Hydrofoil Sailing

Summary Report

FUTURE FOILS

THE HIGH SPEED FUTURE OF SAILING

THE UNIVERSITY OF
WARWICK

PROJECT SUMMARY

This report covers the work of seven masters of engineering students from the engineering disciplines of Mechanical, Manufacturing, Electronics and EDAT.
The purpose of the project is to establish a hypothetical business in order to investigate the commercial viability of hydrofoils in dinghy sailing.

The initiation of this Hydrofoil Sailing project follows the successful completion of a third year engineering project investigating the application of hydrofoils in surfing.

Sailing is a sport enjoyed by many people in the UK, with many active clubs in coastal and inland regions. People of many ages enjoy dingy sailing from young children to pensioners. The variety of boats sailed is very large and an opportunity for hydrofoil sailing was identified. Although a hydrofoil sailing dingy will not appeal to all sailors, the younger sailor is always interested in exciting and high performance developments.

The report has been divided into three sections – Summary, Technical, and Management and Finance. Although the Summary Report constitutes the bulk of this report, the Technical section contains much detailed information into the mathematics and details of topics covered within the Summary report. However, due to the importance placed on Background Theory to Sailing, this section has been placed within the Summary Report, and not the Technical.

The first stage of the project was Hull design. A new hull was built instead of retrofitting an existing one, providing a design more applicable to the purpose, with strong load points at hydrofoil attachment. Many hull shapes and manufacturing methods were considered. For commercial viability it was decided to build a hull that was not dissimilar in shape to a Laser sailing hull, ensuring a familiar shape that would appeal to sailors. Glass fibre with polyester resin and a honeycomb core was chosen to manufacture the hull, using a purpose built wooden frame.

By use of a computer programme called *Hanley Innovations: Visual Foil*, foils with a trailing edge flap were designed to give optimum variable lift. A trailing edge flap was preferred to adjusting the whole foil to avoid the unwanted scenario of a single hinge supporting the entire weight of the boat. The foils were manufactured using glass fibre with polyester in plaster moulds. This ensured the precise shape of the foil was retained and an ultra-smooth finish was provided – imperative for the aerodynamics of the foils and hence efficiency of lift generation.

A range of options existed for control system design including an original concept using air holes to separate the flow over the foil. The options were investigated and a final design emerged, consisting of trailing edge flaps controlled by a trailing wand.

The electronics aspect of the project was concerned with data collection and processing. A number of methods were considered for data collection including a wireless system but the lower cost option of a storage datalogger was chosen. The performance of the boat was to be measured using sensors placed around the boat which were developed to measure boat speed, apparent wind speed, apparent wind direction and height above water. A microcontroller datalogger design was produced and a program developed and tested ready for system installation.

The different aspects of the project were brought together to produce a final design.

Issues involving the management of the project were broken down into six categories: Human resource management, Communication, Budget, Material resources, Goodwill and Time and progress.

Due to time constraints the boat has not yet been tested, however upon completion in the near future, it will be tested at Draycote Water, and the necessary data will be collected for use by future groups.

At the end of the report it is proposed that in the following two years the project will progress to achieve our long-term objective of designing a mass-produced, commercially viable, hydrofoil sailing product.

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1 INTRODUCTION

The long-term vision of the Future Foils project is to design and build a commercially viable hydrofoil dinghy sailing boat.

This is the pilot year of a project that has the potential to run for a further three years. To this end, the aim for the project this year is to design and build a prototype boat to introduce the concept.

Dinghy sailing is a worldwide popular sport enjoyed by people of all ages, backgrounds and skill levels. For many of these people, enjoyment increases with speed. One extremely effective way of increasing the speed of a sailing dinghy is to incorporate hydrofoils.

Whilst the project group recognises that previous attempts at designing hydrofoiling dinghies have been successful they have generally been one-off prototypes built by enthusiasts. An important component of the Future Foils project is the commercial viability of the finished product.

The project needs to function as a hypothetical enterprise in order to assess the business prospects and to introduce an element of reality, representing a sailing product that competes in an existing market. Hence the team has taken the name Future Foils as a company identity.

The design and manufacture of a prototype has been broken into four constituent parts; the hull, hydrofoils, control system and electronic testing equipment. The hydrofoil design, control system and electronics system looked more closely at innovation, and new concept ideas, and the hull was the opportunity to develop various manufacturing techniques.

1.1 Project Objectives

In order to satisfy the aim, the project has been broken down into fundamental objectives. These objectives follow a natural progression through the design and build and evaluation stages of the project.

The project objectives for this year provide a starting point for future years by:

- Researching and evaluating theoretical background
- Investigating possible arrangements (foils, control system etc.)
- Investigating materials and manufacturing processes for prototype development.
- Addressing issues of commercial viability
- Producing a working prototype
- Providing performance data through the use of an electronic testing and data-logging device.

1.2 Background to Sailing

A dinghy is a small, low cost and typically low maintenance sailing boat that can be sailed by one or two people. Their size and agility make it possible to sail on small bodies of water, including lakes, estuaries and wide rivers.

The aim of every sailor, both recreational and competitive is to maximise the potential of the boat. Different classes of boat offer different styles of sailing from course sailing and racing to leisure and teaching. Future foils aims to approach the niche market interested solely in speed racing.

From an engineering perspective, it is possible to categorise watercraft into three main groups based on the significant fluid mechanism by which they interact with the body of water. These categories are:

- Displacement hulls
- Planing hulls
- Hydrofoil boat.

These groups also represent a basic chronological evaluation of watercraft, and the development throughout sailing history. It is important to note that many boats incorporate all three methods of travelling through water, where as others will use only one.

1.3 Displacement Boats

Perhaps the simplest and most widely used form of boat, the displacement hull works on the principle of buoyancy through displacement. That is, the volume of water displaced by the hull must have mass equal to the total mass of the boat in order for it to remain on the free surface of the water – 'afloat'.

Displacement hulls are designed in such a way that the hull and lower section of the boat displaces most of the water, leaving the top half of the boat, and the deck dry above the free surface. When a hull is pushed through the water while speeds are low the forward motion of the hull through the water causes in the first instance water to be pushed aside by the bow, resulting in a system of waves being formed along the length of the boat. The length between one crest and another of these waves is directly proportional to the speed at which the boat is being propelled through the water [Pierson and Leshnover].

The typically large wetted area of a displacement hull means that they are subject to significant skin friction drag, often magnified by the fact that the low speed of the boat results in a greater likelihood of laminar flow.

To increase roll stability, displacement hulls are often broad and bulbous in their design. This typical shape gives the hull a large frontal area around which the approaching water must flow. In order for the boat to pass through the water, it must displace water to the sides and underneath of the hull, and in doing so change its velocity and hence its momentum.

As a displacement hull remains on surface of a body of water, it is subject to free surface drag mechanisms such as wave drag generated in the wake of the moving boat, and small surface random-directional waves.

1.4 Planing Boats

Most planing boats are adequately buoyant at rest, but unlike pure displacement boats, the hull is shaped such that as the speed of the boat increases, water is pushed under the hull rather than to the sides, generating dynamic lift. This mechanism means that although skin friction drag has effect at the initial speed of the boat, as it begins to plane, the wetted area is greatly reduced enabling high speeds.

The hydrostatic principles, which supported the boat at rest, will provide the lift. The extent to which this hydrostatic lift will assist in producing equilibrium in the vertical sense will depend mainly on the speed, area and shape of the planing surface. The tangential force will depend upon the friction between water and the surface of the planing bottom.

