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Experimental characterisation of alternative propeller designs

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ABSTRACT

The following thesis is an investigation into the drag of five different sail boat propellers whilst under sail (i.e. when they are not providing mechanical propulsion). The propellers were all used on Volvo Penta Sail drives and were investigated in both the free-wheeling and locked positions. A testing rig representative of a sail drive unit was used to perform the tests at the tow tank facility at the Centre for Marine Hydrodynamics, Glasgow. The purpose of the thesis was to further develop the work previously carried out in this field and to add to it by investigating other types of propeller. The propellers investigated included: two blade and three blade fixed propellers, two blade and three blade folding propellers and a three bladed feathering Kiwi Prop™. This is a new type of propeller that had never been investigated in such a study until now. The drag of these propellers was firstly predicted using guide estimates for their drag coefficients and was measured experimentally in the tow tank to show the accuracy of these estimates. The drag coefficients of the propellers were also calculated and compared with the estimates used to predict the drag. Finally, a relationship involving the drag of the propellers and the exposed areas was found for further use in the field.

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NOMENCLATURE

Symbol	Definition & Unit
A	Exposed Propeller Blade Area (m^2)
AR	Advance Ratio
C_d	Drag Coefficient (Non-dimensional)
D	Drag (N)
d	Propeller Diameter (m)
g	Gravitational Acceleration (m/s^2)
GF	Gauge Factor
K_t	Coefficient of Thrust
K_p	Coefficient of Power
m	Mass (kg)
n	Rotational Speed (rev/s)
ΔR	Change in resistance caused by strain (Ω)
R	Resistance of Un-deformed Gauge (Ω)
T	Thrust (N)
U	Velocity (Knots)
V	Velocity (m/s)
V_a	Velocity of Advance (m/s)
W	Weight (N)
ρ	Density (kg/m^3)
η	Efficiency
E	Strain

CHAPTER 1: THE SAILING WORLD

Throughout the world, in any harbour there will always be sailing boats and yachts. These need the wind to help them sail – something which is not always readily available when at sea. To counter this dependence upon nature, sailing boats are fitted with engines and propellers to help them cruise when there is a lack of wind – most commonly in sail-drive or propeller shaft configurations. Figure 1 shows the sail-drive configuration – an L-shaped propeller drive mounted directly below the hull of the yacht. Figure 2 shows a propeller shaft mount – this is a long, thin shaft protruding out the bottom of the yacht with supports to keep it mounted to the hull of the yacht.

Figure 1 – Sail Drive Configuration

Figure 2 – Drive Shaft Configuration

There are however, sacrifices that must be made – most notably in the case of adding a propeller an increase in drag whilst under sail. This will reduce the overall cruising speed and also the time taken for the boat to reach its destination. There are many propellers available on the market – the most common of these are two, three, four and even five bladed fixed propellers. Unfortunately, these generate very high drag forces which will the slow the boat considerably. One of the possible solutions to reduce this drag is changing the fixed propeller for a folding or feathering propeller. However, there are still a great number of fixed blade propellers in use throughout the world. One of the main reasons for this trend is the initial cost of folding and feathering propellers – many yachtsmen believe that the cost of these propellers is not justified by their decreased drag force whilst under sail so still use fixed propellers. There have already been several papers published on the issue of sailboat propeller drag, many of which have conflicting views – two such examples are Warren [1] who states that a locked propeller would give the lowest drag and MacKenzie and Forrester [2] who state that a free-wheeling propeller produces the lowest drag.

The aim of this investigation is to find the drag and subsequent drag coefficients of five Volvo Penta sail drive propellers over a range of sailing speeds in the locked and free-wheeling positions, continuing the work of Lurie and Taylor [3] and MacKenzie and Forrester [2] and introducing a feathering Kiwi Propeller, which neither of these papers investigated. The Kiwi Prop™ is a relatively new type of propeller developed in New Zealand by Kiwi Feather Props Ltd. Further information on this type of propeller will be given in the literature review section of this paper, along with data and information for the other four propellers that will be investigated.

Chapter two of the thesis discusses the investigations that have already been carried out in this area and presents any relevant conclusions and conflicting views that arise from them – such as any existing methods for estimating sailboat propeller drag. This section also discusses hypotheses that this thesis was based upon and how these other papers have influenced the work undertaken, if at all. The chapter also provides information on the performance characteristics of propellers and the equations that govern these. Chapter two discusses each propeller in turn (number of blades, blade area, feathering/folding/fixed blades etc) and states relevant performance characteristics from the sail drive manufacturer's performance statistics given in their website's Propeller Selection Guide [4]. The chapter also provides information on the Tow Tank facility that was used for the experimental stage of the thesis.

Chapter 3 of the thesis discusses the experimental design stage of the thesis. It introduces the underlying theory that was the basis for the design and also predicts the drag of the propellers given this already established theory. This chapter also shows the different stages of design, from initial concept development through to the final design that was used for testing. It also discusses the method used for drag measurement – the strain gauge. The chapter gives details of how a strain gauge is used to measure drag, the tests performed on them and the calibration that was required to measure the drag accurately. This chapter also discusses the problems that arose during the experimental stage of this thesis and how they were overcome.

Chapter 4 discusses the results of each of the propellers in detail, in order to investigate which one would give the best overall performance given the experimental situations. This involved looking at their drag forces and their drag coefficients. Included in the section are graph plots of each propeller's drag, tables of the data that was recovered during testing, graph plots comparing each propeller's performance and discussion of all of these results. The chapter also alludes back to the drag estimation carried out in Chapter 3 and discusses the accuracy of the estimation.

The conclusions section sums up the results of the paper; gives specific conclusions that can be taken from the results obtained and also any possible improvements that can be made to the experiments carried out. This section will also discuss any suggested future work that could be carried out in the field in order to provide more accurate, realistic and definite results.

CHAPTER 2: PROPELLER DESIGN AND PERFORMANCE

The following literature review contains arguments from different authors and papers which have previously investigated propeller drag. This review concentrated on the results of papers that investigated the drag of propellers under sail and also those that included free-wheeling and locked propellers and their results. It also discusses the different approaches suggested to calculating propeller drag in papers and textbooks and their advantages and disadvantages. The review discusses the advantages of testing in a Tow Tank as stated in a technical paper published when they were becoming more widely used. The review also discusses some unconventional propulsion arrangements mentioned in a naval architecture textbook, their pros and cons and if they are at all relevant to the investigation. Finally, the review discusses the hypotheses that this paper is based upon having discussed the points raised in the papers.

MacKenzie and Forrester [2] investigated several propellers in the free-wheeling and locked positions and came to the conclusion: *"… that a locked propeller produces greater drag than does a freewheeling screw…"* However, Warren [1] indicated that the best position for a propeller to give the least drag is the locked position: *"It takes only a small amount of shaft friction to create* more *drag than that of the locked propeller."* Naranjo and Minick [5] suggested that in some cases the free-wheeling position is the best for reducing drag, but states that this also depends upon the transmission/gearbox that the propeller is mounted to – as some types can only tolerate free-wheeling for a short period of time due to cooling and lubrication problems. Lurie and Taylor [3] did not have the equipment available to carry out free-wheeling tests, but they did manipulate their results for a locked propeller to give an indication of the reduction of drag. From the results they obtained, they stated: *"The conclusion from these calculations is that a substantial reduction in drag, and thus gains in boat speed, can be realized when a fixed pitch propeller is allowed to freewheel. The decision to freewheel or not, though, must also take into* *account the factors of noise and wear and tear on the engine and bearings."* Given the wide range of viewpoints stated in these papers, it would be logical to suggest that the question of whether or not a propeller is better to be locked or allowed to free-wheel is a highly debateable one. With this in mind, the work of this thesis was geared towards establishing if a definite answer to this problem can be found. Also, the propellers used in these investigations covered a wide range – fixed, folding, feathering, two blades, three blades etc. They did not however, investigate a feathering Kiwi Prop^{TM} which is why this paper will include results for a three bladed version of this propeller. This will continue the work of the previous papers whilst introducing a new type of propeller which produces low drag under sailing conditions.

All of the papers that have been previously mentioned investigated a wide range of propellers. The results of all of the papers appear to follow a similar pattern – the larger, fixed bladed propellers produce the most drag in both positions, with feathering and folding propellers having much smaller values of drag at similar testing speeds. For example, Naranjo & Minick [5] tested several propellers at speeds of 2, 4 and 6 knots. Table 1 shows the average drag values for each type of propeller (whilst in the locked position) at 4 knots.

Prop Type	**Average Drag (N)**
Fixed Blades	78.96
Folding Blades	26.68
Feathering Blades	25.80

Table 1- Naranjo & Minick drag results

It should be pointed out however, that there were more feathering propellers tested in this study, so a better average was found for these in comparison to the other two types. Comparing these results with those of Lurie and Taylor [3] and MacKenzie and Forrester [2], they all have similar results for these propeller types at this speed. There are some slight discrepancies (the feathering propellers performing better than the folders, for example), but these can be put down to differing testing conditions (Naranjo & Minick [5] tested in open water, whilst the other two papers testing using a tow tank) and the different models/makes of propeller used.

The papers also include a wide range of methods for testing the drag of propellers. MacKenzie and Forrester [2] used practical tow tank experiments to evaluate drag, Lurie and Taylor [3] used only experimental work, again in a tow tank situation with similar results to those of MacKenzie and Forrester [2]. Naranjo & Minick [5] performed all of their tests in open water, with several different investigations into the propeller drag and performance. With the time and budget constraints on the thesis and the fact that open water testing is very difficult and with extremely variable local weather conditions, this would prove extremely problematic and time consuming – therefore a tow tank was used for tests.

Kirkman [6] discussed the use of tow tanks in yacht design. Before this paper was published, many did not see the merits of testing in a tow tank given that the results were so varied. However, with new understanding of scale effects, the paper explained why using tow tanks was becoming increasingly important. Kirkman argues that open water testing is inaccurate and difficult to carry out methodically. He also argues that open water testing is not reliable for evaluating small differences in performance, as the interference of the weather can skew results considerably. Whilst this paper did not directly discuss the use of a tow tank to measure the drag of propellers, it did provide an excellent insight into the use of such a facility, aiding the understanding and planning of the experimental stages of this paper.

As previously mentioned, there are two main types of propeller mount in sailing yachts – the sail drive and propeller shaft configurations. However, there are also some unconventional propulsion arrangements that could be investigated. Schneekluth & Bertram [7] discusses some of these propulsion arrangements and their merits. They include rudder propellers, overlapping propellers, contra-rotating propellers and controllable-pitch propellers. Whilst these arrangements may have benefits in the ship building industry, they have no real merit in the private sail boat sector, so investigating these configurations as part of this paper would be of no real interest or benefit to the industry as a whole.

Taking all of the information from these papers into consideration, the following decisions were made for the purposes of this paper and the experiments:

The propellers were mounted on a basic test rig, representing a sail drive configuration. This method was selected because sail drives are becoming more and more popular in the sailing world; this will add to the literature already published by further investigating propellers mounted in this position. The experiments also incorporated both the free-wheeling and locked propeller positions in an effort to provide more data for comparison to further address the question of which position is best, given that there is such a split in opinion of previous researchers. The tests were carried out at the tow tank which is part of the Centre for Marine Hydrodynamics, Glasgow (see the Experimental Chapter of this paper for more information on the facility). The choice to use a tow tank rather than open water for testing was taken because the environment is controllable – there are no other factors to be taken into consideration whilst testing other than the previously defined control conditions (in the case of this thesis, the velocity of the towing carriage and the position of the propeller), which would not be the case during open water testing. The influencing conditions in this case (such as high winds, choppy seas, or indeed no wind and calm seas) could influence the results considerably.

Whilst the work of this paper will overlap with some of the work that has already been carried out in the field (see MacKenzie and Forrester [2], Lurie and Taylor [3] and Naranjo and Minick [5]), the introduction of the Kiwi Prop™ will add a new low-drag propeller to the investigation (which previously had never been tested in such a way) meaning the investigation will still be of benefit to the industry.

The following equations define the nature and performance of propellers. These can be found below, with a brief description of each and what it is calculating.

$$K_T = \frac{T}{\rho n^2 d^4} \qquad \ldots (1)$$

Equation 1 gives the thrust coefficient, K_T, where *T* is the thrust (N), d is the blade diameter (m), *n* is the rotational speed (rev/s) and ρ is the density of the working fluid (kg/m^3). This is a standard performance characteristic of a propeller that relates the amplification of the thrust of the propeller due to its rotational speed.

$$K_P = \frac{P}{\rho n^3 d^5} \qquad \ldots (2)$$

Equation 2 is for the coefficient of power, K_P, where P is the power (W), d is the blade diameter (m), n is the rotational speed (rev/s) and ρ is the density of the working fluid (kg/m^3). This coefficient tells you how effectively the propeller converts its power input into rotational energy.

$$AR = \frac{V_A}{nd} \qquad \ldots (3)$$

Equation 3 defines the Advance Ratio of a propeller, where *AR* is the advance ratio, V_A is the velocity of advance and the other symbols have the same meanings as in the previous equations. The advance ratio is defined as “The ratio of the water speed along the axis of the propeller to the speed of the blade tip.”

Equation 4 gives the final characteristic of propellers is related to both the coefficient of power and the coefficient of thrust – the efficiency. This term describes how efficient the propeller is at providing thrust – it determines how much of the energy from the power output is transmitted into thrust/useful energy.

$$\eta = \frac{V}{nd} \cdot \frac{K_T}{K_P} \qquad \ldots (4)$$

Where η is the efficiency of the propeller and the other symbols have the same meanings as defined previously.

Five separate propeller types were investigated in the experimental stages of this investigation. The following section shows a photo each propeller, gives a brief description and any information from technical papers/textbooks/websites that is relevant to each propeller. Table 2 displays the blade areas of all of these propellers which were found by tracing their shape on 5 mm^2 graph paper and counting the squares that were inside the blade. To counter the problem of squares that were at the edges of the blades with only a small portion of their areas taken up, only squares with half or more of their area within the blade were counted – this is a relatively slow method of measuring the areas, but tends to be accurate enough for experimental data. All of the propellers used in the experiments had diameters of 16 inches.

Propeller	Exposed Area (m^2)
2 Blade Fixed	0.0364
3 Blade Fixed	0.0596
2 Blade Folding	0.00485
3 Blade Folding	0.00935
3 Blade Feathering	0.0225

Table 2 – Propeller Exposed Areas

Figure 3 shows the first propeller used was a small two bladed fixed propeller. This is a very basic type of propeller, with no "special" features (such as folding/feathering blades). This propeller was used primarily as a test prop for the rig, to ensure that nothing went wrong during testing the more expensive propellers (the two & three bladed folding and 3 bladed feathering props).

Figure 3 - Two Bladed Fixed Propeller

D. Gerr [8] states that whilst the ideal number of blades for a propeller is only one (as it means no other blades disturb the water); however it does state that trying to use a single blade propeller for a sailboat is practically useless. It also states the logical answer to this is to add a second blade; however the problem with this is that the blades require to be very large in both area and diameter – a problem for sleeker, more hydrodynamic vessels with propeller mounts close to the bottom of the hull. Referring to the manufacturer's official Propeller Selection Guide [4] the propeller is "manufactured of an aluminium alloy, developed to withstand salt water and cavitation damage." The propeller was also covered in a protective blue coating which further prevented corrosion and cavitation damage.

