar between the two different h/c ratios and that the h/c ratio of 1 would result in less drag than a ratio of 2. This is due to the reduced amount of strut in the water, resulting in less resistance. As seen in Figure 8 and Figure 9, the h/c ratio of 1 has slightly lower minimum and maximum drag compared to that of a h/c ratio of 2. The magnitude of the differences is 1-2N, which can be argued to be negligible when relating the data back to real world sailing conditions. Whilst the relationship is opposite in Figure 6, with a h/c of 2 having a lower average drag than that of a h/c of 1, the difference is no more than 2N.

4.2 P = 0.2

A proportional value of 0.2 results in a medium contouring mode, larger heave motions were observed on the rig along with greater pitch angles compared to that of a proportional value of 0.06. Figure 6 shows that both h/c ratios experienced the same speed of 3.2 m/s, but a h/c ratio of 1 experienced an average drag of 35.2N compared to 31.8N for h/c of 2. Once again, the difference between the two runs is to be considered small, and when related back to real world sailing conditions are almost negligible. In Figure 8 a pattern is beginning to form with respect to maximum drag between the two different h/c ratios. As expected, whilst the lift remains constant and the strut is immersed deeper into the water, the drag is increased due to the greater resistance of the strut. However, for a proportional value of 0.2, the relationship is not the same for minimum drag. As seen in Figure 9, the lowest minimum drag is for a h/c ratio of 2, which doesn't align with the theory that less strut results in less drag. The reason behind this is currently unknown and could also be effected due to low sample frequency of the load cell which results in its inability to capture data at high rates. For future experiments it is highly recommended to use a load cell with higher sample frequency in order to capture the data more accurately.

4.3 P=0.5

The largest contouring mode, as expected returns the greatest average drag. As seen in Figure 7 for a h/c ratio of 2, the average drag is 42.7N which is a considerable increase compared to the medium contouring and platforming modes of P values of 0.06 and 0.2. A h/c ratio of 1 has a lower average drag of 31.2N which can be seen in Figure 7. When compared to the h/c ratio of 2, this value is significantly less. Likewise, as the contouring is amplified, the difference between the two h/c ratios' maximum drag values increase due to the resistance from the strut immersion. In Figure 9 an interesting occurrence happens with the minimum drag values being almost identical between the two h/c ratios. The minimum drag values are expected to occur at the crest of the contouring profile, as seen in Figure 5, the crests of the different h/c ratios for a proportional value of 0.5 are 100mm apart, meaning that it would be expected that a h/c of 1 would have a lower minimum.

5 DISCUSSION

As seen above, a few relationships can begin to be observed from the data. Firstly, when contouring motions are increased, average drag and maximum drag will increase, whilst the minimum drag will decrease. Whilst it was expected that the different h/c ratios would result in a larger difference, it is very noticeable that minimal differences were observed for the two values tested. Along with this it was clear that the difference of speed did not vary the results by a considerable amount.

The design and construction of the test platform, that aimed to be capable of testing full scale moths proved to be successful. The rig offers the flexibility to be able to test any foil configuration and control system imaginable. Whilst the method for measuring drag is not as accurate with the methods seen in more controlled facilities, it offers an overall picture into the performance of the moth.

If an electronic ride control system was to be pursued for a moth, it was very clear from observations that a control surface on the aft foil is needed. Whilst sailing the sailor can change the location of their mass along with make small changes in the aft foil AoA to the change the trim of the vessel. This ability to make small changes proved to be vital whilst testing. It was often found during testing that the aft foil was raked too far forward. When speed was increased the aft foil would fly higher than the front foil causing the rig to enter a state of bow down pitch. During sailing, the sailor has the ability either to shift their mass aft or decrease the AoA on the aft foil, correcting the pitch motion. However, the control system has no way to correct this pitch motion as it only has one control surface on the front foil. Therefore, it was often found that during these scenarios the rig will slowly lose height and gradually nosedive. Comparing an ERCS to the current wand control system on a moth, the benefits of the ERCS become very clear. The ERCS offers the user the ability to easily adjust parameters that affect how they fly. The ability to be able to change the fly height and how responsive the system is to the sea state, whilst all out on the water is unparallel.

6 CONCLUSION

The system developed offers an excellent method of testing a highly dynamic system in a semi-controlled environment with the added value of drag measurements. Such data is critical to validate and develop numerical procedures for the analysis of dynamic behavior of foiling vessels.

In conclusion, it is rather apparent that in the real world the differences between platforming and contouring between different h/c ratios offer little to no advantage. Whilst the average drag did not always result in a lesser value for the smaller h/c ratio, the maximum drag was always greatest for a h/c ratio of 2. From a sailor's perspective, it would be far safer to fly at a greater h/c ratio if the increase in average drag is only as small as 3N. It would be vital moving forward that further work is done to better understand the point of where considerable losses in performance will occur with a greater h/c ratio. From these results the dynamic nature of hydrofoiling must be considered when establishing optimum flying conditions.

From observations during testing, it is very clear that an ERCS like the one used has a future in the world of sailing, its ability to be able to change ride height and sensitivity to the sea state whilst flying is unparallel and has the potential to offer more performance gains than may be anticipated. The test rig used to conduct the experiments proved to be sufficient in design and construction. It resulted in the capability to mimic a moth in both heave and pitch and will allow for a range of foil configurations or control system to be tested in the future. If future work is to be conducted using the Davis cat and test rig, it is essential that the recommendations are consulted and that improvements are made to the safety and operation of the Davis cat.

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