The most significant form of drag, to which all pure planing boats are subject to, is spray resistance, caused by the ejection of water from the free surface by the action of the planing hull passing over the surface. This high velocity jet of water travelling in an opposing direction to the direction of travel represents a hugely inefficient loss of energy from the boat. The problem of this effect is described further later in the project.

Planing can be defined as that stage at which dynamic forces due to the motion of the hull through the water begin to make their influence felt. A desirable feature in a planing hull besides the reduction of wave-making resistance is the reduction of wetted surface of the bottom in contact with the water. This in turn leads to the skin friction being reduced.

1.5 Hydrofoil Boats

Hydrofoils enable a boat to travel much faster by lifting the hull out of the water. As explained above, when a conventional boat moves forward, most of the energy expended goes into moving the water in front of the boat out of the way.

A hydrofoil works in the same way as an aerofoil, producing lift due to flow over the wing surface. However, the foils on a hydrofoil boat are much smaller than the wings on an aeroplane. This is because water has a density 1000 times that of air. The higher density also means that the foils do not have to move as fast as a aeroplane before they generate enough lift to push the boat out of the water.

The increased density of the fluid in which they act, the possibility of cavitation, and the presence of a free surface boundary present a different set of design criteria to the aerofoil, but generation of lift is the same.

A hydrofoil must be controllable in pitch, roll, and yaw modes of stability, see Figure 1.

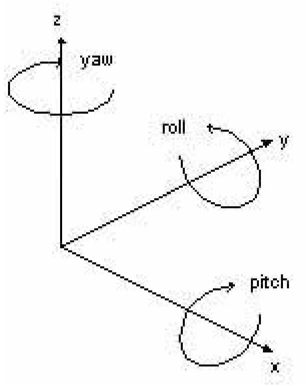


Figure 1 - Diagram Demonstrating Pitch, Roll and Yaw

It is not vital that an aeroplane maintains a constant height as it has a range of about 40,000 feet in which to maintain its altitude. However, a hydrofoil must also maintain a consistent depth and is therefore limited to the length of the struts, which support the boat above the foils.

An altitude control system must therefore be integrated into the manufacture of the foil arrangement, see Chapter 5. There are two alternative methods for this control system. The first is based on controlling the lift coefficient of the submerged foils; this can be controlled by changing the foil incidence or by using trailing edge flaps. The second method is based on varying the immersed area of the foils.

The main advantages of using a boat that runs on hydrofoils are:

- Hydrofoil boats improve boat performance with a reduction in wave drag; high speeds and increased efficiency.
- Hydrofoils cut through waves, resulting in a smoother ride.

- Hydrofoils generate lower wakes. Further, hydrofoil bow and stern positioning can produce negatively interfering wakes, resulting in even lower drag and smaller waves.
- Hydrodynamic noise is minimal since there is less hull-surface interaction.
- Hydrofoil boats are aesthetically exciting.

It is vital to remember that adding hydrofoils to a conventional boat will not produce a satisfactory hydrofoil craft. The essence of successful design lies in treating the hull and foils as an integrated system. It is the hydrodynamics of the foil system, which creates new physical principles when designing the hull.

1.6 Current Commercial Hydrofoil Dinghies

To date, two companies have developed boats that have made it to the commercial stage. Both of these designs have appeared in the past three years, and although available to the general public, they have not yet developed a trend or international market. Both the Windrider Rave (Figure 2) and the Hobie Trifoiler (Figure 3) are trimaran (three-hulled) craft with submerged style foils arranged with one in place of a traditional rudder, and the other two fixed to the two out-rigged hulls.

Figure 2 - Windrider Rave **Figure 3 - Hobie Trifoiler**

Response from the sailing public has differed greatly between the two products. Whilst the RAVE has been hailed as a feat of contemporary sailing design, the Trifoiler has been branded as not being a 'true sailing boat' with limited upwind performance making the boat very limited in terms of maneuverability. This aspect of design has seen the initiation of a racing class appear especially for the Rave, whereas the Trifoiler has very little market.

These two potential competitors to the Future Foils are only available in Canada and the United States, meaning there is no current comparable product readily available in the UK.

More detailed material on both boats can be found at:

Windrider Rave: http://www.windrider.com/wrrave.shtml

Hobie Trifoiler: http://www.hobiecat.com/sailing/models_trifoiler.html

2 BACKGROUND THEORY

The following section provides the theory and arguments behind the preferential use of hydrofoils over planing devices. The work also takes into account the drag a displacement vessel creates. The conclusions drawn are based on a comparison of the lift and drag created by each method, and the ratio produced. Hence valuable theoretical conclusions will be drawn in order to substantiate the reason for undertaking the initial hydrofoil based project.

The following section is technical in content however it represents the fundamental theory and reasoning behind the project, and has consequently been included in this summary section of the report.

Lift and drag calculations for a displacement hull and planing surface can be found in Chapter 9.

2.1 Lift on a Hydrofoil

The resultant force acting on a hydrofoil is calculated by firstly finding the velocity distribution. Secondly calculating the pressure distribution, using the Bernoulli equation. Finally integrating the pressure vector over the object surface to get the resultant force. Using the same method it is possible to obtain the resultant moment.

The two-dimensional irrigational flow, due to the existence of complex potential and its analytical nature, the resultant force and moment can be obtained through the integration of analytical function. This is known as the Joukowski theorem.

The solution begins by analysing the flow over a cylinder where circulation = 0:

For this first step the circle (the two-dimensional projection of the cylinder) is modelled as a pair of singularity flows, a doublet, and hence the model has a net circulation of zero over the total surface of the circle. A uniform flow with velocity V_∞ (free stream velocity) is superimposed over the doublet model of the circle.

Figure 4 describes the superimposition

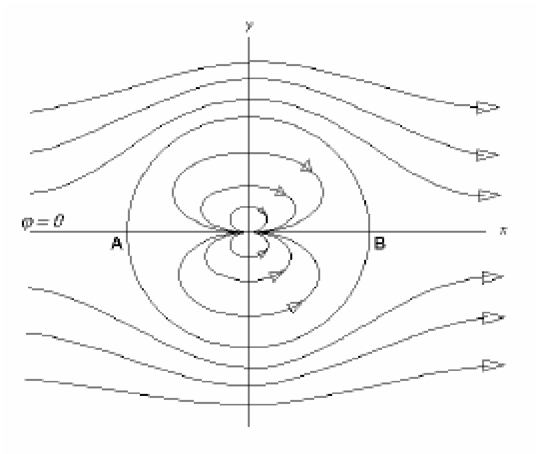


Figure 4 - Doublet flow, modelling the flow over a cylinder

The theoretical flow around the model can be described by the complex potential

$$(w(z) = \psi + \phi) \qquad \textbf{Equation 1}$$

and where the circle is modelled as impenetrable flow.

$$w(z) = V_\infty \left(z + \frac{a^2}{z} \right) \qquad |z| \geq a$$ **Equation 2**

where *a* is the radius of the circle (arbitrarily radius is *r*) given by the expression:

$$a = \sqrt{\left(\frac{m}{2\pi V_\infty} \right)}$$ **Equation 3**

m is the strength of the point sources in the doublet flow and can be expressed as a function of the free stream velocity and *a*:

$$m = 2\pi V_\infty a^2$$ **Equation 4**

On the circle, $z = ae^{i\theta}$ and from this the complex velocity can be derived in polar form:

$$v_\theta = -2V_\infty \sin\theta$$ **Equation 5**

The origin for the Cartesian and Polar co-ordinate systems is the same.