The next propeller used was a three bladed fixed propeller, this is displayed in Figure 4. This is the next logical step to take moving on from the two bladed fixed propeller, as it increases both the number of blades and the total area of the propeller. This type of propeller (as previously stated) is one of the most common in the world of sailboats and yachts – mainly due to their relatively low cost and high propulsion efficiency.

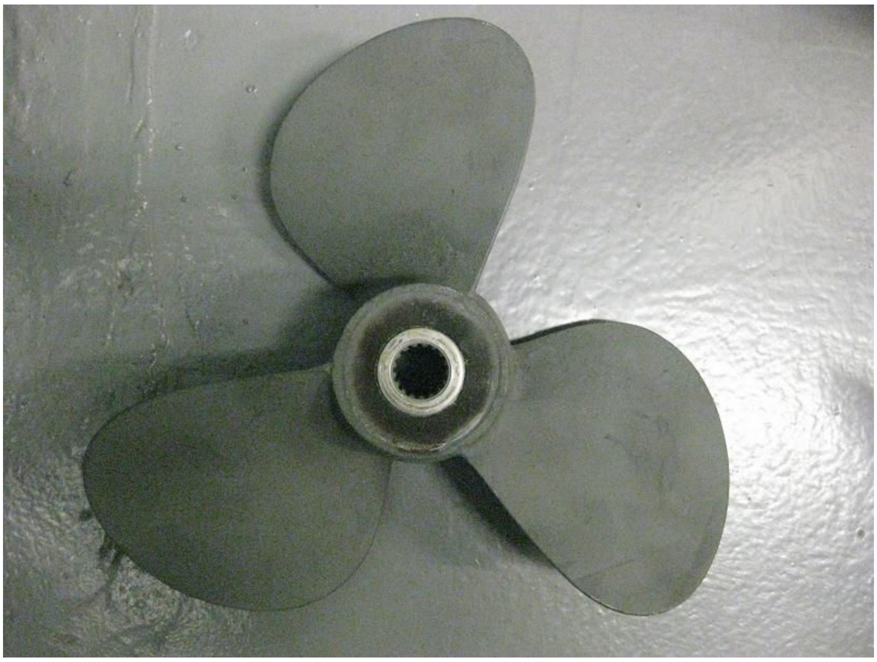


Figure 4 - Three Bladed Fixed Propeller

D. Gerr [8] states that this type of propeller is "generally proven to be the best compromise between balance, blade area and efficiency". Given this quotation and the popularity of the propeller type, it is obviously an excellent choice of propeller to investigate. Similarly to the two-bladed fixed propeller, the three-bladed fixed is also manufactured of an aluminium alloy (again, this information is taken from the Propeller Selection Guide [4], obtained from the Volvo Penta website) to help prevent corrosion and cavitation damage. Both of these propellers were clear of any marine growth (small shells, areas of salt on the blades etc) when they were received and required no cleaning before the testing.

The next two propellers investigated were both folding propellers. The first of these was a two-bladed folding propeller, which is shown in Figure 5. The blades of this propeller fold away with the water force whilst under sail. This figure also has an inset image which shows the blades in their folder position.

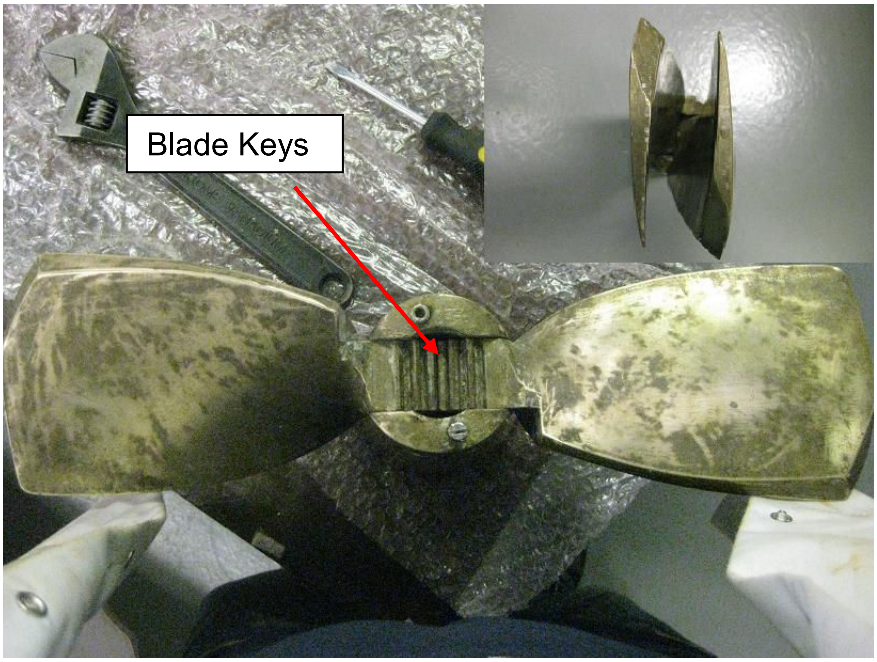


Figure 5 - Two Bladed Folding (Inset - Blades Folded Away)

Figure 6 shows the three bladed propeller is similar in how it folds its blades – it uses the force of the water acting on the blades to force them into their folded position. This hugely reduces the exposed area of both propellers to the water flow, which greatly reduces the drag of each propeller. Figures 5 and 6 display each propeller in their open position with an inset image provided showing them in their closed positions – this provides a comparison of the difference in area.

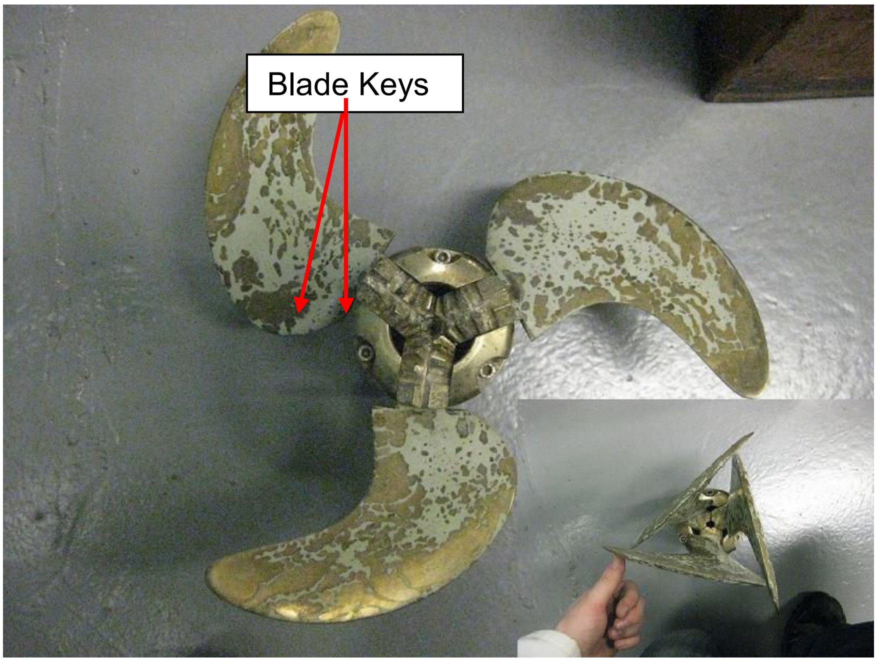


Figure 6 - 3 Bladed Folding Propeller (Inset - Blades Folded away)

This three bladed folding prop, similarly to the two bladed, had some marine growth on its main body, where the blades were mounted. Again, this was removed using very fine sandpaper to prevent damage to the blade hub. The manufacturer's Propeller Selection Guide [4] provides excellent information on the construction and features of this propeller: *"A conical toothed section ensures that the propeller blades are in correct position. With no complicated machinery or mechanisms to cause trouble, the propellers provide superb reliability. The folding propellers are manufactured from a nickel-aluminium-bronze alloy which ensures no growth and excellent corrosion resistance. It is fitted with a bushing at the hub, this absorbs the shock which the propeller and shaft are subjected to during quick shifts forwards and backwards."* D. Gerr [9] states that there may be several problems with these types of propeller: "The blades can often open and close out of step with each other and, on folders, the lower blade will often hang down in an annoying fashion under sail." This statement may well be relevant for some folding propellers, but the two investigated had keyed blades that opened at the same time in step with one another to prevent this problem occurring.

Figure 7 shows the final propeller that was tested was a Kiwi Prop™ Three bladed feathering propeller. This is a relatively new design of feathering propeller developed in New Zealand that uses composite materials to decrease the weight of the propeller and prevent corrosion damage to the blades.

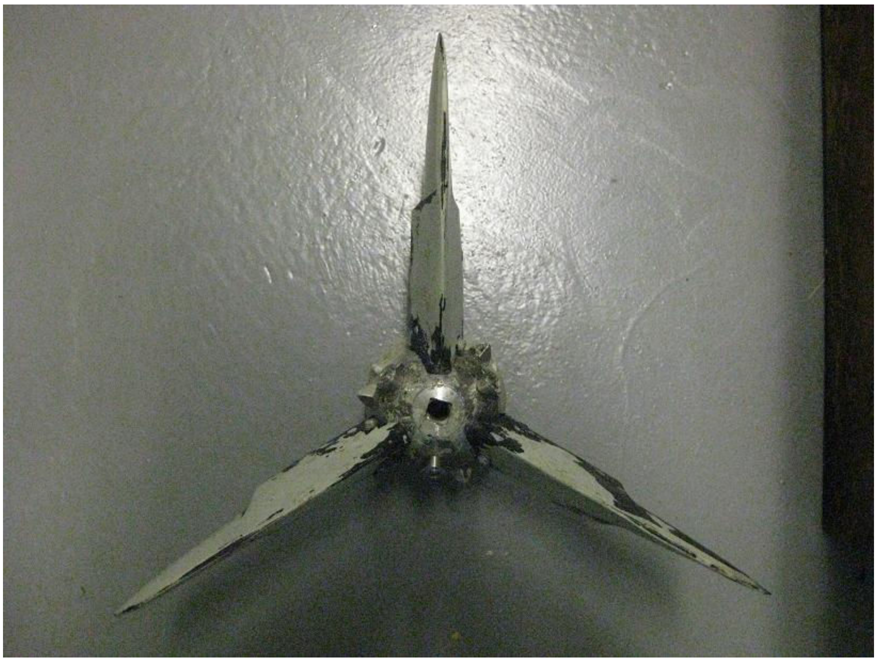


Figure 7 - Aligned Kiwi Prop Blades

Due to the composite construction of this type of propeller, the blades can have very fine tips – something that folding propellers cannot have as they depend upon a higher mass at the end of their blades to effectively operate in reverse. This reduces the exposed area of the propeller to the flow considerably. Similarly to other feathering propellers, the blades of the Kiwi Prop align themselves with the flow of the water over them to reduce the exposed area and the drag under sail. However, the Kiwi Prop's blades are not geared as other types of feathering propeller are – this allows them to align with the flow through any angle of sail, whilst other folding and feathering propellers will only align with the centre of the hull. The blades of this propeller are flat, rather than twisted like fixed propellers – some people believe that this is a disadvantage, but testing by the manufacturers of the props on their website [10] shows no significant difference in performance when compared to that of fixed propellers. The Kiwi Prop™ has blades which are constructed of Zytel (a composite of Nylon type plastic with glass fibre reinforcement). Whilst this material can be brittle when first moulded, with pre-soaking the nylon expands slightly and pre-stresses the glass fibre to create very high levels of tensile strength. Another huge advantage of any feathering prop (particularly the Kiwi Prop™) is that folding propellers only open about half way in reverse – whilst in contrast feathering propellers have full pitch and blade action in reverse.

The experimental stage of this paper took place at the Centre for Marine Hydrodynamics on Acre Road, Maryhill, Glasgow. The specifications of the tow tank are as follows (taken from the centre's website [11]):

Specifications

Tank dimensions: 76m x 4.6m x 2.5m

Carriage: Computer-controlled digital drive: max speed 5m/s. Equipped with digitally-controlled sub-carriage.

Wavemaker: Variable-water-depth computer-controlled four-flap absorbing wavemaker generating regular or irregular waves over 0.5m height (subject to water depth)

Data acquisition: PC based modular data acquisition/control system. Up to 64 input and 20 output channels, sample rate up to 60 kHz.

Figure 23 shows the test carriage fitted to the tow tank and Figure 24 shows the Tow Tank.

Figure 8 - Tow Tank Test Carriage

Figure 9 - Tow Tank

CHAPTER 3: EXPERIMENTAL DESIGN

The following chapter discusses the design process in detail and provides sketches of the design and the theoretical considerations that had to be alluded to during the design stage. The first of these considerations was the drag that was being measured. The basic drag equation is given in Equation 5.

$$D = \frac{1}{2} \rho A C_d V^2 \qquad \dots (5)$$

Where D is the total drag of the testing rig and propeller measured in Newtons, ρ is the density of water, which for the purposes of this thesis was set at a constant value of 1000 kg/m^3, A is the exposed area of the propeller in m^2, C_d is the drag coefficient and V is the velocity in m/s.

The three test runs for each blade were performed at 2 knots, 4 knots and 6 knots. However, the towing rig used could only take inputs in m/s, so a conversion equation was required – the equation used can be found below (Equation 3).

$$V = \frac{U}{1.7} \qquad \dots (6)$$

Estimates of the drag coefficients of each propeller were given by Lars & Eliasson [12] which are:

C_d = 1.2 for Fixed Blades,

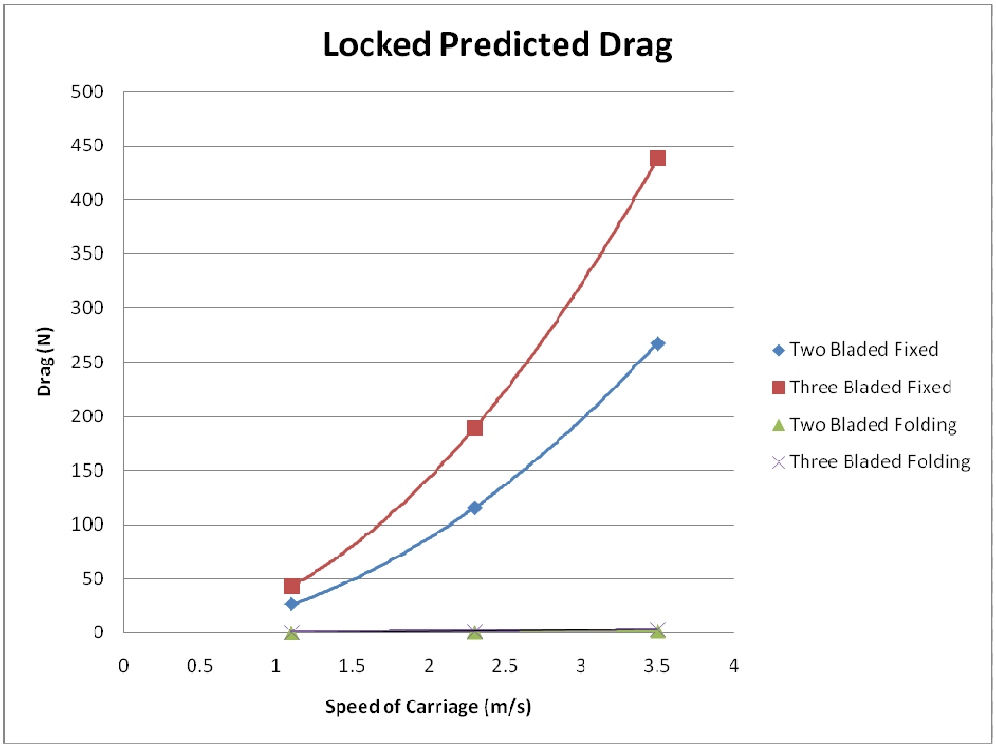
C_d = 0.3 for Fixed Blades, free to rotate,