Flow over a circle where circulation $\Gamma = 0$.

We can further modify the above model, by super-imposing two flows:

- Flow over a circle with $\Gamma = 0$
- A point vortex at the circle's centre of strength Γ, this therefore introduces non-circulatory flow. A physical explanation of the superimposition of the two models is that the cylinder is now rotating:

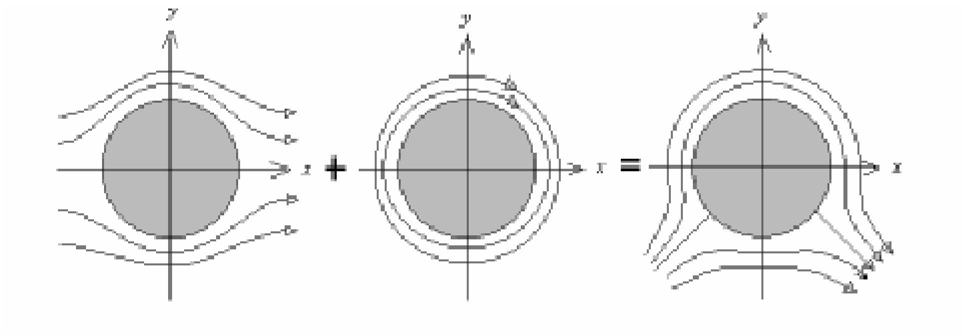


Figure 5 - Super imposition of non-circulatory flow and point vortex flow. Anti-clockwise rotation will be considered positive.

The new model generates a new complex potential that describes the flow in this superimposition:

$$w(z) = V_\infty z + V_\infty \frac{a^2}{z} + \frac{\Gamma}{2\pi i}\ln z$$ **Equation 6**

The change of flow symmetry about the *x*-axis implies that the fluid passing above the circle is caused to accelerate as a result of viscous contact and transfer of momentum from the edges of the central vortex. Similarly the fluid passing under the circle is retarded as a result of contact with the vortex, and slows.

The relative variation in fluid velocity above and below the circle creates an area of lower pressure, and an area of higher pressure respectively. This effect is an example of Bernoulli.s theorem.

The lift force formula can be deduced using Figure 5. The complex potential for the case $\Gamma = 0$, and for the superimposed flows Figure 5.1 and Figure 5.2 are already expressed, this allows the point vortex flow alone can be expressed by the complex potential:

$$w(z) = \frac{\Gamma\theta}{2\pi} - \frac{i\Gamma}{2\pi}\ln r \qquad \textbf{Equation 7}$$

On a circle where r = a, a polar form of this expression can be given;

$$v_\theta = -\frac{\Gamma}{2\pi a} \qquad \textbf{Equation 8}$$

This expression enables us to define the velocity of the flow at any point on the circles edge, the pressure at that point, and hence collectively the resulting lift force on the body. We begin by inputting the above velocity expression in Bernoulli.s equation:

The resultant lift force;

$$p = C - \frac{\rho v^2}{2} = C - \frac{\rho}{2}\left(2\mathrm{V}_\infty \sin\theta - \frac{\Gamma}{2\pi \mathrm{a}}\right)^2 \qquad \textbf{Equation 9}$$

The resultant force on the circle is

$$\overline{R} = -\oint p\overline{n}ds \qquad \textbf{Equation 10}$$

The lift force is the y-component R_y.

$$iR_y = -\oint p\cos(n, y)ds = -i\int_0^{2\pi} p\sin\theta.ad\theta \qquad \textbf{Equation 11}$$

By substituting in Equation 9

$$iR_y = \frac{|\Gamma|\rho V_\infty}{\pi}\int_0^{2\pi}\sin^2\theta d\theta = \rho V_\infty|\Gamma|$$ **Equation 12**

or in the complex vector form, the lift force R_L is

$$R_L = -i\rho V_\infty|\Gamma|$$ **Equation 13**

2.1.1 CONFORMABLE TRANSFORMATION

The conformable transformation method allows us to take the simple model for the lift generated over a rotating cylinder, and map the flow fields for other forms onto it using an analytical complex function *w(z)*. The hydrofoil is geometrically most similar to the circle, and can therefore be used in modelling techniques.

The derivation of the transformation method is most easily explained by considering major steps taken by engineers Kutta and Joukowsky. Their work will assist in generating the first mapped model of a foil.

Lift on a hydrofoil is derived using the Joukowski (Жуковский) transform theory.

Let the circle previously defined, be named *K*, and exist on plane (z), and the transform, foil *C* exist on a dissimilar plane (ζ). The mapping of the points in *K* onto C can be described by the Жуковский transform:

$$z = \frac{1}{2}\left(\zeta + \frac{b^2}{\zeta}\right)$$ **Equation 14**

Where 2*b* describes the diameter of circle *K*:

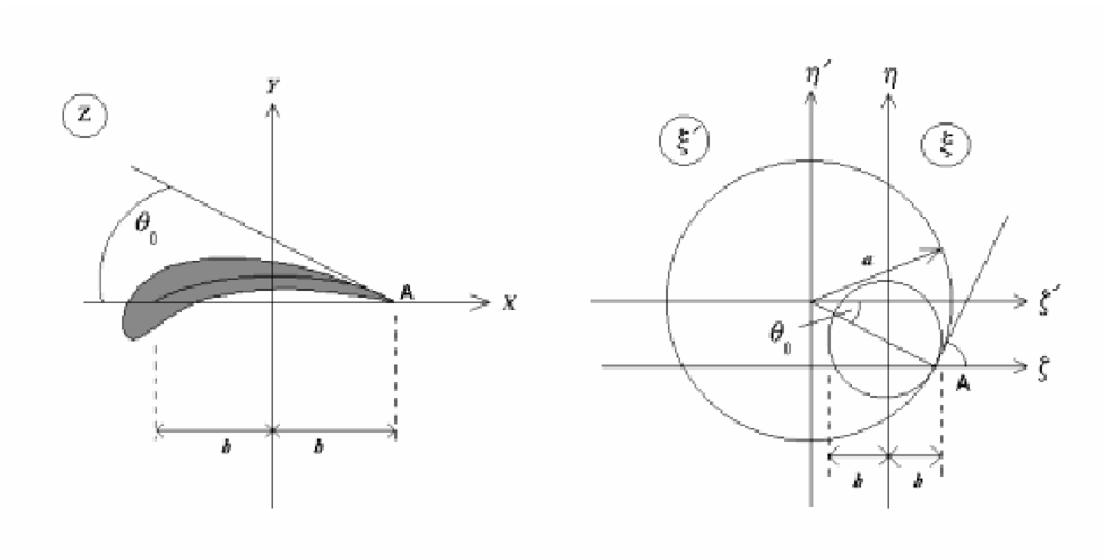


Figure 6 - Diagrammatic explanation of the Жуковский foil and its geometric generation. represents the zero lift angle, i.e. the angle of attack for which no lift is generated by the foil.

Figure 6 contains one less circle than Жуковский.s original transformation, a feature modified by Kutta, in order to generate a foil with a finite tail angle (the internal angle between the upper and lower surfaces of the wing at the trailing edge)

A new co-ordinate system (ζ, η) can be established with its origin at ζ_o. Thus we can write the circle equation on the new plane as

$$\zeta = ae^{i\theta}$$ **Equation 15**

Therefore, on (ζ) plane

$$\zeta = b + a(\cos\theta - \cos\beta) + ia(\sin\theta + \sin\beta)$$ **Equation 16**

Substituting this into the transform Equation 14 gives

$$z = \frac{1}{2}\left\{ b + a(\cos\theta - \cos\beta) + ia(\sin\theta + \sin\beta) + \frac{b^2}{b + a(\cos\theta - \cos\beta) + ia(\sin\theta + \sin\beta)} \right\}$$

Equation 17

Flow over the Жуковский foil:

The transform function Equation 17 satisfies the following condition at infinity for the z plane:

$$z = \infty \quad \zeta = \infty \qquad \left[\frac{dz}{d\zeta}\right] = \frac{1}{z}$$ **Equation 18**

Hence the complex velocity $\frac{dw}{dz}$ (which describes the flow over the foil) is subject to the condition:

$$\left[\frac{dw}{dz}\right]_{z=\infty} = V_\infty e^{-ia}$$ **Equation 19**

With the transform function, this condition can modified to show the same condition for the flow over the eccentric circle, which using the fact $\zeta = \zeta - \zeta_0$ can be expressed in terms of plane ζ :

$$\left[\frac{dw}{dz}\right] = \frac{1}{2} V_\infty e^{-ia}$$ **Equation 20**

The complex velocity for the eccentric circle is already known (Equation 5) and can also be expressed in terms of plane ζ (circle centre (0,0)) due to Equation 20. This gives us an expression for the complex flow $\frac{dw}{d\zeta}$

$$\frac{dw}{d\zeta} = \frac{1}{2}V_{\infty}\left[e^{-ia} - \frac{a^2 e^{ia}}{(\zeta - \zeta_0)^2}\right] + \left(\frac{\Gamma}{2\pi i}\right) \times \left(\frac{1}{\zeta - \zeta_0}\right) \qquad \textbf{Equation 21}$$

From the Жуковский transform, we have:

$$\frac{dw}{d\zeta} = \frac{1}{2}\left(1 - \frac{b^2}{\zeta^2}\right) \qquad \textbf{Equation 22}$$

Therefore, the flow over the Жуковский foil can be expressed by the complex potential:

$$\frac{dw}{dz} = \frac{\frac{dw}{d\zeta}}{\frac{dz}{d\zeta}} = \frac{\frac{1}{2}V_{\infty}\left[e^{-ia} - \frac{a^2 e^{ia}}{(\zeta - \zeta_0)^2}\right] + \left(\frac{\Gamma}{2\pi i}\right) \times \left(\frac{1}{\zeta - \zeta_0}\right)}{\frac{1}{2}\left(1 - \frac{b^2}{\zeta^2}\right)} \qquad \textbf{Equation 23}$$

the complex velocity satisfies the following condition, such that the $z = b$ at the trailing edge:

$$\left(\frac{dw}{d\zeta}\right)_{z=b} \to \infty \qquad \textbf{Equation 24}$$

From this expression a finite theoretical expression for circulation G around the foil can be found:

$$\Gamma = 4\pi a V_\infty \ \sin\alpha$$ **Equation 25**

which can be expressed more generally:

$$\Gamma = 4\pi\rho l \left|V_\infty\right| \sin(\alpha - \theta_0)$$ **Equation 26**

Having found a defining value for circulation around a foil (from its complex velocity), we can express the theoretical lift of the foil, by substituting Equation 26 into the lift Equation 13:

$$R_L = -\rho\Gamma V_\infty$$ **Equation 27**

$$R_L = -\rho(-4\pi a V_\infty \ \sin\alpha)V_\infty$$ **Equation 28**

And finally, the general term is:

$$\boxed{R_L = 4\pi a V^2 \rho \sin\alpha}$$ **Equation 29**

2.2 Conclusions

Three expressions have been produced for the lift generated by the different methods of boat movement. The two principle methods, by hydrofoil and by planing, can be compared in greater detail. In order to carry out this comparison, the length term, a, given in equation 31 must be expressed as $2a = l$. This is due to the differing calculation method being used in both derivations.

The foil lift equation can be written as;

$$\Re = 4\pi \frac{1}{2} v^2 \rho \sin\alpha$$ **Equation 30**

Hence, for small values of α;

$$\Re = 2\pi v^2 \rho\alpha$$ **Equation 31**

The lift generated from the foil is

$$R_L = 2v^2 l\rho\pi\alpha$$ **Equation 32**

The lift generated from the planing surface as described in section 9.1 is

$$R_L = \frac{1}{2} v^2 l\rho\pi\tau$$ **Equation 33**

Hence the lift produced by the foil is 4 times more than that of a planing surface.

3 HULL DESIGN AND BUILD

3.1 Introduction

The hull is a very important feature of the boat, and hence was given a great deal of consideration. However, optimal hull design as required for normal sailing boats is not essential. Our requirements of the hull are different, and it is imperative that these are satisfied principally.

The hull is a platform where the foils can be positioned. For commercial viability it needs to be strong and durable, yet low in weight to reduce drag and increase speed. The weight also needs to be kept to a minimum to ensure it is easily transportable, like any other sailing boat. Furthermore, dimensions are limited in this sense, allowing the hull to mount effortlessly onto standard trailers, hence appealing to the general sailing public. For the same commercial reasons the rig should be kept the same, as changing it would only unsettle sailors. Therefore the hull should be able to retrofit an existing rig.

The overall design of the hull should be kept simple, therefore remaining appealing. This will also allow for customisation by individual sailors. Displacing, planing and hydrofoiling hulls will be investigated and considered in the design process.

Mast placement is also very important to hull design, as this affects hull strengthening and bulkhead design.

3.2 Design Specification

Construction of a new hull was chosen in preference to retrofitting an existing one, as readily available hulls are not relevant for the purposes we require. This allowed the application of appropriate technology and permits easy strengthening at the attachment points of the hydrofoil frame to be included in the original hull design. Hence the hull was designed for use in and out of the water, i.e. when sailing on the hydrofoils – "flying".

The aim of this project is to build a hydrofoil sailing dinghy that will appeal to the majority of the sailing market at a competitive resale value. Laser sailing dinghies are one of the most popular planing sailboats on the current sailing market. Although they are not as fast as international moths, which are displacement sailing boats and can reach higher speeds for similar length hulls, Lasers are much easier to sail.

Therefore, from a commercial aspect of the project, it was decided to design a hull based on the vital statistics of a laser hull, but influenced by the slim-line design of international moths to take advantage of this speed difference. The main difference between the foiling hull design and an original Laser design is a much slimmer hull, allowing faster sailing with the same amount of ease, justified by the added stability from the foils. It should be noted that the hull is designed to be in the water until it reaches a speed of 8 knots, at which point the lift generated by the foils will lift it out of the water. Hence it will no longer act like a sailing dinghy hull until it re-enters the water.

It was also decided to keep the weight of the hull to a minimum, no more than that of a Laser sailing hull, 59 kilogrammes. Not only will it require less lift to fly, this will also ensure the hull is transportable on standard trailers.

Relevant changes were made to the Laser hull design where necessary as detailed in the “Design” section of this chapter. However, they were kept to a minimum to ensure the overall design still appealed to the current sailing market.

In order to be able to control a sailing boat effectively the centre of effort (CE) of the sail must be in the correct position in relation to the rest of the boat. The position of the mast determines where the centre of effort of the sail will be and is consequently an important design consideration.

Correct positioning of the mast depends on the position of the centre of lateral resistance (CRL) of the boat. The lateral resistance is experienced when one tries to push the boat sideways through the water. The centre is the point at which the boat will not turn as it is pushed. Therefore, if the mast is too far forward of this point the boat will tend to turn away from the wind. Conversely, if the mast is too far back the boat will turn into the wind. Either situation will require constant adjustment of the rudder to counter the turning motion, which will slow the boat down.