C_d = 0.06 for Folding Blades

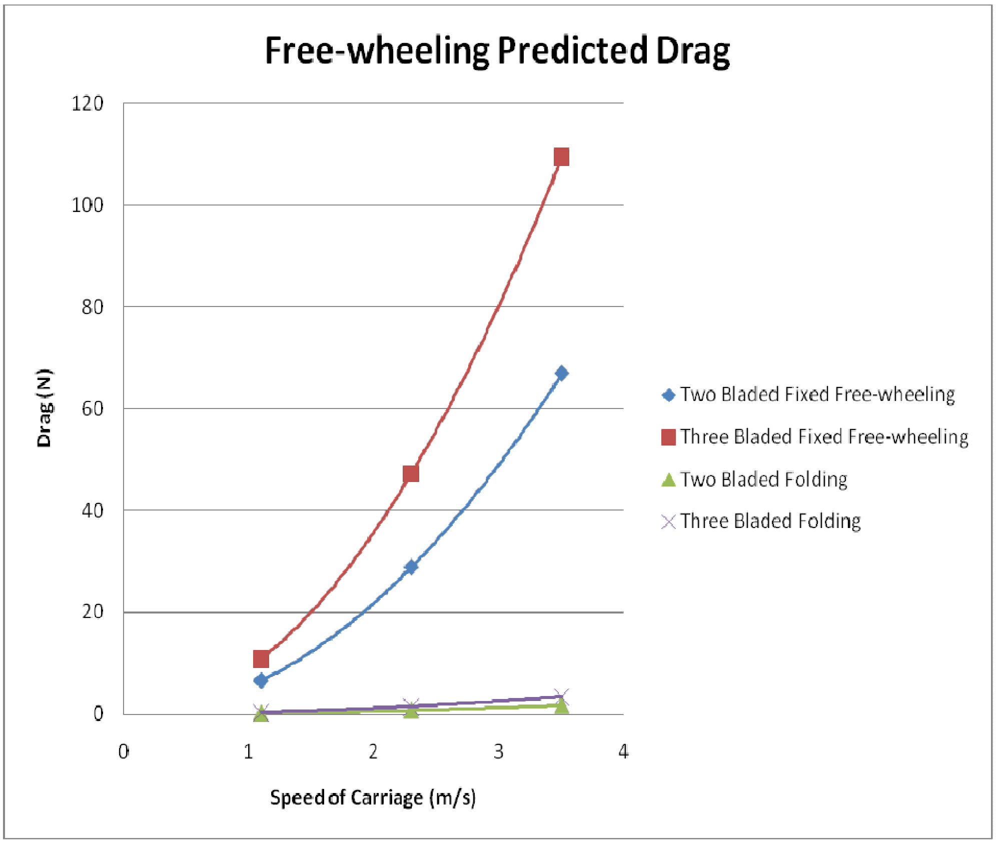
Using these values, the total drag for the three coefficients given was calculated using Equation 5, the previously measured propeller areas and the velocities over which the test runs would be performed. Table 3 shows the results obtained, whilst Graphs 1 & 2 display plots of the predicted drag curves.

Velocity (m/s)	Density (kg/m^3)	Cd	Area (m^2)	Propeller	Drag (N)
1.1	1000	1.2	0.0364	Two Bladed Fixed Locked	26.42
2.3	1000	1.2	0.0364	Two Bladed Fixed Locked	115.53
3.5	1000	1.2	0.0364	Two Bladed Fixed Locked	267.54
1.1	1000	0.3	0.0364	Two Bladed Fixed Free-wheeling	6.60
2.3	1000	0.3	0.0364	Two Bladed Fixed Free-wheeling	28.88
3.5	1000	0.3	0.0364	Two Bladed Fixed Free-wheeling	66.88
1.1	1000	1.2	0.0596	Three Bladed Fixed Locked	43.26
2.3	1000	1.2	0.0596	Three Bladed Fixed Locked	189.17
3.5	1000	1.2	0.0596	Three Bladed Fixed Locked	438.06
1.1	1000	0.3	0.0596	Three Bladed Fixed Free-wheeling	10.81
2.3	1000	0.3	0.0596	Three Bladed Fixed Free-wheeling	47.29
3.5	1000	0.3	0.0596	Three Bladed Fixed Free-wheeling	109.5
1.1	1000	0.06	0.00485	Two Bladed Folding	0.17
2.3	1000	0.06	0.00485	Two Bladed Folding	0.76
3.5	1000	0.06	0.00485	Two Bladed Folding	1.78
1.1	1000	0.06	0.00935	Three Bladed Folding	0.33
2.3	1000	0.06	0.00935	Three Bladed Folding	1.48
3.5	1000	0.06	0.00935	Three Bladed Folding	3.43

Table 3 – Predicted Drag



Graph 1 - Predicted Locked Drag Curves



Graph 2 - Predicted Free-wheeling Drag Curves

From the two graphs, it is obvious that in both cases the fixed propellers are outperformed by the two folding propellers. These results are compared with the actual measured drag results taken during the experimental stage of this paper in Chapter 4.

As alluded to in Chapter 2, the desired design would be a simple test rig that represented a sail drive configuration. Initial brain-storming came up with several ideas, the first of which would incorporate a hull model just below the surface of the water. Figure 10 shows initial design concepts and initial development of the sketches considering using a hull model with a sail-drive propeller mount.

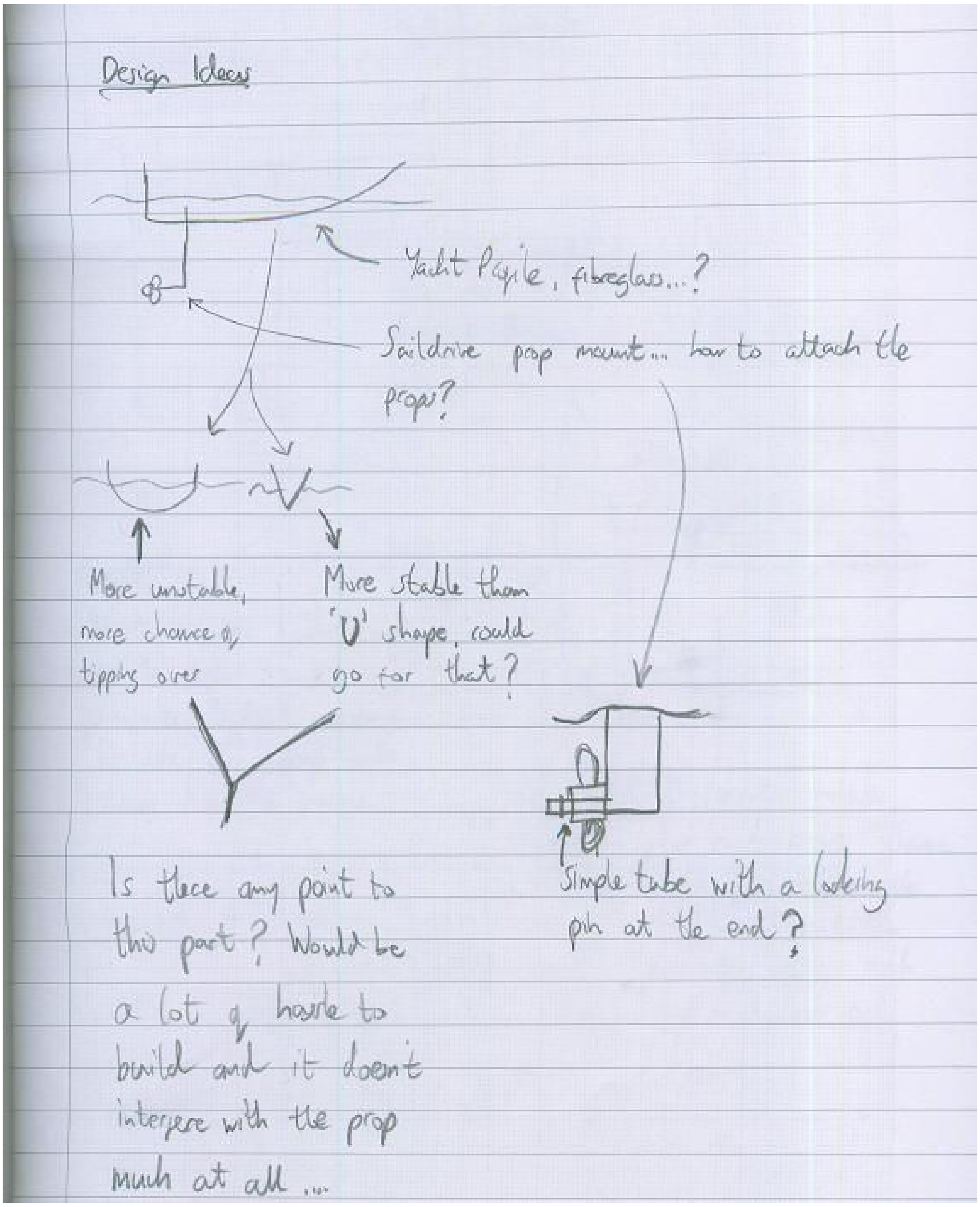


Figure 10 - Basic Hull concept & development

The initial design stages also took into consideration the mounting of the propellers – in the first instance, if a protective cage could be fitted to prevent damage to the propellers (see Figure 11, overleaf).

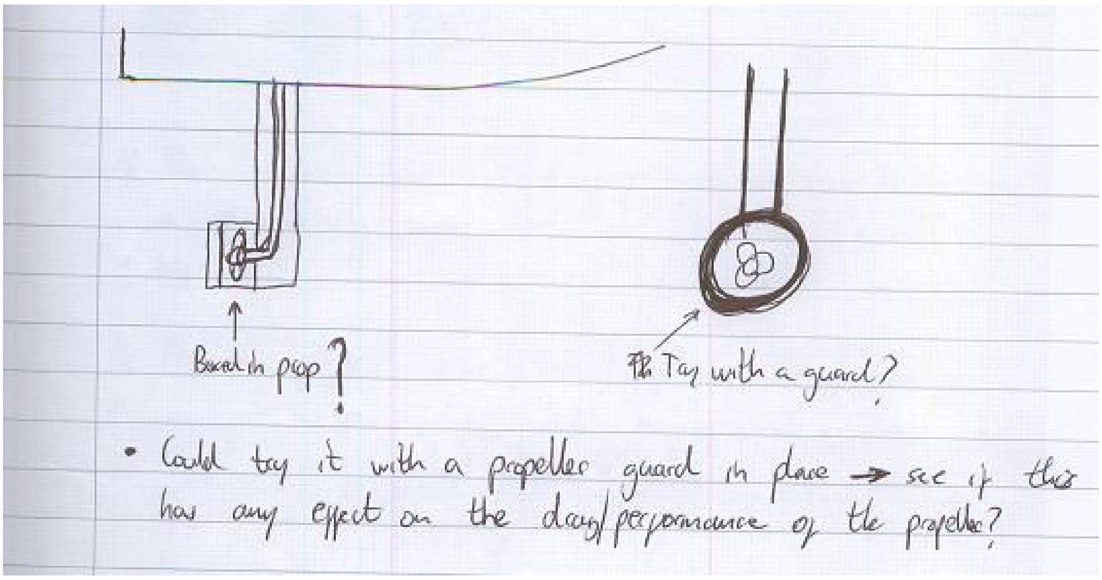


Figure 11 - Caged Propeller Sketches

Whilst these two initial concepts were of interest to the project, the hull model was deemed un-necessary as a sleek fibreglass hull tends to have a very small effect on the drag of the propeller below it. The caged propeller idea was rejected because most sailing boat propeller mounts do not incorporate guards, so investigating this area would only be of interest to a small portion of the industry.

The first major design concept involved using a large testing rig, based around a propeller drive shaft configuration as seen in Figure 12. This design incorporated the sail drive concept, with an easily interchangeable propeller mount to incorporate the different designs of propeller and speed up the changeover time.

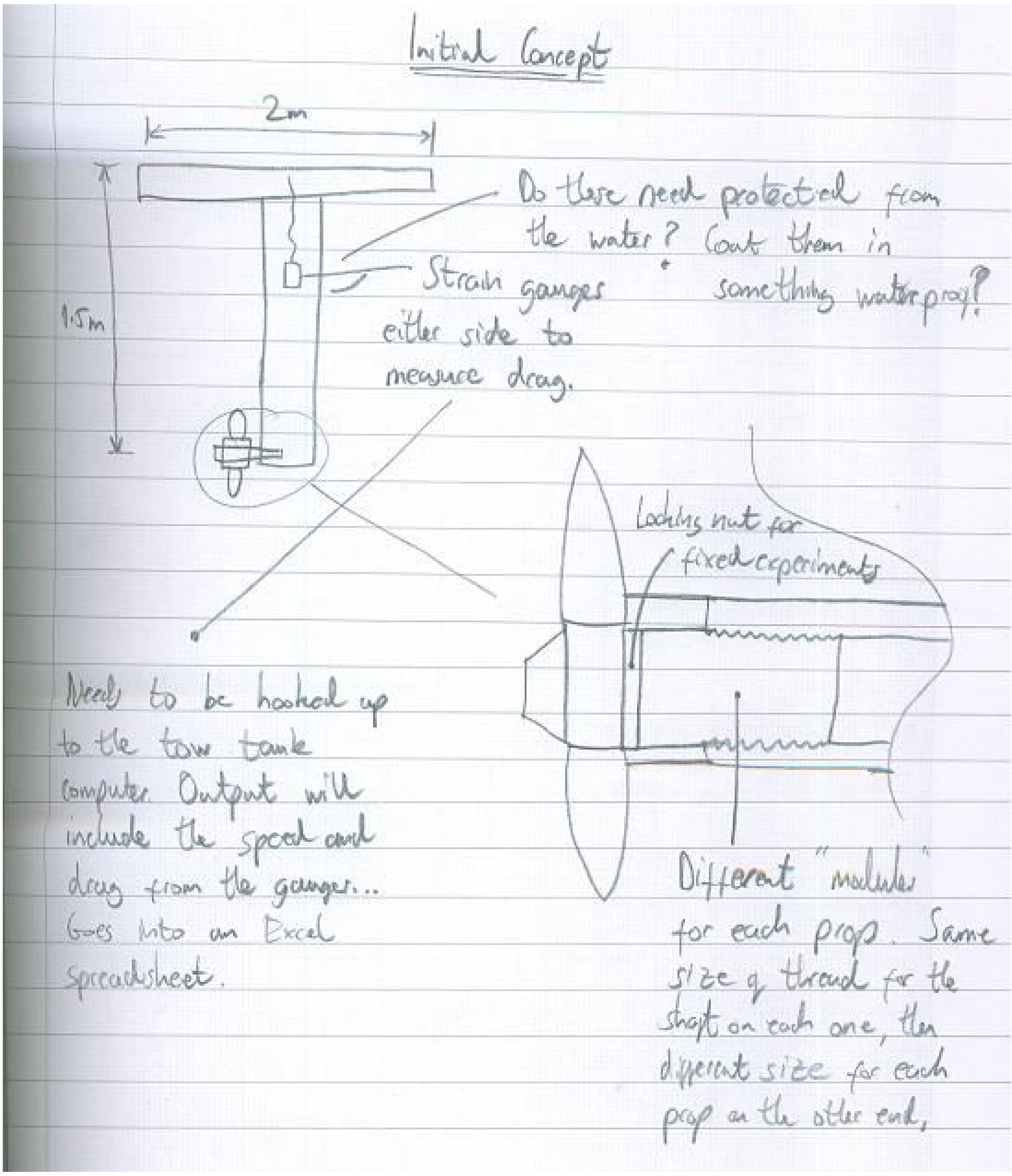


Figure 12 - First Concept

This initial design concept led to a final design that was the preferred testing method. Figure 13 shows this design with dimensions and annotations.