3.3 Hull Design

The hull was designed using a program called Hullform. This allows easy generation of different hull shapes and provides vital hydrostatic information used for calculations to establish buoyancy, righting moments and mast placement in normal and extreme sailing conditions. The aim of this project is not to design an optimum sailing hull, but to design a body that satisfies the criteria outlined previously in the introduction section of this chapter. Therefore, Hullform is used as a tool to generate a basic hull shape, which is then developed on to produce a hull suitable for this project.

The optimum hull design is when there is sufficient buoyancy and stability, yet minimum drag in all conditions of sailing. Hull design must carefully consider the three different operating modes of the boat: displacement, take-off and foil-borne. During displacement operation, a narrow beam is more favourable as it produces less drag. A wider beam would be necessary for satisfying stability criteria, but this is not the case here as the foils are extended during displacement sailing and provide an increased righting moment and increased stability. Therefore, it is possible for the hull width to be smaller than that of a Laser, thus reducing the overall weight of the boat. For takeoff and foil-borne use, the structure of the hull needs to be stiff enough to resist the impact from waves at high speeds, and be able to distribute the concentrated loads at the strut attachment points. The hull is therefore designed with a deep forward vee and high dead rise for cresting the tops of waves while foil-borne.

Relevant ratios were calculated and entered into a design matrix, as detailed in the Technical Report, section 10.1 Hull Design.

The design of the hull's internal structure is dependent on mast placement. There are many rules that dictate where to place the mast; the following two are taken from Free Boat Design Resources [http://home.clara.net/]:

"For balance, The lead of the centre of effort over the centre of lateral resistance should be 12-14 per cent of the waterline length in the case of a shallow hull, fin keel or centreboard craft; about 10 per cent for deeper, more traditional yachts; and about 8 per cent for cruising yachts of classic form."

John Teale

"Balance: for racing machines of the scow type the lead of CE over CLR should be 5 to 15 per cent of the waterline length…"

Norman L Skene

The 'lead' is the distance of the centre of effort ahead of the centre of lateral resistance.

The hull design resembles the centreboard craft described by Teale. Teale's range is much smaller and fits within the range given by Skene. Therefore 13% of the hull length is a suitable value for the lead of the centre of effort to the centre of lateral resistance.

For a normal sailing dinghy, mast placement is simple because the centre of lateral resistance is fixed. However a hydrofoil boat is more complex as it has two different modes of sailing, each having a different centre of lateral distance.

When the boat is displacement sailing the hull is partly submerged in the water so the lateral resistance of the hull contributes to the total lateral resistance and position of its centre. When the boat is hydrofoiling the hull is out of the water and is supported by the struts that connect the boat to the foils. Therefore the centre of lateral resistance moves when the hull leaves the water. When the boat is foiling the hull does not contribute and it is purely the struts and foils that determine the lateral resistance and its centre.

Therefore, the two situations require different mast positions. There are several options for the position of the mast:

- Design an adjustable mast that can change position when the boat begins to foil.
- The mast is placed as determined by the centre of lateral resistance of the foils because it is most important to have good control at top speeds.
- The mast is placed as determined by the centre of lateral resistance of the hull because realistically the boat will spend more time in displacement mode than in foiling mode and good control is necessary when turning.
- The mast is placed in a position that is suitable, but not perfect, for both displacement and foiling (a compromise)
- The foils are placed so that their combined centre of lateral resistance is in line with that of the hull

It is impractical and unnecessary to design an adjustable mast. It would add extra complications to sailing the boat and includes extra moving parts. It is important to have good control of the boat in all situations so choosing the position of the mast to fit either displacement or foiling sailing would produce a poor design, as would making a compromise between the two.

The only option left was to design the boat to have its centre of lateral resistance in the same place for both displacement and foiling. This does not cause any balancing problems and also helps to decide where to place the foils.

The centre of effort of the sail was calculated from the measurements of the sail. However, the centre of effort moves when the sail angle changes. Therefore the average longitudinal position was assumed to be at the same position as when the sail is at 45 degrees to the direction of the boat.

The lateral resistance is proportional to the profile area under the water and the centre of the lateral resistance is the centre of that area. Hullform does not give the centre of lateral resistance. It has been found by inspection of the shape of the profile area below the waterline. The actual area is given in Hullform and the profile area of the struts holding the foils is easily calculated.

3.4 Hull Design Output

The final hull design resulted in a 30% decrease of beam width, reducing weight and thus increasing displacement speed. The beam could have been reduced further, but it was decided for stability reasons to only decrease by 30%, giving a beam width of 0.997m. The overall length was kept to that of a Laser sailing dinghy to make the boat appeal to sailors, that is 4.396m.

Appendix 1 – Hull Design Decision Matrix gives a sample of the model used to calculate the mast position. It first calculates where the centre of lateral resistance is when the boat is riding on foils and consequently where the mast should be placed, for different positions of the front foils. It then repeats this for when the hull is in the water. It finds out the position of the front foils that makes the mast positions coincide. A line-for-line explanation of the programme is included in the Technical Report; section 10.2 Explanation of Mast Position Spreadsheet.

Results from the spreadsheet decided the positions of the front foils and mast as 1.7 metres and 1.4 metres from the bow respectively.

3.5 Material and Production

3.5.1 Material Selection

As can be seen from the material section in the technical report, there are a wide variety of factors to be considered when choosing the materials that are used to build a boat. The performance of the materials in compression and tension should be studied, as should the resilience to water and rot.

This section looks at the material that has been chosen to build the boat hull in more detail. Due to the project constraints of time, cost, and technical knowledge/specialisms we have had a more limited choice of material than perhaps would have been liked.

Referring to the attached ‘thought plan’ document in parallel with this section will clarify the decisions taken to choose our hull material. Initially we began the material choice by looking at different polymers. It was recognised that we needed to keep the boat light and easy to produce. Using materials such as steel and aluminium would have produced a heavy boat; we would also need accurate forming tools to produce the hull shape. We did not have access to tooling to produce the hull shape, so this material was removed from our choices.

Wood could produce us a lightweight and stiff boat, but needs highly skilled labour to produce the accurate shapes and forms that we needed to shape the hull. Extra treatments would also be needed, adding to the complexity of the production process.

This left us with polymer materials to produce the hull with. To increase the stiffness to weight ratio it was decided to use a cored structure as explained in the previous section. Within the polymers we could choose thermosets or thermoplastics. Thermoplastics were immediately removed from the choice, as we did not have access to an oven to process the material. This meant we would be looking at the thermoset materials.

For the reinforcement we had several materials we could choose from. The list that was drawn up was as follows:

- Glass
- Carbon
- Kevlar

To provide a screen to process our decision we looked at the cost of the materials. With a limited budget cost was a major consideration. There was little point in selecting a material that we could not afford to use. Glass was the cheapest reinforcement at £1 - £2 per kilogram. Carbon and Kevlar were far more expensive at £20/Kg and £15/Kg respectively. This was too expensive for us to use to produce the whole hull. Therefore glass was chosen as the reinforcement.

Now the reinforcement material had been chosen it was necessary to choose a core material. Again we had several choices for us to pick from. The choices were as follows:

- Polypropylene honeycomb
- Nomex honeycomb
- Aluminium honeycomb
- PVC foam

Again as cost was an important consideration this was used as the screening method. Nomex honeycomb is very expensive so this was removed from the choices. Aluminium honeycomb was eliminated, as we did not have access to the technical skills to use this material in the manner with which we were going to use it.

This left polypropylene honeycomb and PVC foam. Both of these materials were acceptable to use, with relatively cheap costs. Polypropylene honeycomb costs £10/m^2, and PVC foam costs £20/m^2. This meant there was a need to further investigate the pros and cons of each material.

PVC foam posed an immediate problem. Due to its thickness we would be unable to bend it to match the mould we would build to form the hull. To make the foam bend we would need to heat it, with the sizes of foam we would be using it would be hard to heat the foam to mould it. One method found to get round this problem would be to make strips of foam that could then be butted together to form the form of the boat, rather like using planks of wood. The downside to this would be the time needed to cut the foam and correlate it correctly to form the hull shape.

A further problem with the foam would be the method of attachment to the mould. Stiff fasteners such as screws or nails would be needed. This would mean that after production the nails/screws would be left in the foam, added extra weight, and possible areas of weakness.

Foam would also present a problem when in service. PVC foam will break down on contact with water. This would mean that we would need to produce an entirely watertight structure, after the various fittings had been attached to the boat this could prove problematic.

Honeycomb proved easier to use for the production process. The honeycomb was flexible as a full sheet so could be added into the mould in one sheet and fixed to the mould. This meant there would be little shape alteration to the material.

Fixing the material was far easier. Pipe cleaners could be passed through the honeycomb cells and then fixed around the mould slats. This would remain in the material after production, but would not add as much weight to the structure. The pipe cleaners would also soak up the resin used to avoid areas of delamination.

As can be seen from the charts in the previous section the physical properties of the honeycomb are very similar to the PVC foam.

Overall it was felt that the polypropylene honeycomb offered the best all round performance at a price we could afford due to the project budget. This was chosen in conjunction with the glass fibre. The next section looks in more detail at this honeycomb material.

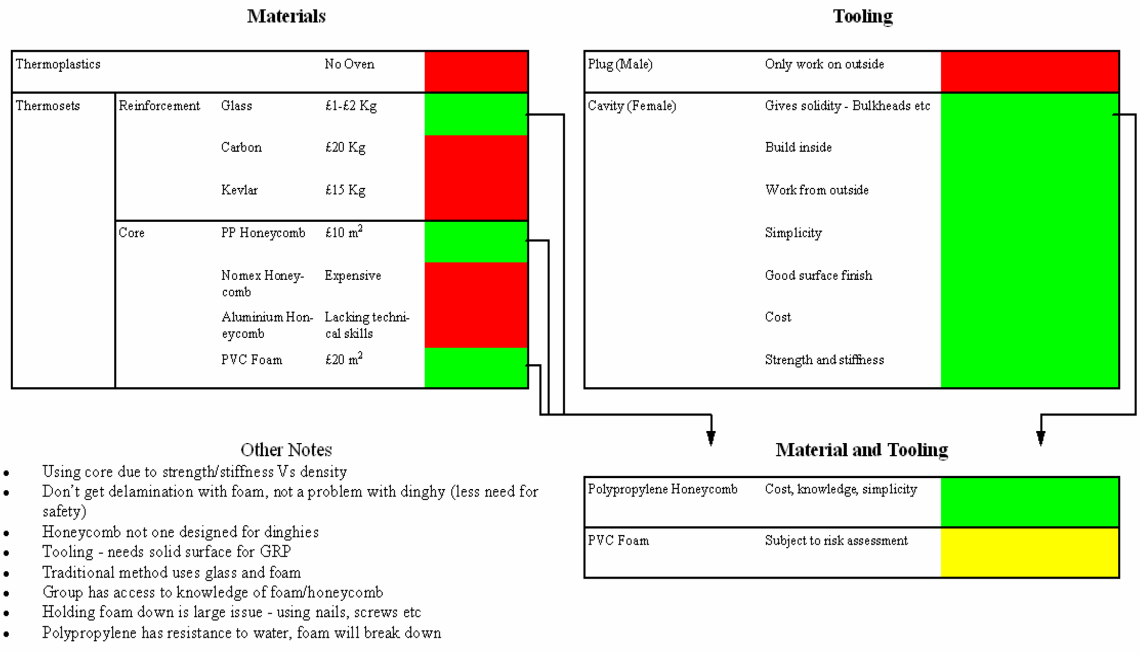


Figure 7 – Materials and Tooling Breakdown

3.5.2 Polypropylene Honeycomb

As discussed earlier we decided to use the polypropylene honeycomb. This is sold under the trade name 'Nidaplast'. At the beginning of this section the problems with honeycomb were discussed, mainly the adherence of the resin to the thin edges of the honeycomb section, and the cells filling when the resin is applied. The Nidaplast honeycomb has a non-woven dry polyester layer covering the honeycomb for the resin to adhere to and to stop the cells filling. This is shown diagrammatically below:

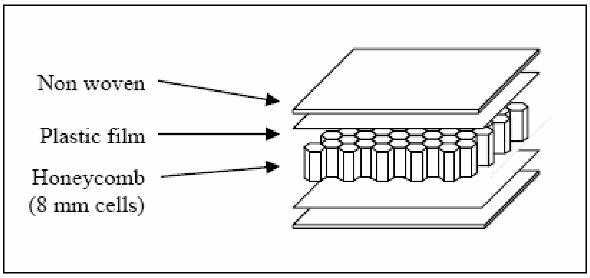


Figure 8 - Nidaplast Structure

The combination of the polypropylene and honeycomb structure gives several advantages. They are lighter than other materials for the same stiffness. This reduced weight and enhanced stiffness means that the material will not bend under its own weight, which is advantageous when making flat horizontal structures, such as the deck. Another advantage is that the structure can take significant distortion without breaking, this is important as we are using the material in a 3D form.

The Nidaplast can be used in a variety of ways, including hand lay-up. This is important for our manufacturing process as it allows us to use a simple process with no expensive or sophisticated equipment.

Importantly the material performs very well when exposed to water, and has good general chemical resistance.

The material comes in a variety of different thickness. For the hull we are using 10mm thick honeycomb. This has sufficient physical properties for our design. The table below gives a summary of the physical properties of the material:

Density	80Kg/m^3
Compressive Strength	1.3MPa
Compressive Modulus	15MPa
Ultimate Perpendicular Tensile Strength	0.5MPa
Shear Strength	0.5MPa
Shear Modulus	8MPa

Table 1 – Physical properties of honeycomb

It has already been discussed that we will be using the honeycomb covered in glass fibre. Below is a chart that compares the strength of a variety of materials.

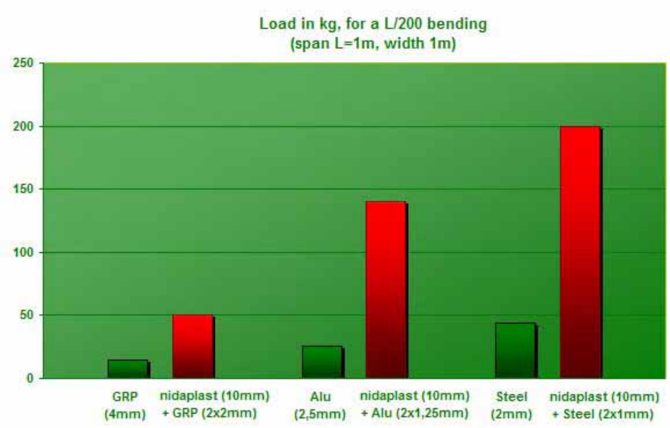


Figure 9 - Nidaplast Loading

As can be seen using the Nidaplast honeycomb the load that a structure is able to take is greatly increased. It is this increase in strength, with minimal weight gain that the hull will gain from when trying to minimise the weight of the hull.