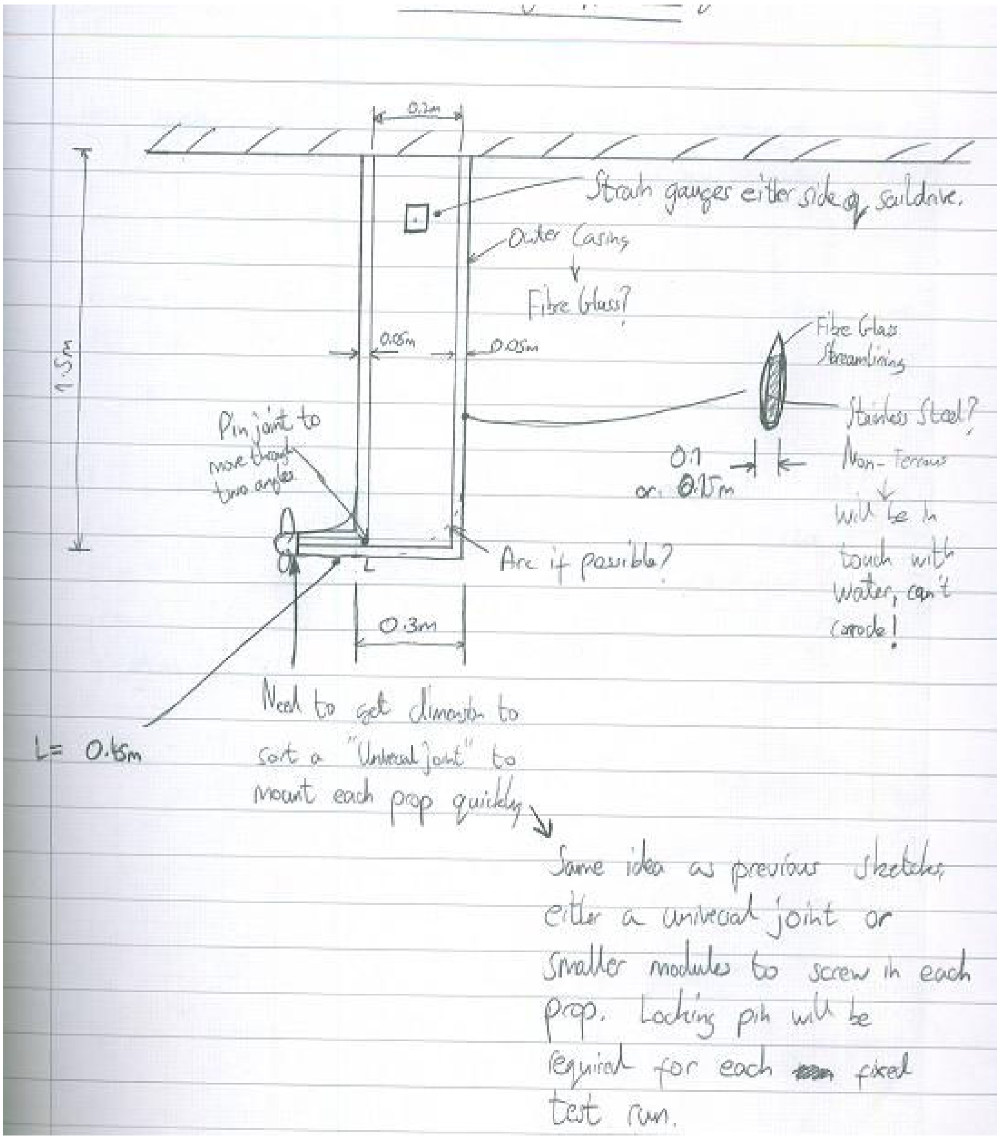


Figure 13 - Final Design

From the drawing, it can be seen that the design is a very basic sail drive configuration. A previous meeting with the staff at the tow tank had established that the preferred surface shape for dragging through the water was an aerofoil – this has been incorporated in the design as a streamlining on the main leg. The preferred material for the main support/leg of the design was aluminium, and a piece measuring 2m by 15mm by 30mm was purchased for the design. The strain gauges were to be mounted either side of the main support leg, and connected to the equipment on the testing rig using a BNC adaptor connected to a +/- 10 volts amplifier for the data collection.

The final design was realised through the previous work of MacKenzie and Forrester [2] and modifying the existing design to fit the propellers. Figure 14 shows this design in full.

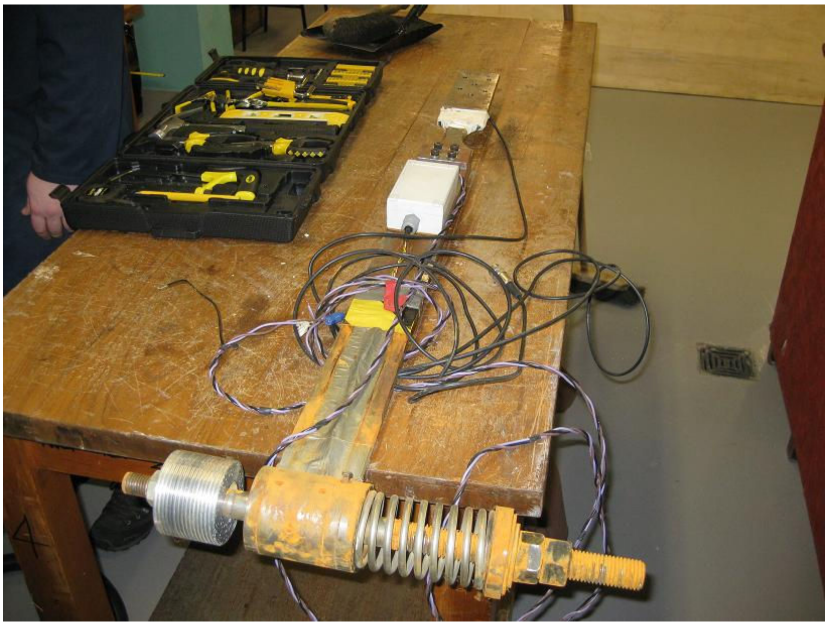


Figure 14 - Actual Design

This design was already fitted with the necessary strain gauges and adaptor for it to be linked with the tow tank computers. However, it did require to be modified to mount the sail drive propellers as it had previously investigated screw-on shaft mounted propellers.

The testing rig had already been drilled so that it could be mounted easily from the towing rig at the tank. An image of the position and size of these holes can be found in Figure 14.

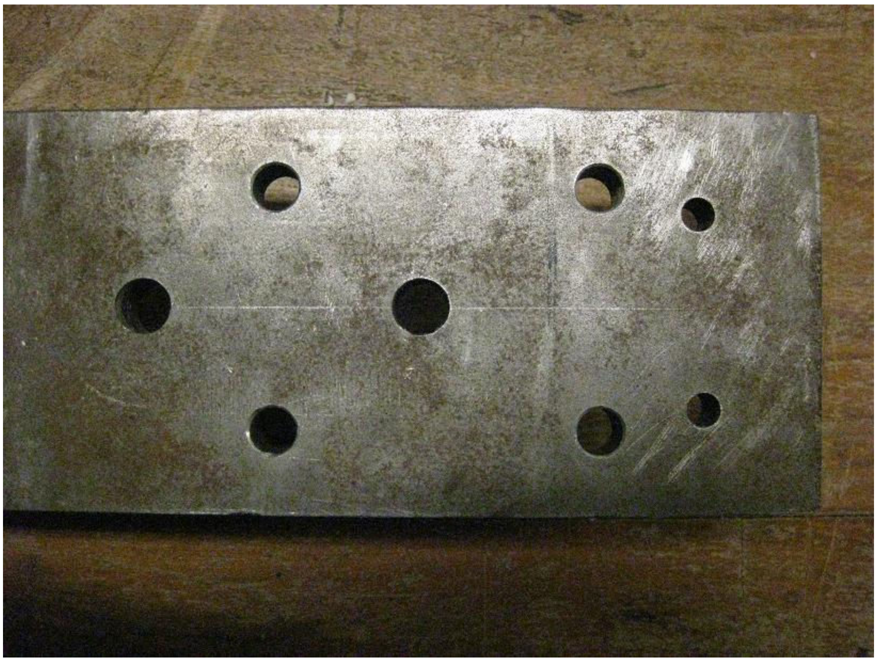


Figure 15 - Holes used for mounting the rig

A meeting with an industrial contact was organised through the supervisor of this thesis. This meeting was first and foremost to verify the work of the project was correct and that the design concept was viable and true to the design of a sail drive. The design problems were discussed, which were mainly to do with the mounting of the different propellers to the rig. After discussion regarding the testing rig, solutions to the problems were proposed by the contact with and implemented in the design. A visit was paid to the Centre for Marine Hydrodynamics Tow Tank where the testing was to take place. This allowed the industrial contact and project supervisor to see where the testing was to take place and how the experiments would be performed.

The alterations to the design included constructing a suitable mount to attach to the rig and in turn to attach the propellers to, constructing several “washers” to protect the propellers from a fairing on the test rig and manufacturing locking bolts to keep the propellers on the shaft during testing. All of the propellers utilised a single 1” diameter mounting hole, which helped with construction, as only one mount needed to be made. However, the propellers were all of different lengths and the mount had to be altered to incorporate all of the propellers. The mount itself was constructed of 1” diameter aluminium tubing; with an M20 threaded inside diameter to attach it to the test rig. This is displayed in Figure 16.

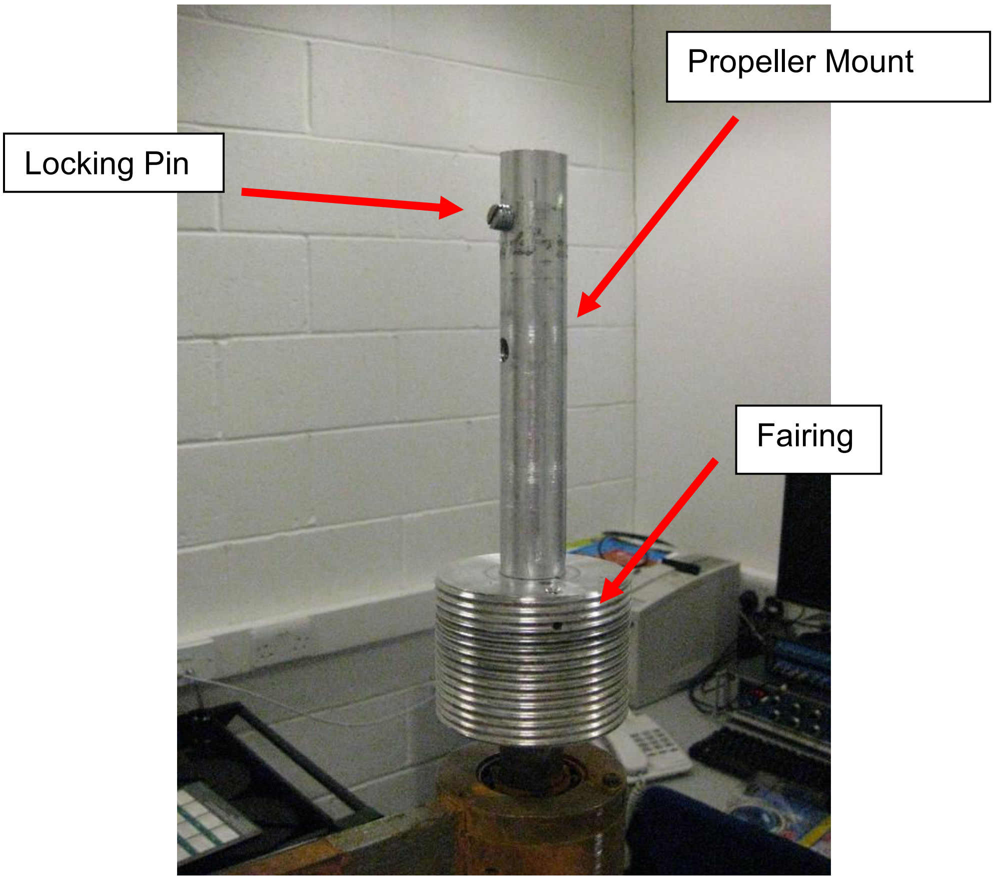


Figure 16 - Test Rig Prop Mount

The propellers all fitted this mount and to fix the propellers on the mount, measurements of their length were taken and holes drilled in positions on the tube that corresponded to the end of each propeller. Only two holes were required, as the fixed propellers both had the same length and the feathering propeller was the largest of all of the propellers. The hole for the feathering propeller was used for both of the folding props, with the washers for the folding propellers being made larger to compensate for the difference in length. An image of the tubing marked and ready for drilling is shown in Figure 17.

Figure 17 – Marked drilling positions

These holes were drilled and tapped for an M10 bolt. The bolts were cut down to be as small as possible (to prevent damage during free-wheeling tests) and were covered in electrical tape during testing to prevent scratch damage to the propellers.

Once these holes had been drilled and tapped, the washers to prevent the fairing damaging the propellers during testing had to be constructed. These were made of high density foam, which was strong, lightweight and did not corrode in water. The measurements of the length of each washer for the types of propeller can be found in Table 3.

Propeller	Washer Length (mm)
Two Blade Folding	66
Three Blade Folding	47
Three Blade Feathering	16
Fixed Blade Propellers	52

Table 4 – Washer Dimensions

An image of the completed washers can be found in Figure 18, with an inset image showing the smaller washer constructed for the feathering propeller (all of the washers are individually annotated to show which propeller they correspond to). An image of the three-bladed fixed propeller mounted on the test rig with its washer in place can be seen in Figure 19.