A test piece of the Nidaplast honeycomb covered in a glass fibre layer is shown below, also shown is a fillet used to fix two pieces together.

Figure 10 - Sample of glassed Nidaplast honeycomb

Due to the good bonding strength epoxy is the resin of choice for honeycomb structures that do not have the additional layer of scrim attached. Epoxy resins are more expensive than the other resins, 'but because of the better qualities of an epoxy laminate and the amount used with regard to a comparable polyester laminate, the price difference will be negligible' [Anon, 2003E].

3.5.3 Hull Production

The design of the vessel will be a compromise of various factors such as budget, performance, safety, comfort, building ability, and resources available. A number of possible productions methods are detailed in the production section of the technical report, but selection is largely determined by the materials incorporated in the hull design discussed above.

As the strength to weight ratio is critical in this project the aim is to design a light boat, which will be able to withstand high-speed sailing. Fibre Reinforced Polymers (FRP) can provide high strength with relatively low mass and are usually made from foam or honeycomb, glass fibres and epoxy resin. In his case the composite is known as Glass Reinforced Polymers (GRP) as several layers of glass and resin provide the structural integrity of the hull. After evaluating the possible production methods available in relation to our specifications GRP was considered the appropriate choice. The following factors were the key reasons why GRP was used.

- The hull will be made from one continuous piece of GRP if manufactured correctly. This method does not require any caulking as it leaves no joints or gaps which stops water penetrating the hull.
- Shaping strips of wood to make a hull requires high carpentry skills, which are not available due to cost constraints. The planks on wooden hulls also shrink when they are removed from the water and placed in the sun. This shrinkage may also occur when the wood is laid up. GRP is relatively easy to work with and does not shrink or swell in different environments so leakage and re-caulking are avoided.
- GRP is a non-organic material and will therefore not rot or be susceptible to marine borers.
- Most metallic hulls suffer from corrosion and consequently require electrolysis or some other surface preparation. GRP is inert and as a plastic material it will not corrode.
- This method is suitable for mass production as the mould can be re-used to make identical copies of the hull. Once the mould is made the time taken to produce a single hull is greatly reduced.
- Once a basic training of using GRP is conducted the skill required to complete an entire hull is relatively low.

However, GRP manufacture does have its disadvantages, as detailed below:

- Once the hull is designed and the mould is made any modifications are difficult to implement.
- Some of the chemicals used in the GRP production methods are considered a fire and health hazards. The appropriate safety precautions including assessment, protection and use will be observed.

3.5.3.1 Method

This section will provide a brief overview of the production method used to create the hull. The production process is explained in more detailed in the technical report. Please refer to the previous section for details on the selection of materials.

The moulds can be made out of wood, sheet metal, plaster, or GRP composites and can be virtually any size. A frame is built in which stems or uprights are attached at regular intervals, which provides the shape of the hull. Battens or stringers are then attached perpendicularly stem to stem providing the exact shape of the hull. A release agent or plastic sheet is required between the mould and the composite material to aid the ejection of the hull.

Hand lay up is the easiest and oldest method for manufacturing plastic reinforced laminates. The first stage is to create a negative mould of the hull which allows the GRP materials to be laid up on the inside. If a positive or plug mould was it would be difficult to access the inside of the hull to lay the composite materials. The dimensional accuracy and surface finish of the mould is crucial as it determines the shape of the GRP hull.

The shape of the hull will be made from a double skin laminate combined with internal structures to strengthen the hull. The ‘Nidiplast’ honeycomb (core) will be laid inside the wooden mould and located into shape with pipe cleaners. The sections of honeycomb can be cut easily with a Stanley knife and a bradle will be used to make the holes for the pipe cleaners.

The reinforcement used in this case will be glass woven into cloth. The thickness of the cloth varies with the weight of the glass in grams per square metre. The glass will be cut into sheets using scissors and then draped smoothly over the honeycomb in preparation for the resin.

The resin provides the matrix in which the reinforcement is saturated providing a smooth relatively hard finish to the hull. For the resin to cure a catalyst is needed to turn the monomeric unsaturated polyester resin into a polymeric saturated resin. After the lay up is finished the surface can be sanded down and smoothed with filler (if required) and painted with a gel coat.

Internal reinforcements (bulkheads) must be installed with filler to join the two surfaces together completely. Resin putty (P38 car body filler) will be applied to both joining surfaces and then smoothed off after they have been pressed together. The filler can also be sanded down after it has dried. The join between the bulkhead and the hull (or other bulkhead) will be reinforced with glass and resin, as the filler does not provide any strength.

3.5.3.2 Mass production considerations

A production line system is possible for producing high volumes of boats but is a big step from traditional boat building methods. The management of flow production is crucial to keep the entire process running and should consider supply of resources, operator management and continuous improvement in particular.

After the composite hull is finished the mould can be used to make more hulls of the same dimensions. The demand for boats is not as high as it is for cars so production volumes for hulls will be relatively low and could be satisfied by reusing the wooden mould.

Jigs and templates could be incorporated into the manufacturing process to increase productivity and repeatability. Plywood templates of the bulkheads used inside the boat would aid the cutting of the honeycomb sheets. Jigs could be used to locate the position of bulkheads, rigging attachments and other components included in the hull.

For large surface areas a spray lay up technique would be appropriate. A spray gun is used to apply chopped glass strands, which are mixed with resin and catalyst at the gun nozzle. This method is very fast and designed for heavy workloads but provides a weaker structure than laying the glass and applying the resin by hand.

Three strips of glass mat (80mm, 120mm and 160mm in width respectively) were used to attach the glassed bulkheads into the hull. These strips were cut from a large roll of glass sheet, which was time consuming and difficult to cut accurately. Using 80mm and 140mm wide rolls of glass tape would be a more productive but more expensive.

High quality injection moulding equipment can be used to insert the resin into a cavity between reinforcements in a male and female mould. This eliminates hand consolidation but the initial investment is very high and should only be considered for high volumes.

3.5.4 Hull Production and Material Selection Evaluation

The combination of material choice and chosen production method worked successfully despite being a new innovative technique not used in this manner before. Previously the material has been used in yachting for producing flat shapes such as decks, but never in a three dimensional structure.

As with any new technique there were problems with the material and production methods. To try and minimise production problems small tests were carried out on samples of the material to ascertain suitable processes, for instance the amount of resin to use. This preparation enabled the operator to apply the correct amount of resin on to the glass without leaving it too dry or using too much resin. The glassing process was successful throughout the manufacture of the hull and de-lamination was kept to a minimum. The joins between the hull and bulkheads were stronger than expected and could consist of two layers of glass instead of three.

The honeycomb material was easy to cut with ordinary hand tools, such as knives and saws, but due to the cell structure it was hard to get accurate cuts as the blade was deflected during cutting. To address the problem glass paper was used to smooth and profile the edges.

The structure of the honeycomb sheet caused some forming problems. The sheet would only bend in one direction easily which was laterally across the boat. This meant there were large off cuts of wasted material which could not be reused elsewhere, increasing the material costs.

Further forming issues were encountered in complex and tightly curving sections of the mould. The large sheets would not form effectively into the curves, so smaller strips were used which increased production time due to increased amounts of profiling needed.

When laying the honeycomb sections on the hull tool it was difficult to align the edges together without leaving any gaps. These gaps would have reduced the structural integrity of the hull and therefore needed to be filled with highly absorbent paper.