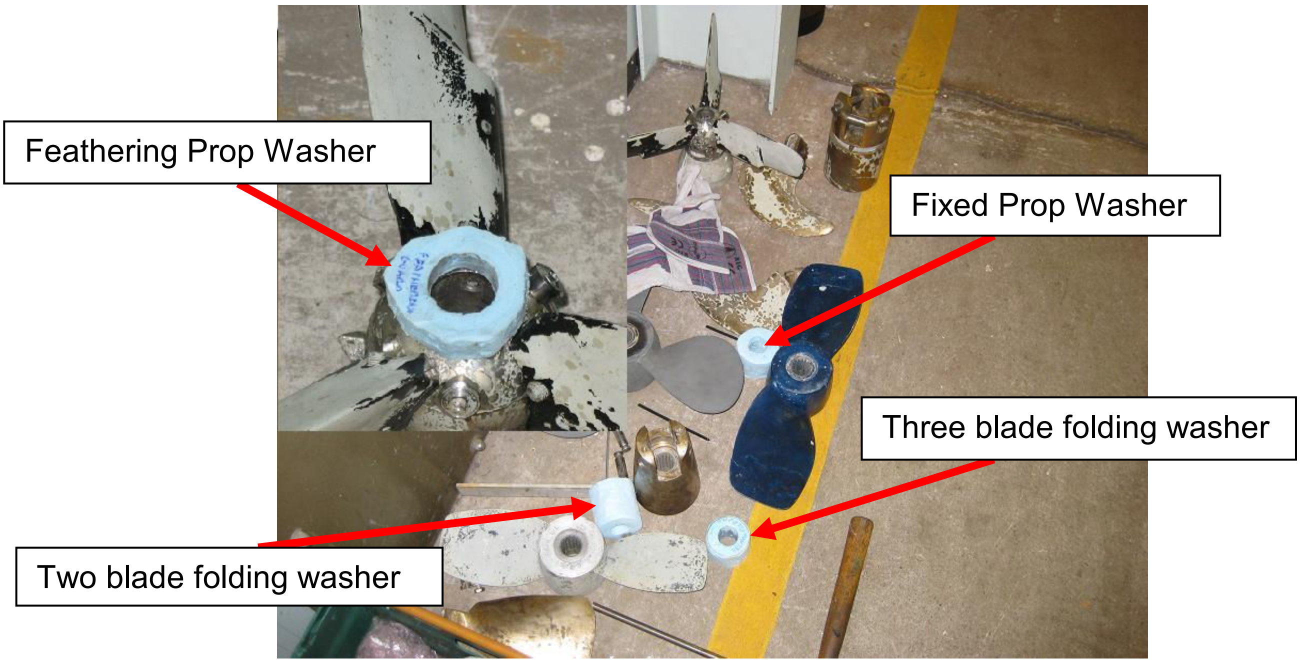


Figure 18 – Washers (Inset – Feathering prop washer)

Figure 19 - Three Bladed Prop with washer

From this image, it is clear that the washer is doing its job – protecting the end of the propeller from the fairing on the aluminium mount. All of the washers did this adequately and none of the propellers suffered any damage during the experiment because of the fairing.

The method of drag measurement used involved the use of strain gauges on the design. Whilst these are used primarily to measure strain, their readings can be altered easily using calibration software in order to give drag as an output. The gauges themselves are very easy to construct, wire up and inexpensive to produce. Given their small size, the gauges could be incorporated anywhere on the design to measure the drag, with the possibility of more than one set of gauges to give several readings in order to produce an average. The strain gauge was the preferred method of measuring the drag because of these factors. Another benefit was that the software used at the towing tank could easily calibrate the gauges to measure drag and the staff had made use of this method in previous tests, so already had experience in the use of strain gauges.

A strain gauge works by detecting the deformation of the object it is attached to using a Wheatstone Bridge. It uses the principal that when an electrical conductor is deformed and reaches the limits of its elasticity without breaking or deforming permanently, its resistance will increase from end to end. This is due to it becoming narrower and longer. If an electrical conductor is compressed and does not buckle, its resistance will decrease from end to end as it is becoming broader and shorter. The resistance change is measured by the Wheatstone Bridge and is related to the strain using the gauge factor, which is defined in Equation 7.

$$GF = \frac{\Delta R / R_G}{\varepsilon} \qquad \ldots (7)$$

Where GF is the gauge factor, ΔR is the change in resistance caused by the strain (Ω) R_G is the resistance of the un-deformed gauge (Ω) and ε is the strain.

This design used was already fitted with all of the necessary instruments to take the measurements of drag from the software at the towing tank. It featured two strain gauges near the top of the support bar which were to be used to measure the drag forces, Figure 20. These were coated in wax to prevent water damage during testing.

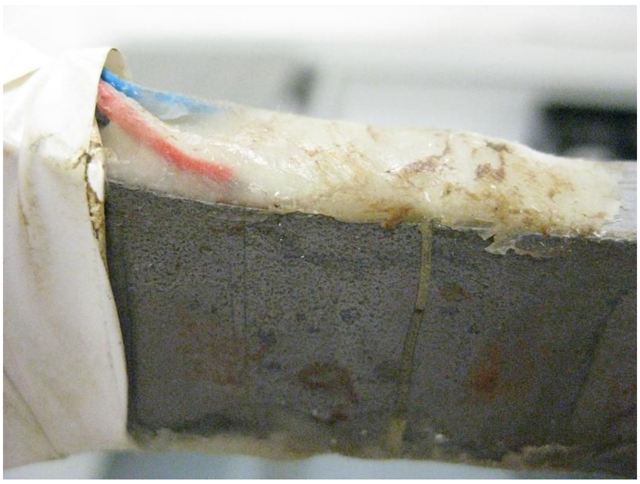


Figure 20 - Strain Gauges

These strain gauges already had the BNC adaptor +/- 10 Volts connection that was required for data collection at the tow tank. This meant that they only had to be checked for the correct voltage pairings across their bridges to establish if they were still working correctly.

As mentioned previously, there were several additions that had to be made to the design to fit the propellers correctly. However, there were also a number of checks that had to be made – the first of these was testing the strain gauges for the correct voltage pairings. A technician qualified to test the gauges performed the tests and the correct voltages (120 volts across the correct pairings and 90 volts across in the incorrect pairings) were measured, which showed that in theory the gauges were working correctly. However, because of the wax masking the actual gauges, only the connection wires in the BNC adaptor could be tested. This only gave an indication that the gauges were in correct working order, as the gauges themselves could not be tested because of the wax coating. The only method that would determine if they were reading correctly would be calibrating the test rig.

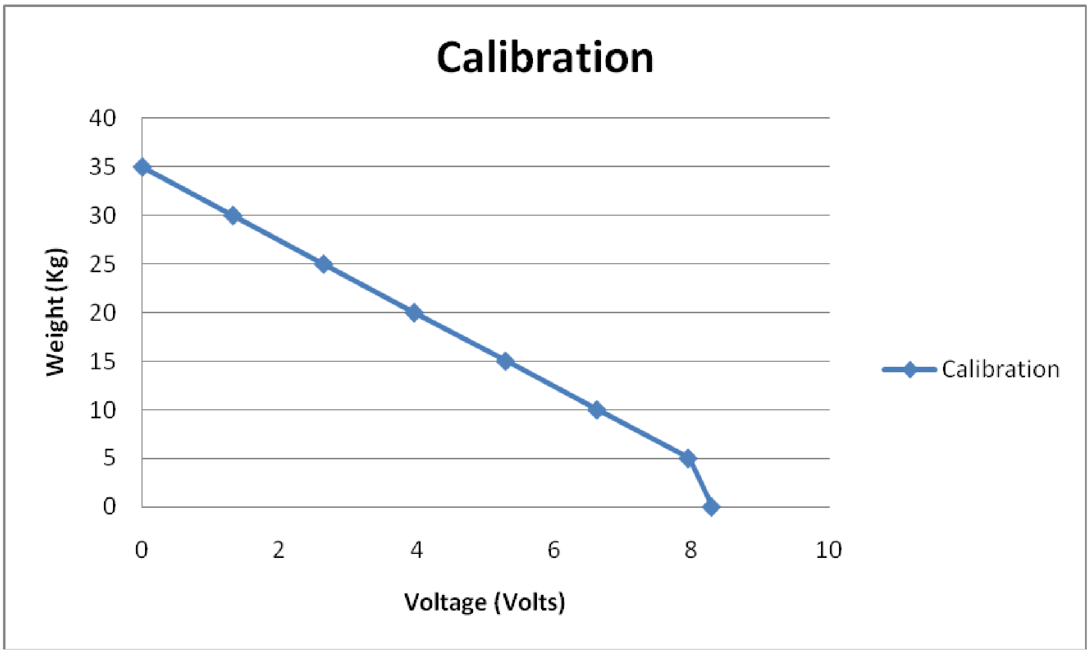
In order to record the results of the drag, the strain gauges had to be calibrated using the software at the towing tank. The software used was called "Spike" and was developed by the CED Company in America. This system reads the electronic output from the strain gauges (through the BNC adaptor and amplifier) and using a correction factor, converts the readings into the unit of drag, the Newton (N). It was decided to calibrate the test rig for a maximum drag of 350N – this was a rough maximum value taken from the results of previous work in the field. To do this, the test rig was mounted horizontally at 0^{o} and seven 5kg certified calibration weights were hung from the end to simulate the 350N of drag, shown in Figure 21.

Figure 21 - Test Rig undergoing calibration

To begin the calibration, all seven of the weights were added and the voltage of the amplifier set to zero volts. After the weights had settled and were not moving, a single 5kg weight was removed at a time, and the voltage for each weight recorded, shown in Table 5. If the calibration had been performed correctly and accurately, the results should be represented straight line graph, shown in Graph 3.

Mass (kg):	35	30	25	20	15	10	5	0
Voltage (Volts):	0	1.32	2.64	3.96	5.29	6.62	7.95	8.29

Table 5 – Initial Calibration Voltages



Graph 3- Calibration Line

From the graph, it can be seen that the calibration is predominantly a straight line. The drop off at the end of the calibration was due to the weight of the cable and mass mount being slightly more than the 0kg stated. However, the graph was intended to be a straight line through the origin – this did not occur because the calibration was done in reverse (i.e. weights were removed rather than added). This was not a problem, as the calibration was all relative and the calibration number would be the same. Once these readings had been taken, it was established that every 5kg weight corresponded to 1.32 Volts. Using this value and the equation for Weight (Equation 8, below) the number of Newton/Volt was calculated by dividing the Weight by the voltage (1.32 Volts). The value of g used in the equation was 9.806m/s^2.

$$W = mg \quad \ldots (8)$$

This gave an initial calibration number of 37.14N/Volt, which was then used in the next calibration to determine the drag output of the gauges. Using the weights for calibration again (this time starting with 0kg rather than 35kg), the calibration factor was checked for accuracy. The results of this calibration can be found below in Table 6.

Mass (kg):	5	10	15	20	25	30	35
Drag (N)	49.322	98.68	148.04	197.35	246.62	295.91	345.63

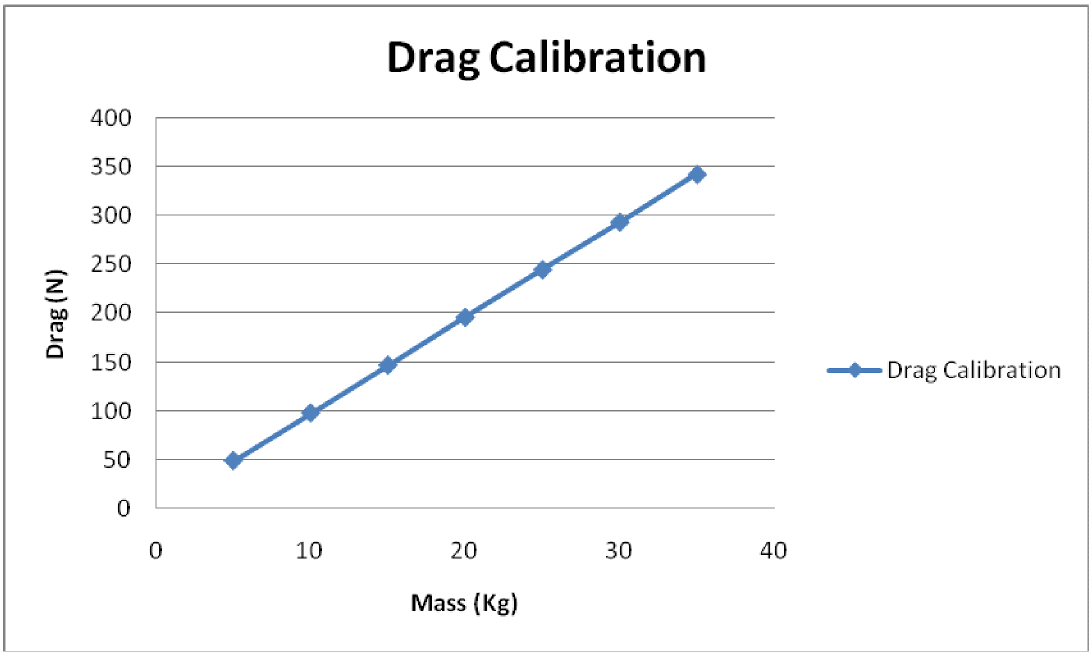
Table 6 – Second Calibration

Using this information and comparing the measured result for 35kg with the actual numerical calculation (using Equation 8). The numerical calculation gave a value of 343.21N for a mass of 35kg. Comparing this to the value given in Table 6 shows a discrepancy of just over 2N. By dividing the numerical value by the measured value, it gave the percentage accuracy of the measurement to be around 99%. However, given the possibility of very high drag measurement, the calibration number had to be changed to increase the accuracy. Multiplying the calibration number used (37.14 N/Volt) by the percentage accuracy gave a new and final calibration number of 36.88 N/Volt. This calibration factor was then used with the software to check the outputs of the software were accurate. The results of this calibration can be found below in Table 7.

Mass (kg):	5	10	15	20	25	30	35
Drag (N)	48.91	97.85	146.91	195.88	244.80	293.71	342.69

Table 7 – Final Calibration Numbers

These values gave an accuracy of 100% to two significant figures and were deemed acceptable to be used for the experimental stages. A graph of this calibration can be found below (Graph 4).



Graph 4 - Final Drag Calibration

From the graph it is clear that the calibration forms a straight line which is the desired shape, as the mass and drag are directly proportional to one another. During the testing, there was no visible evidence of hysteresis on the testing rig and it was deemed safe for testing.

During the calibration it was discovered that the test rig had a very low natural frequency (bumping into the test rig in its mounting caused it to shake for long periods of time). This was initially considered to be a problem, but given the nature of the tests (i.e. there would be no forces acting at 90^{o} to the rig during the experiments) its effect would be negligible. The frequency of the measurements was also determined to be 30Hz, which is half the maximum value of the software.

CHAPTER 4: EXPERIMENTAL RESULTS

The following section contains the results of the experimental stage of this paper. The results for each propeller are discussed in turn and plotted to compare the results of the free-wheeling and locked positions. The propellers are then all compared in two separate graphs of the free-wheeling and locked results to show which propeller had the smallest drag. Finally, the drag coefficients of each propeller for the two positions (free-wheeling and locked) are tabulated and the average values calculated. In total there were 24 experiments performed. These experiments tested the propellers in both the locked and free-wheeling positions through a variety of speeds.

The first three test runs carried out were to establish the drag of the test without any propeller mounted. Using the drag values found at each speed (2, 4 and 6 knots), the drag of each propeller was then calculated by subtracting these values from the total drag force measured on each run. There were no problems during this section of the testing, with the experiments running smoothly.

The next results taken were for the two-bladed fixed propeller in the free-wheeling position. The first two test runs went smoothly, with no problems occurring. During the final test run however, right at the end (when the carriage was slowing to a stop) of the run the propeller spun in reverse, which screwed the aluminium prop mount off of its mounting on the test rig. The propeller and the mount then sank to bottom of the tank. After it was retrieved, the prop mount was screwed back onto the test rig, and using a hammer and a bolt screwed into one of the locking pin holes, the mount was “tapped” to screw it in more securely (it had previously been tightened by hand, which proved extremely difficult). This solution worked as the prop mount did not fall off on any other occasion during the free-wheeling or locked propeller tests. The remaining propellers were all tested for the free-wheeling position and results obtained without any further problems.

The propellers were then tested in the locked position. This proved to be difficult, as the propellers could not be altered in any way to lock them easily. The first option was to try and lock the shaft the aluminium mount was attached to, but this proved very difficult due to rusting of the joints and the stiffness of the spring. Another option that was tried was using a small metal bracket attached to the main support leg that would block the propellers from spinning. Unfortunately, during the alteration of the metal bracket, it snapped – this was probably a good thing however; as if it had snapped during testing it would have damaged the propellers. Figure 22 displays the next solution, which involved wrapping a cable tie around the blades of the first propeller (the two bladed fixed) and attaching them to the main support leg. This solution worked for the two & four knot tests, but the cable tie was snapped by the force of the propeller rotating at the 6 knot speed. The final method used to fix the blades was simply tying string around the blades & leg of the test rig as tightly as possible, which is shown in Figure 23. This solution proved the most successful with all of the remaining test runs being accomplished without the string breaking (apart from the three bladed fixed at 6 knots – the string snapped approximately two seconds into the test). This did increase the time taken to mount each of the propellers (tying the string tightly took several minutes for each blade), but since the two folding propellers had rotated during the free-wheeling tests, there were only three propellers tested in the locked position – the two fixed propellers and the feathering Kiwi Prop.

Figure 22 - Cable Tied Propeller

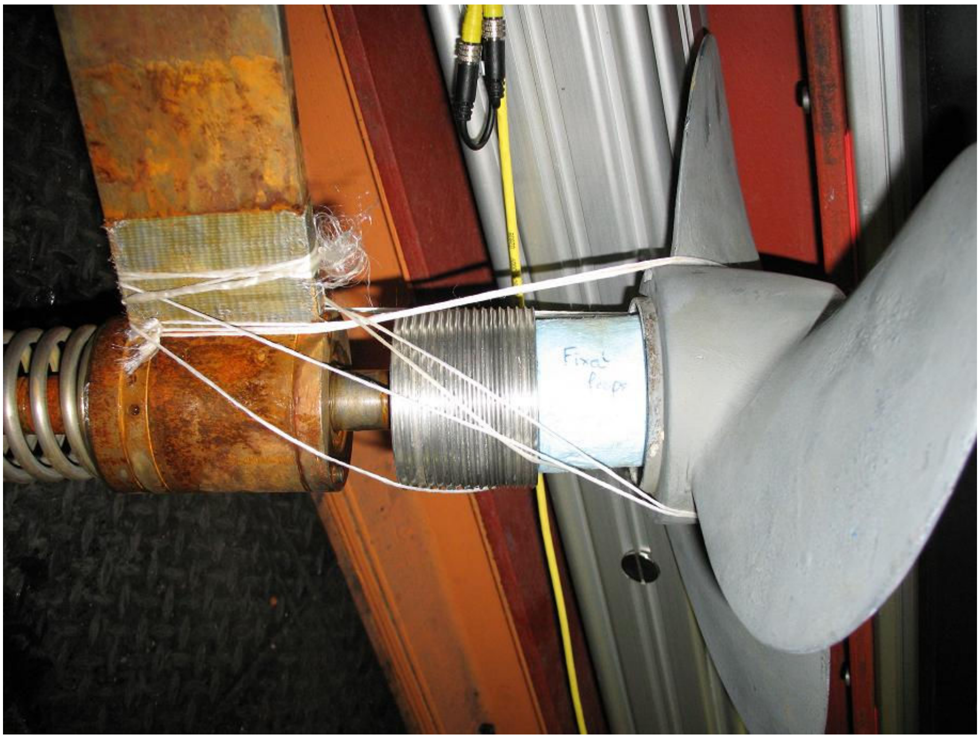


Figure 23 - Three bladed propeller locked using tightly bound string

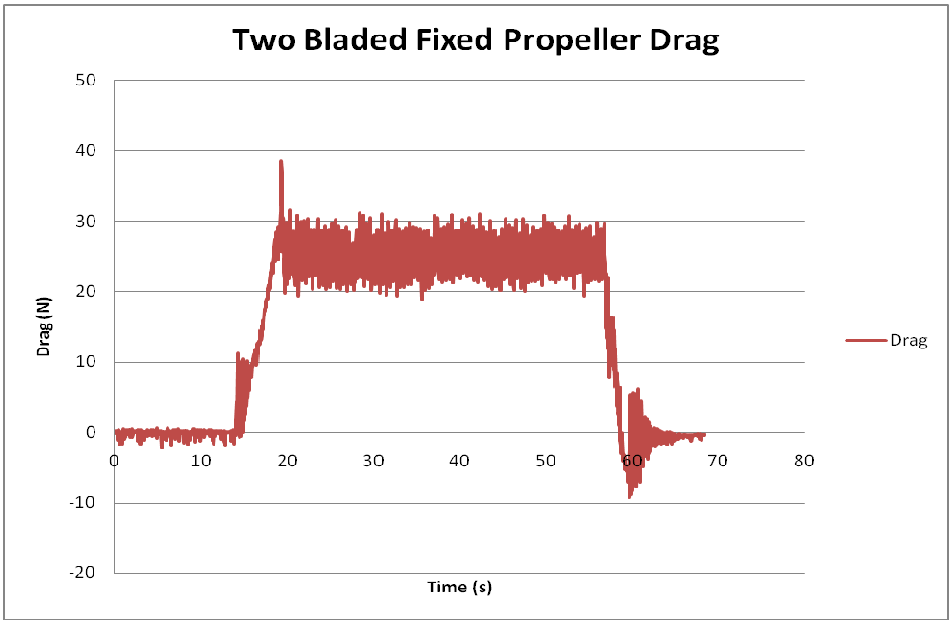
Unfortunately, the testing carriage malfunctioned during the locked propeller tests and eventually stopped working. The brakes on the carriage were slipping during the tests which could have caused the carriage to stop suddenly and damage the equipment and operator severely. Figure 25 shows the process of fixing this problem, which caused a significant delay, as one of the technicians had to go under the carriage in a small dinghy to fix the brakes and check the motor.

Figure 24 - Technicians fixing the brakes and motor

Once this problem had been fixed the remaining test runs were carried out with no further problems.

Sample Spike Result

As mentioned previously in the paper, the results were taken with a frequency of 30Hz – i.e. there were thirty results taken every second to measure the drag. In some of the results, this gave a plot of well over 2000 points. The Spike software used calculated the average value of the drag using a "Zero region" and "Measuring Region". These were defined using selection lines on the graph in Spike and these sections were averaged to give a value of the drag for each experiment. An example Spike output graph can be seen in Graph 5.



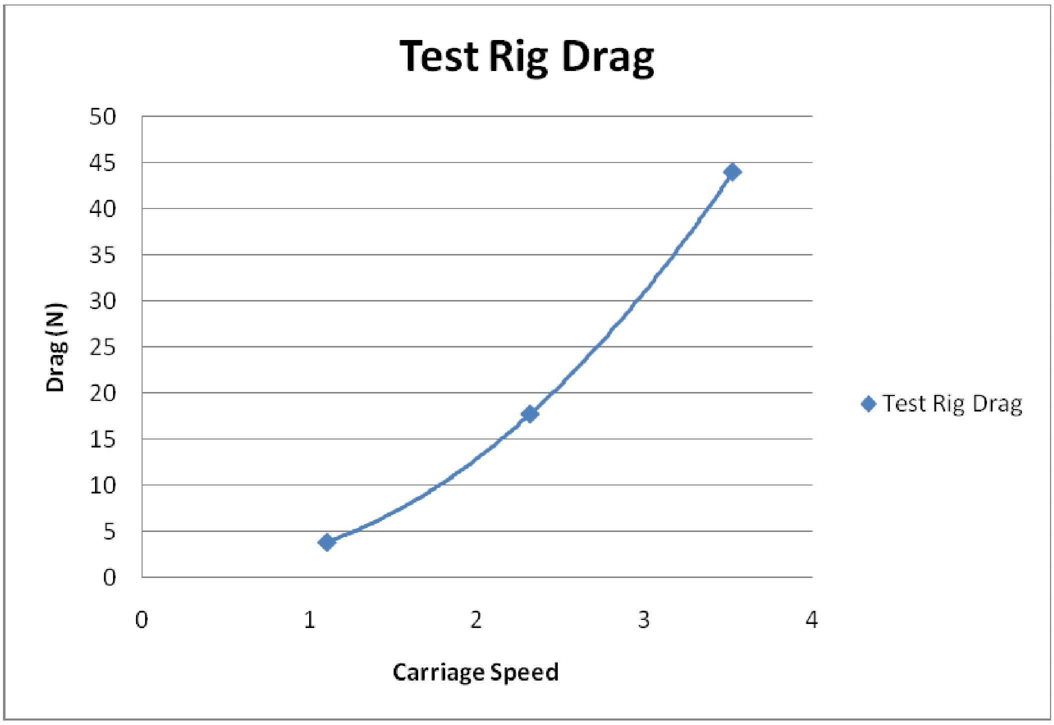
Graph 5 - Spike Output Graph

Test Rig Drag

The first three test runs performed were used to record the drag of the testing rig without a propeller attached at the three testing speeds of two, four and six knots. These values were then subtracted from the recorded drag for each of the propellers tested to give the drag of the propeller, rather than the drag of the propeller and test rig. These results can be found in Table 8 and in Graph 4.

Speed (m/s)	Propeller Condition	Drag (N)
1.10	No Prop	3.84
2.31	No Prop	17.74
3.52	No Prop	43.97

Table 8 – Test Rig Drag



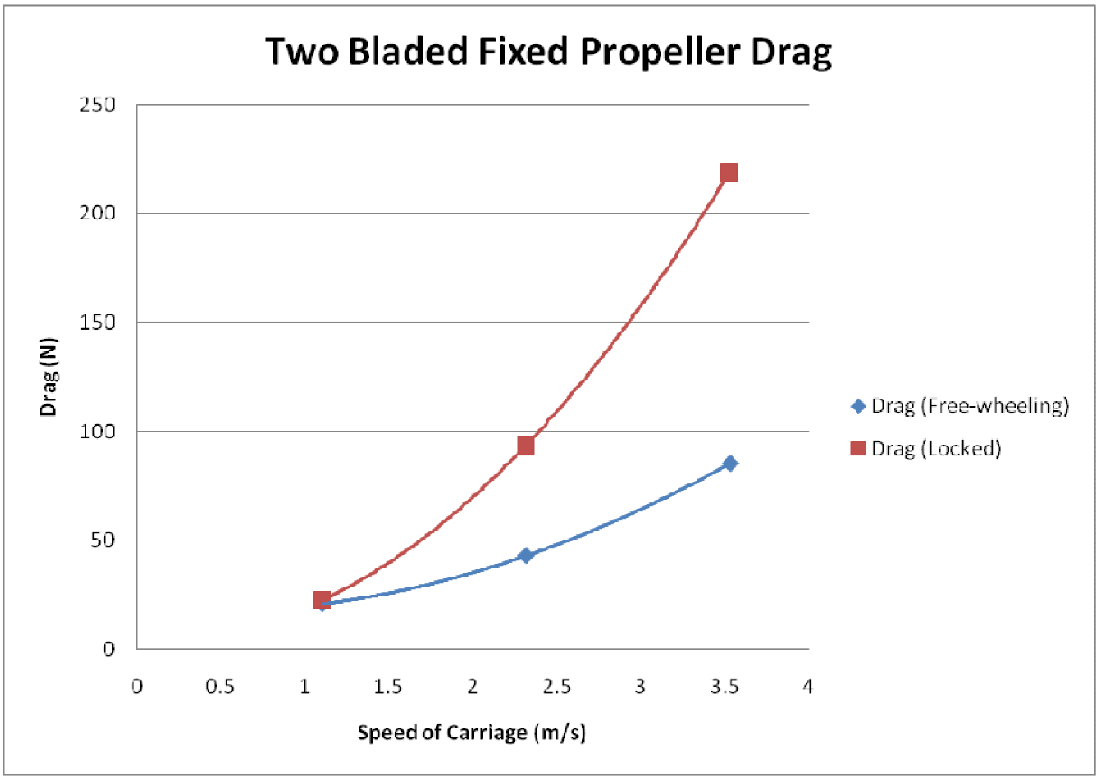
Graph 6 - Test Rig Drag

Two Bladed Fixed Propeller

The following results are for the two bladed fixed propeller in both the free-wheeling and locked positions. The results found can be seen in Table 9, below and Graph 5 for comparison and discussion.

Speed (m/s)	Propeller Condition	Drag (N)
1.10	2 Bladed Fixed Blue Test Prop (Free-wheeling)	21.12
2.31	2 Bladed Fixed Blue Test Prop (Free-wheeling)	43.13
3.53	2 Bladed Fixed Blue Test Prop (Free-wheeling)	85.34
1.10	2 Bladed Fixed Blue Test Prop (Locked)	22.53
2.31	2 Bladed Fixed Blue Test Prop (Locked)	93.61
3.52	2 Bladed Fixed Blue Test Prop (Locked)	218.88

Table 9 – Two Bladed Fixed Results



Graph 7 - Two Bladed Fixed Results

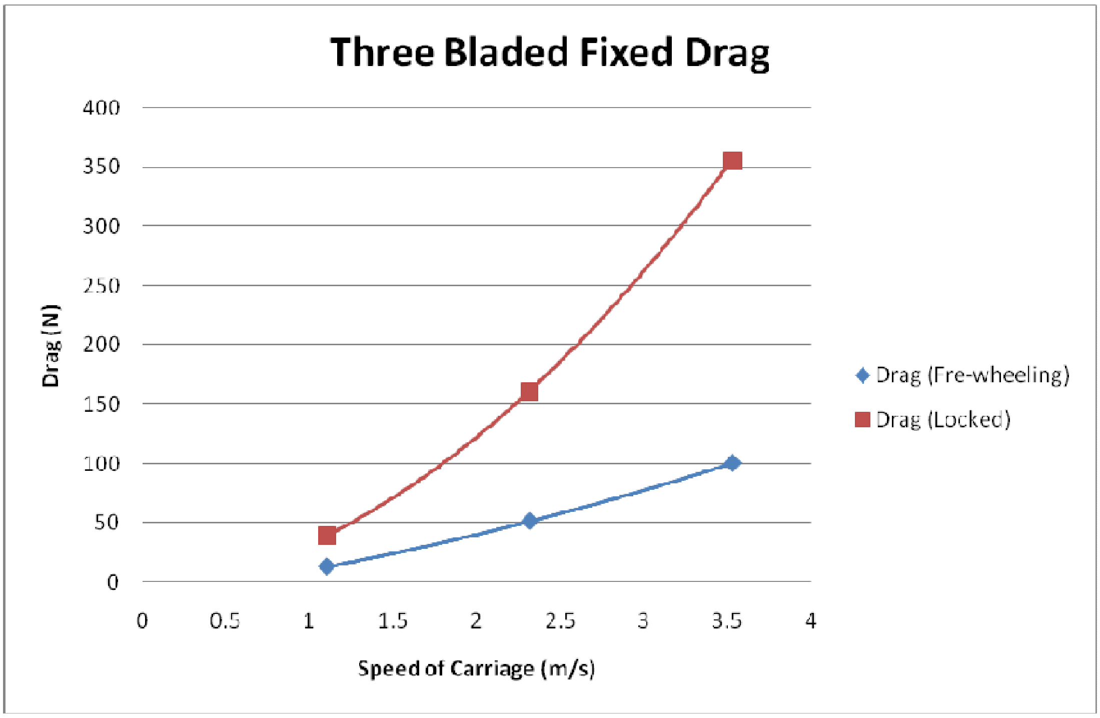
From the graph, it is clear that the free-wheeling position produces the least drag in the case of the two bladed folder. However, the values of drag at the two knot speed are very similar, so at lower speeds having a free-wheeling propeller over a locked one is not that advantageous. The increase of drag at the higher speeds is quite alarming – the drag recorded at six knots in the locked position is just under treble that of the free-wheeling position at the same speed.

Three Bladed Fixed Propeller

The next results obtained were for the three bladed fixed propeller. Given that this type propeller is very popular in the sailing world, it was of high interest to investigate this type. The results obtained can be found in Table 9 and Graph 6, below.

Speed (m/s)	Propeller Condition	Drag (N)
1.10	3 Bladed Fixed (Freewheeling)	13.28
2.31	3 Bladed Fixed (Freewheeling)	51.42
3.52	3 Bladed Fixed (Freewheeling)	100.26
1.10	3 Bladed Fixed (Locked)	39.44
2.31	3 Bladed Fixed (Locked)	160.94
3.52	3 Bladed Fixed (Locked)	355.74

Table 10 – Three Bladed Fixed Results



Graph 8 - Three Bladed Fixed Results

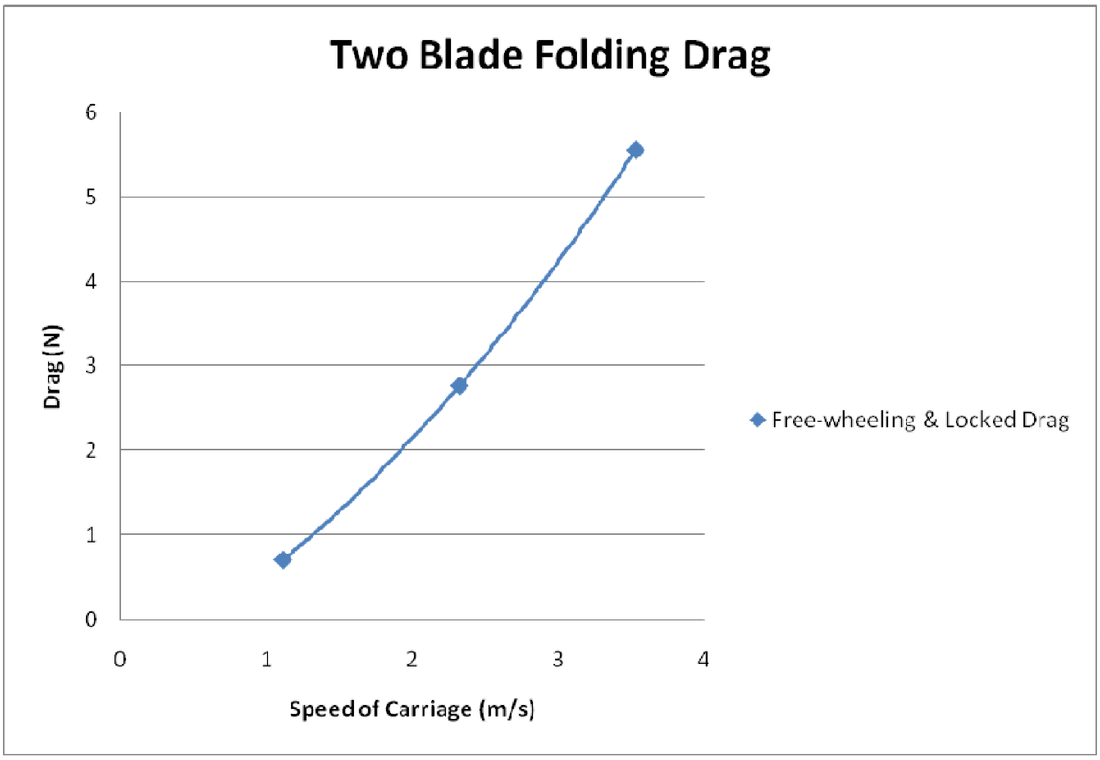
Similarly to the two bladed fixed propeller, it is obvious that the free-wheeling position is the most advantageous in terms of reducing the overall drag of the propeller. The comparison of the two positions in this case yielded extremely interesting results, particularly at the higher velocity values. Looking at the results for the 6 knot (3.52 m/s) test run and comparing them, the difference in drag is staggering. The drag in the case of the locked propeller is just over three and a half times the drag of the same propeller in the free-wheeling position at the same speed. Given the results of this test and that this amount of drag would dramatically reduce the sailing performance of a boat; the popularity of this type of propeller (in terms of drag) is difficult to justify.

Two Bladed Folding Propeller

The final propeller to be tested was the two bladed folding propeller. Similarly to the three-bladed folding prop, it did not rotate during the free-wheeling test runs, so locked propeller data was not required as there was no rotation. The results can be found below in Table 12 and plotted in Graph 9.

Speed (m/s)	Propeller Condition	Drag (N)
1.10	2 Blade Folding	0.71
2.32	2 Blade Folding	2.76
3.53	2 Blade Folding	5.55

Table 11 – Two Bladed Folding Results



Graph 9 - Two Bladed Folding Results

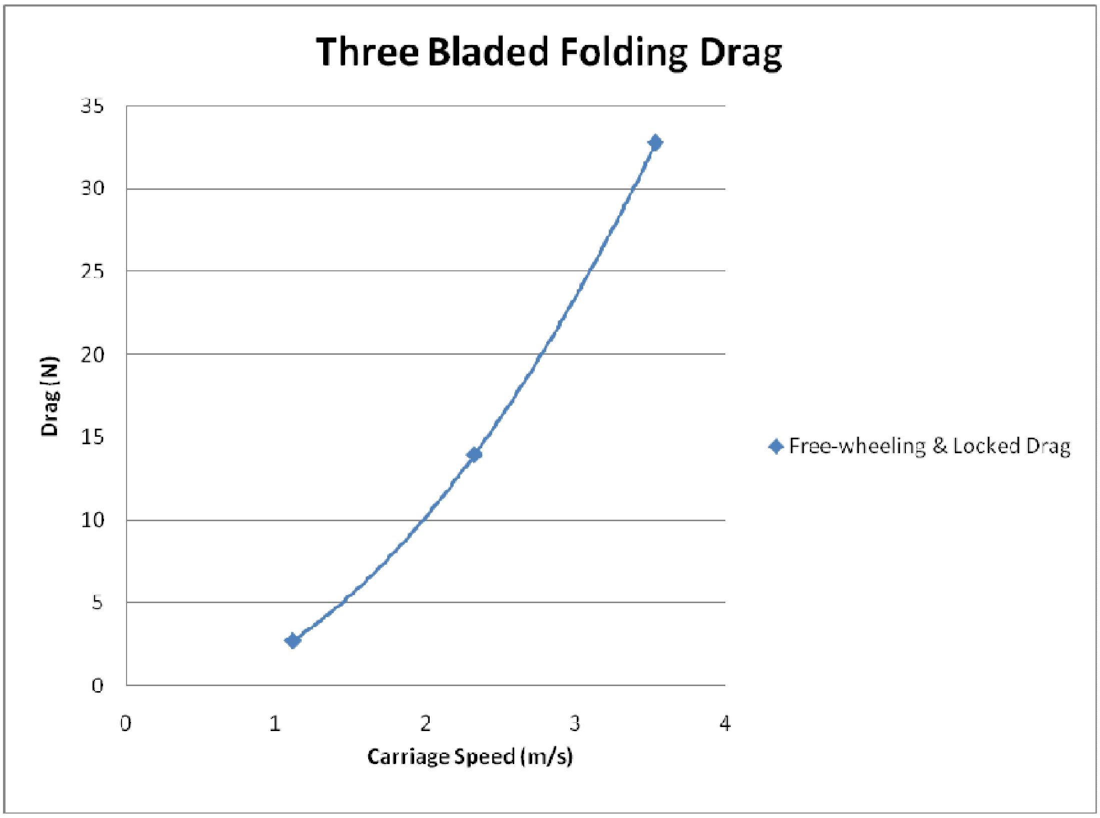
This propeller performed astonishingly well in the tests. Its maximum drag value was only 5N at the 6 knot test speed. This is an extremely low value of drag. The vale taken at 2 knots was less than 1N at 0.714N. It is obvious that the sleek design of the blades and ability of them to fold away entirely behind the hub of the propeller reduces the drag of the propeller considerably.

Three Bladed Folding Propeller

The first of the folding propellers to be tested was the three-bladed version. This propeller was tested in free-wheeling position and did not rotate, so these results were used for both the free-wheeling and locked position. Only one curve was plotted as the results were the exact same for each test. The results recorded can be found in Table 12 and Graph 8.

Speed (m/s)	Propeller Condition	Drag (N)
1.10	3 Blade Folding	2.71
2.32	3 Blade Folding	13.94
3.53	3 Blade Folding	32.76

Table 12 – Three Bladed Folding Propeller



Graph 10 - Three Bladed Folding Results

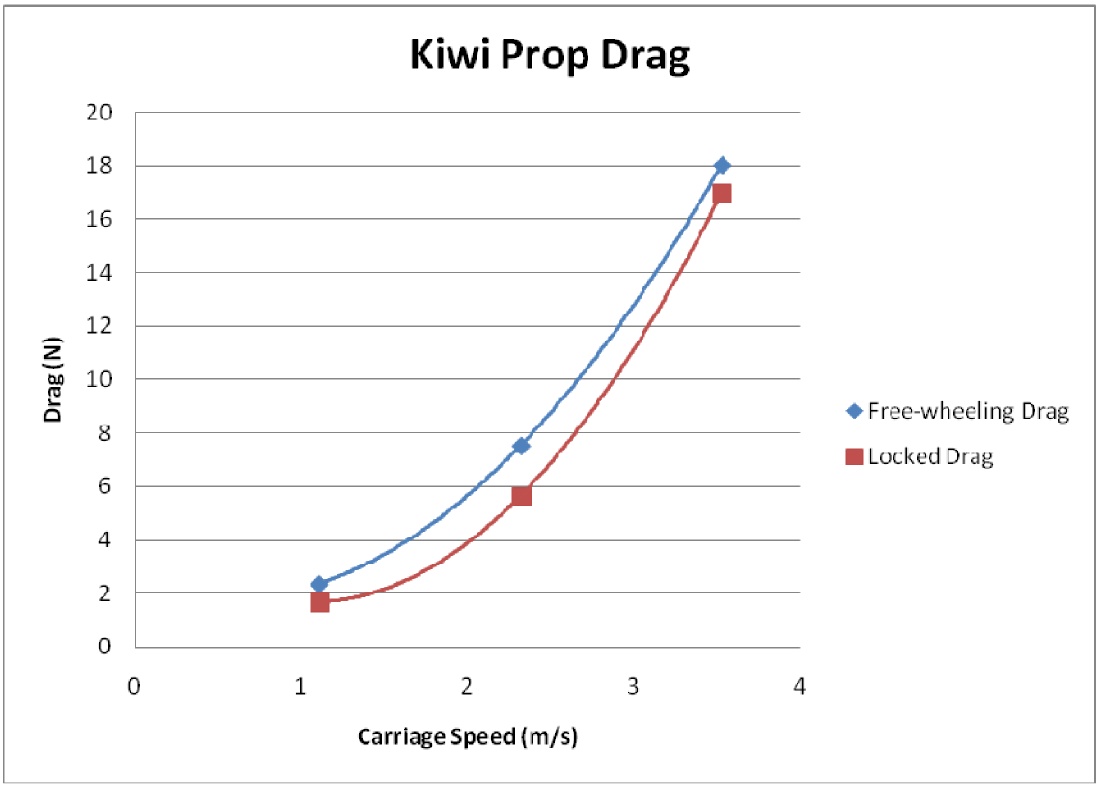
The three bladed folding propeller performed well, with very low values of drag recorded, particularly in comparison to the two fixed propellers. However, its drag was greater than the Kiwi Prop for all of the measured positions, probably due to the position of the propeller blades once folded (the propeller tips remain exposed at around the edges of the hub when folded away, increasing the exposed area compared to the Kiwi Prop).

Kiwi Prop

The next set of results taken were for the feathering Kiwi Prop. These results were of the most interest because a detailed study involving this type of propeller and comparison to other types had never been performed before. These results can be found in Table 10 (below) and Graph 7, overleaf.

Speed (m/s)	Propeller Condition	Drag (N)
1.16	3 Blade Feathering (Free-wheeling)	2.35
2.32	3 Blade Feathering (Free-wheeling)	7.52
3.52	3 Blade Feathering (Free-wheeling)	18.01
1.10	3 Blade Feathering (Locked)	1.66
2.32	3 Blade Feathering (Locked)	5.63
3.52	3 Blade Feathering (Locked)	16.97

Table 13 – Kiwi Prop Results

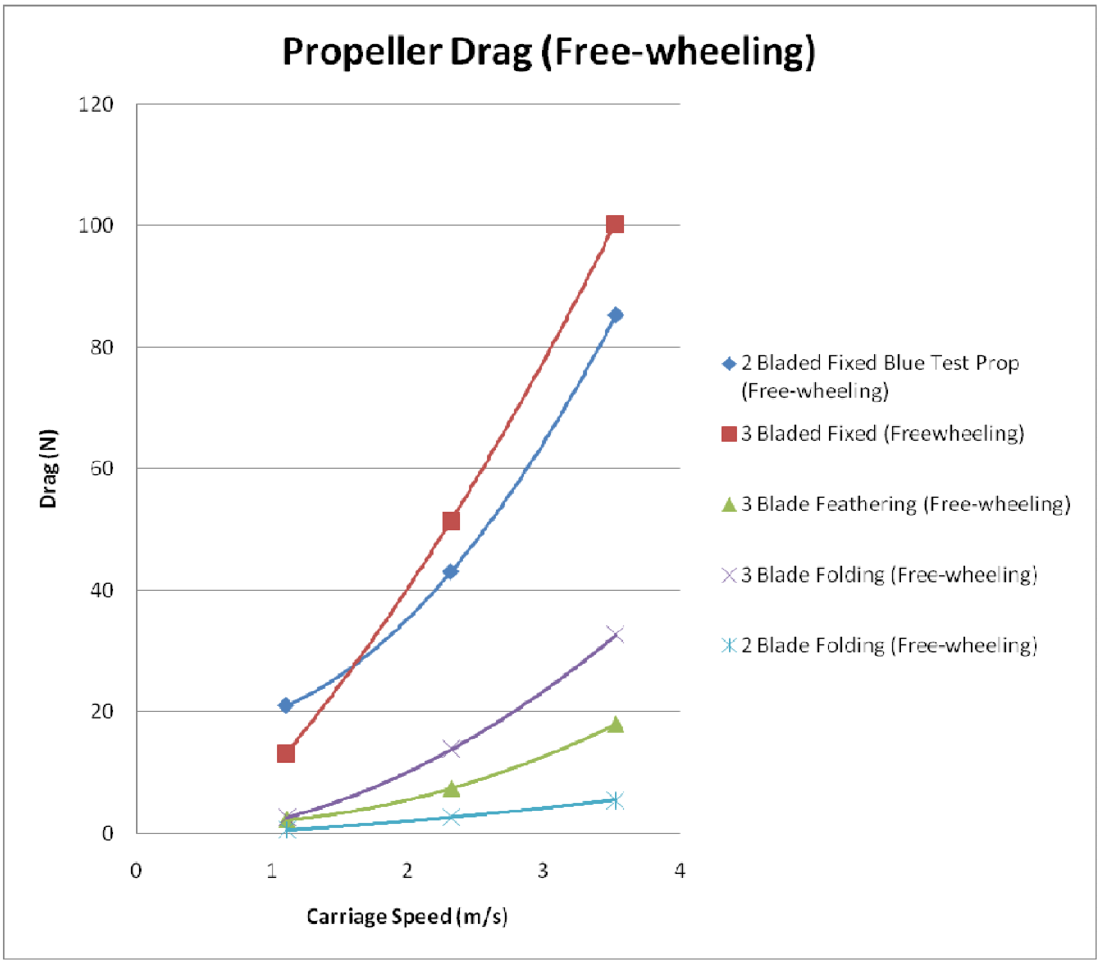


Graph 11 - Kiwi Prop Drag Results

The propeller performed extremely well in both the free-wheeling and locked positions. However, during the free-wheeling test, the blades did not align correctly with the flow, and the propeller rotated slightly during the higher speed tests. This increased the drag slightly in comparison to the locked position. Even in the free-wheeling position, the propeller should not rotate at all, but given that the blades may not align correctly whilst a boat is in open water and sailing, these results are still relevant to the paper.

Comparison of Results

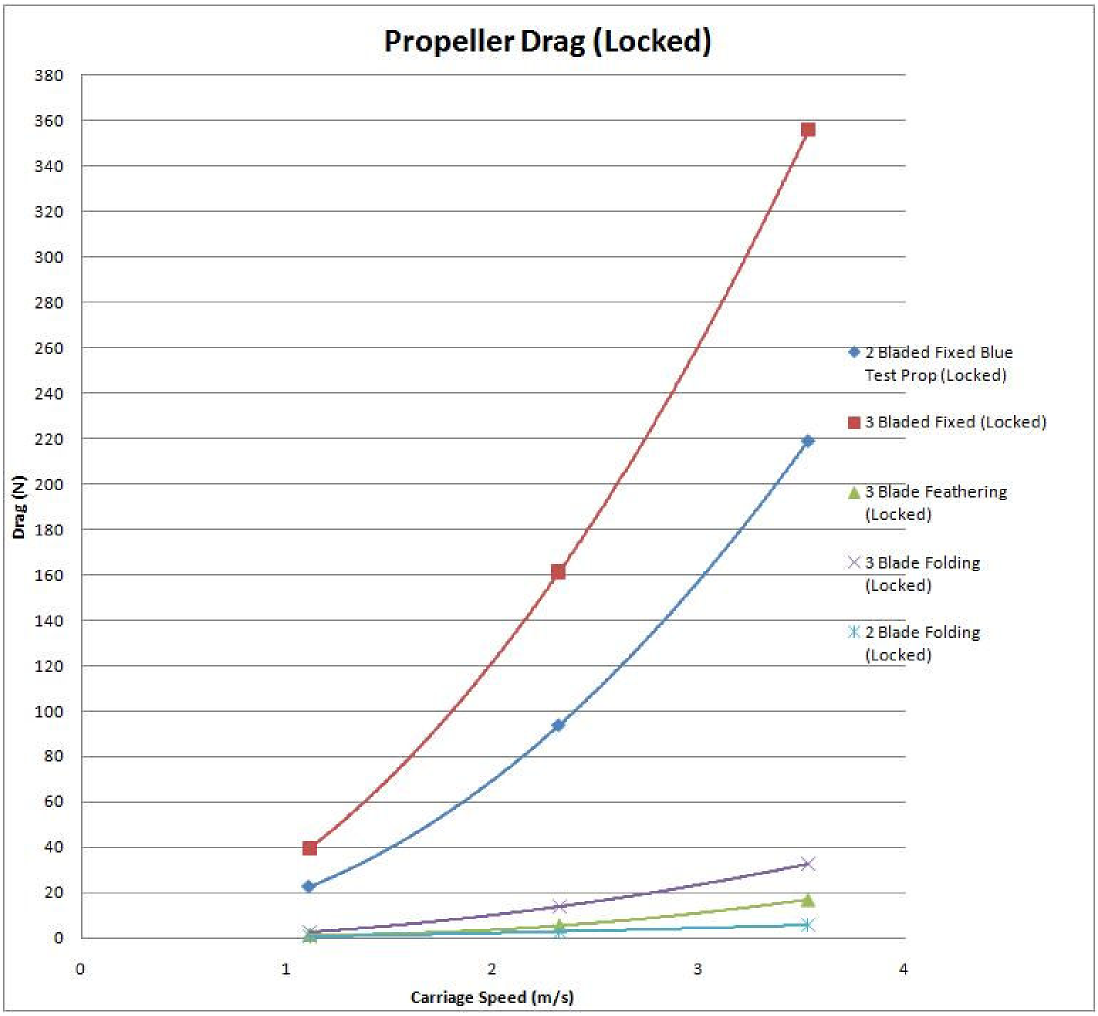
The following section will compare the results of each propeller with the others for both the free-wheeling and locked positions. Each of the graphs will be explained and performance of each of the propellers discussed. The free-wheeling comparison graph can be found below (Graph 10).



Graph 12 - Free-wheeling Comparison

As mentioned previously, the results for each of the propellers showed that the free-wheeling position was the most advantageous to reduce the overall drag of the propellers whilst under sail. Using this comparison graph, it is obvious that the two-bladed folding propeller generates the least drag in this position. Another interesting comparison is between the two fixed blade propellers. The three-bladed fixed has a lower value of drag than the two bladed fixed propeller at the two knot testing speed. This may well be down to an error in the data retrieval, but may also be down to the unpredictability of propellers at such low speeds – given the shape of the three blades on the prop, they may be more hydrodynamic at lower speeds than those of the two bladed propeller, as its blades are "clipped" and not smooth like the three bladed propeller.

The final comparison graph is of the locked position drag measurement. This comparison can be found in Graph 11, below along with a discussion into the results.



Graph 13 - Locked Results

Comparing these results to the free-wheeling test shows a dramatic difference in the drag of each propeller, in particular the drag of the fixed propellers has more than trebled in some cases. These results show that the results of MacKenzie and Forrester [2] are accurate, whilst the results of Warren [1] are questionable. Comparing these results with the predicted curves in Chapter 3, the predictions appear to be higher than the actual measured drag for the fixed propellers – the accuracy is good at the lower speeds, but the difference is much higher at the quicker speeds. In particular, the free-wheeling predicted drag for the three-bladed fixed propeller seems to be reasonably accurate – it is only out by around 10N at the highest velocity.

Also, in both graphs there is clearly a relationship between the three non-fixed blade propellers. This relationship is clearly a power curve looking at the results for each propeller at the given velocities. These curves could easily be extrapolated to predict the drag of these propellers at speeds of up to 10 m/s (around 20 knots) which (theoretically) some yachts can travel at. The main results of this investigation are as follows:

- The three non-fixed blade propellers provide superior performance when compared to the fixed blade propellers.
- The predicted values of drag from the C_d values give higher values for drag than the experimental data recorded which shows the C_d estimates may well be inaccurate for more modern propellers.
- There is a constant difference between the three non-fixed propellers, which is related through a power law.
- Unfortunately, the power law relationship was not clearly defined at the low velocity measurements and a relationship between the drag and the area could not be obtained using these results.

Drag Coefficient Calculation

The results for both the free-wheeling and locked propeller drag were used to calculate the drag coefficient for the propellers at each speed and an average value was taken. Using the rearranged drag equation (Equation 2) and the drag forces, the following values for the drag coefficients were found for the free-wheeling and locked positions. These are displayed in Tables 14 and 15. These results were then compared to the values stated in Lars and Eliasson [12].

Propeller	Velocity	Drag Coefficient	Average
2 Blade Fixed	1.10	0.94	
2 Blade Fixed	2.31	0.44	0.58
2 Blade Fixed	3.53	0.37	
3 Blade Fixed	1.10	0.36	
3 Blade Fixed	2.31	0.32	0.31
3 Blade Fixed	3.52	0.27	
2 Blade Folding	1.10	0.23	
2 Blade Folding	2.32	0.21	0.21
2 Blade Folding	3.53	0.18	
3 Blade Folding	1.10	0.47	
3 Blade Folding	2.32	0.55	0.53
3 Blade Folding	3.53	0.56	
3 Blade Feathering	1.10	0.17	
3 Blade Feathering	2.32	0.12	0.14
3 Blade Feathering	3.52	0.12	

Table 14 – Free-wheeling Propeller Drag Coefficients

Comparing these results to those of Lars and Eliasson [12] show that their estimates appear to be accurate for a fixed blade propeller whilst free-wheeling (C_d = 0.3). They do appear to be inaccurate when comparing to a folding propeller – the drag coefficient here appears to be much higher than the one they state. However, given the very rough nature in which the areas of the propellers were measured, this inaccuracy can be put down to human error, rather than problems with the experiment.

Propeller	Velocity	Drag Coefficient	Average
2 Blade Fixed	1.10	1.01	
2 Blade Fixed	2.31	0.95	0.97
2 Blade Fixed	3.52	0.96	
3 Blade Fixed	1.10	1.08	
3 Blade Fixed	2.31	1.00	1.01
3 Blade Fixed	3.52	0.95	
2 Blade Folding	1.10	0.23	
2 Blade Folding	2.32	0.21	0.21
2 Blade Folding	3.53	0.18	
3 Blade Folding	1.10	0.47	
3 Blade Folding	2.32	0.55	0.53
3 Blade Folding	3.53	0.56	
3 Blade Feathering	1.10	0.12	
3 Blade Feathering	2.32	0.09	0.11
3 Blade Feathering	3.52	0.12	

Table 15 – Locked Drag Coefficient Results

The drag coefficients here (particularly those of the fixed propellers) tend to be similar to the values stated previously in this paper. However, they are slightly lower than the recommended values given by Lars and Eliasson [12], which would suggest that propellers are becoming sleeker and more aerodynamic since the book was published and that revised numbers for each propeller type would benefit the industry as a whole.

Accuracy of Results

The results as a whole were generally deemed to be robust and accurate. However, there were some inaccuracies that must be taken into account when considering the results. The propellers were mounted on an aluminium tube, which is a virtually frictionless surface, providing very little (if any) resistance torque to the rotation of the propellers during the free-wheeling tests. When the propellers are mounted on a sail-drive on an actual yacht/sailboat they would be part of a geared system that would provide a resistance torque when in the free-wheeling position. The rotational speed of each propeller would thus be decreased, reducing its hydrodynamic properties and increasing the overall drag.

The testing rig was also not an ideal representation of a sail drive configuration. Most, if not all sail-drives are shaped to make them more hydrodynamic and to reduce the turbulent flow around the front edge, which in turn reduces the drag effect of the propellers as the flow is laminar around the sail-drive for longer. This reduces the speed and turbulent nature of the water flowing over the blades. Given these inaccuracies, it is impossible to give an indication as to what propeller is best based purely on the information given in this paper, although the best propeller in terms of overall performance given its characteristics is alluded to in Chapter 6.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

The purpose of this thesis was to experimentally measure the drag of a selection of sail boat propellers. The experiments were carried out using a design modelled on a sail drive configuration with the drag being measured using strain gauges. The results were subject to testing in a tow tank which was used because it was a controlled environment where there were no testing parameters out with the control of the experiment. The results of the thesis characterised the drag for the five propellers over a range of velocities (2, 4 and 6 knots) and in two positions – free-wheeling and locked. From these results, it is obvious that the more modern propellers (folding and feathering) outperform the older, fixed propellers considerably. The modern propellers perform just as well when in the locked position compared to the free-wheeling position – this is down to their sleek design and high resistance to rotation when folded/feathered. The modern propellers also demonstrated a constant ratio of difference in drag across the three measured values of velocity – this shows that there is a power law relating all three curves. The best performing propeller was the feathering Kiwi Prop, given that its drag was lower than the three-bladed fixed propeller, whilst having a much higher blade area when the blades are deployed in comparison to the two-bladed folding propeller which increases the available thrust when driving the boat/yacht.

As previously mentioned, there are many experimental points that were not covered in this investigation and there are several improvements/suggestions for further work that can be made. One example is using an actual Volvo Penta Sail Drive for the propeller mount to provide a more advanced and accurate propeller mount. Other improvements would be to construct a fairing for the test rig to reduce the effect of its overall drag on the results and also to reduce the displacement of the water around its blunt face. The experiments could also be changed to include a variation of the angle of the propeller to the horizontal, simulating a shaft drive system. This is an improvement that would provide more results for comparison which could then lead to a recommended propeller choice for different mounting angles. Further work could also introduce a propulsion model where the propellers are spun at varying speeds to provide performance data which could then lead to a much more informed suggestion for a propeller based on its drag under sail, mounting angle and performance. The Centre for Marine Hydrodynamics has a wave generator fitted to the tow tank – if future testing was to be carried out with the boating season, this facility could be used to created "choppy" sea conditions to help further add to the results of the tests. The developers of the Kiwi Prop are also designing and testing their latest design, which incorporates both folding and feathering blades. This is known as the SDC prop (see Appendix 1 for more details on this type) and could be investigated in another study to keep the up to date with the latest propeller designs.

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APPENDICES

APPENDIX ONE: SDC PROPELLER INFORMATION

The developers of the Kiwi Prop™ have also been working on a new type of propeller, which combines the advantages of both folding and feathering propellers. This propeller has been developed by Sail Drive Composites Propellers (SDC) Ltd in New Zealand. The initial design is a two-bladed folder/feathering propeller, built for sail drives that operate at less than 40 horsepower (examples of which are the smaller Volvo, Bukh and Yanmar sail drives). The following review of the propeller is based on information taken from the SDC website *www.sdcprops.co.nz*. The website states that the three over-riding functions required of a propeller to be: *"Motoring ahead at the highest possible speed at both engine cruise rpm and full throttle as can be obtained from a fixed blade propeller, reversing with the same utility as a fixed blade propeller and reducing the drag to a minimum when sailing both on and off the wind."*

There are many benefits of the design of the SDC propeller, firstly its entirely composite construction which eliminates corrosion and marine growth on the propeller blades and hub. The shape of each of the blades is ogival in nature, which has been optimised for motoring and reversing. The prop also provides extremely low drag whilst under sail, it sheds any weed and ropes when sailing and is extremely lightweight (normally under 3kg, with ~1kg of net buoyancy). This propeller marks an exciting development in the world of sailing and yachting, as it couples the advantages of both the folding and feathering propellers to produce an extremely low drag propeller, which will no-doubt out perform both sleek folding and sleep feathering propellers in terms of drag whilst under sail. Similarly to the Kiwi Prop™ the SDC propeller makes use of the Nylon composite Zytel in the construction of its blade, which provides an extremely strong construction. This construction also means that the blade will be "sacrificed" when it strikes an object. Given that the blade tip is predominantly the first area of a propeller to be hit, the composite construction means that the blade will snap off, which would hopefully prevent any damage to the propeller boss and the sail drive unit. The developers believe: *"…it is* *better to loose an easily replaceable blade costing ~ $100 than a whole propeller or drive train when hitting the ground or a floating log or moor chain. This can be very expensive in a sail drive installation where the whole leg is at risk."* Two images of this type of propeller, one installed on a sail drive whilst folded and the other showing the blades open in its propulsion position can be found overleaf in Figures 8 & 9.

Figure 25 - SDC Prop Folded & Feathered away in sail position

Figure 26 - SDC Prop with blades open

Given the unique design configuration of this propeller, and its attributes, it is a very exciting development in the world of sailing. Given that it provides the sleekness and practicality of a feathering prop and a folding prop in one, it is sure to be a very popular propeller amongst the sailing community. One downside to the prop is the lack of any exact experimental data (the type is still undergoing beta testing on several boats in New Zealand with positive results shown to this date) to show its performance in comparison to other propeller types. However, given that this propeller is still in the early stages of development, these results will not doubt be available given time to show whether or not it performs better than conventional feathering and folding props.