At least 300 pipe-cleaners were used to locate the honeycomb sheets on the hull tool. The pipe cleaners were prone to fatigue fracture due to work hardening and created air pockets during the glassing process. Other materials such as silk and wire could have been investigated to minimise delamination.

The battens forming the hull shape (stringers) were difficult to locate at the nose section due to the rigidity of the wood. Consequently, the battens were under severe strain and consequently separated from the uprights and distorted the hull shape. Softwood with more flexibility and metal brackets bracing each stringer on the upright could have been used to rectify this problem. Using MDF instead of plywood on the uprights would have been a better material to screw into.

4 FOILS DESIGN AND BUILD

4.1 Foil Arrangement Design

As mentioned in the report introduction, one of the key aims of the project is to avoid the creation of yet another eccentric hydrofoil sailing craft. While there is a great deal of well educated engineering in the wide spread of designs that have appeared over the past hundred years, very few appreciate the key factor that if they are to enter mainstream / commercial use, overly complex design must be kept to a minimum, and ‘sail-ability’ and sensible solution must be at the forefront of the craft’s purpose.

Many foil geometries and systems of arrangement of these lifting surfaces have been explored over the history of hydrofoil craft with varying degrees of success. At an early stage, it was realised that, unlike an aeroplane, a hydrofoil craft has a very small safe operating envelope in terms of flying height. Too low and the craft will crash into the free surface at high speed, too high, and the foils will break free from the free surface, loosing all lift and causing a similarly catastrophic crash back into the water.

As a result of this critical issue of control, the design of most hydrofoil-based craft to date has been dictated by the design of their control system. Hydrofoil craft can be broadly categorised into two types.

4.2 Foil Geometry based feedback Control

The most common form of control through foil geometry is to arrange the foils such that as the craft moves out of its designed flying height envelope, the amount of submerged lifting surface is adjusted by default by using angled / curved lifting surfaces, this type of system is commonly known as a surface piercing foil. Figure 11 to Figure 14 [International Hydrofoil Society website] show various surface piercing designs:

Figure 11 - US Navy hydrofoil vessel

Figure 12 - Day motor-cruiser with foils

Figure 13 - Sailing catamaran operating under motor

Figure 14 - Hydrofoil motor-cruiser

As the figures above show, a wide variety of surface piercing and ladder systems (Figure 13) have made their way into functional hydrofoil craft. The method has the significant advantage that the support structure between the foil and main body of the boat can double up as the control system, by using structural members that have a foil shaped cross section. This can be seen in Figure 14, and is utilised significantly in larger craft where this support structure must take extremely large loads.

Surface piercing systems and those that require the lifting surface to cross back and forth across the free surface boundary have some major disadvantages however. As water is much denser than air, hydrofoils have the advantage of being able to produce much more lift for the same plan area compared with airfoils. This means that the localised pressure, particularly on the upper surface of the foil is much greater (negative for the upper surface) than for an airfoil.

As this very low pressure field is brought near the free surface or across it, air is drawn down into the region as it is much less dense than the water it replaces, and hence partially satisfying the pressure gradient and hence reducing the lift generation at that point. The problem progresses down the foil as the bubbles of air are drawn along the low-pressure field.

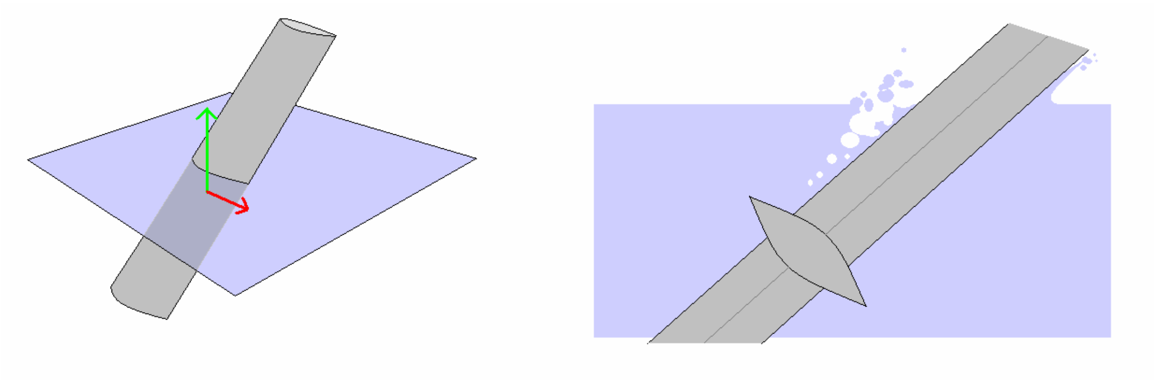


Figure 15 - Diagrams showing ventilation of surface piercing foils

As well as the immediate loss of lift, the presence of aerated water on the lifting surface and non-perpendicular entry to the water causes a number of further problems. The bubbles of air can disrupt and prematurely trip the separation of the flow over the foil, further reducing lift. The lower the overall lift, the greater the length of foil that must be submerged to support the craft, and hence the greater the overall drag.

The water displaced at the surface by the descending air bubbles is thrown into the air above the foil generating significant spray and loss of energy in the process. Further spray and energy loss occur on the lower surface of the foil, as curved surface of foil displaces water up and away from the free surface in semi-planing action.

The problem is a form cavitation known as ventilation and as described by *Acosta* in *Cavitation of Hydraulic Machinery, S. C. Li, 2001* can have a very negative affect on the performance of a foil:

"...a marine propeller of lifting hydrofoil operating near the free surface of the ocean may entrain air from the surface into the low pressure regions of the foil, forming large cavities which have a severe effect on the performance of the lifting surface. ... In this case the contents of the cavity are principally that of the surrounding air; some writers prefer to use the term "ventilation" for this term (Acosta 1973) or "artificial" cavitation." [Acosta, 2001, p.9]

This cavitation effect can be reduced to some extent using a form of wing fence as shown in Figure 15 (left) and in action in Figure 15 (right). This only solves the problem in discrete steps however, and has the disadvantage of further increasing drag.

Despite their wide use and structural advantages, it can be argued that surface piercing foils go only a small way to unlocking the potential of hydrofoils.

4.3 Transducer - Actuator based feedback control

The second of the two commonly existing areas of control system design is the use of passively or actively controlled mechanisms. Many of the more successful sailing hydrofoil craft use this form of control as it enables the design of a much more efficient foil when applied to completely submerged lifting surfaces.

Whilst the energy losses associated surface piercing systems are acceptable with high power motor craft, there is a much greater need for efficient use of energy in sailing. The power supplied by the sail is less predictable, and has a much lower average output than an engine or water jet powered craft of dinghy size.

Figure 16 - Foiler 21

This method of control means that the lifting foils can be completely submerged, with a safe gap between the upper surface of the foil, and the free surface. The foils are then connected to a symmetric foil shaped strut / structure that enters the water normal to the free surface. Whilst the structure still disturbs the water at the free surface, large variations in fluid pressure are only in the horizontal plane, minimising the possibility of entraining water that can be carried down to the lifting foil.

Figure 17 - Chapman's Craft

Figure 16 and Figure 17 [Weymouth Speed Weeks website] show how in similar conditions, at similar speeds with similar sized craft (*Speed Weeks* event) the spray emanating from a craft based on the surface piercing system is far greater than that coming from the foils of a inverted T-foil craft with Transducer – Actuator based control. Figure 16 shows a *Foiler 21* with surface piercing foils in action.

Figure 17 - Chapman's craft, *Ceres* outperformed all the boats in its class at *Weymouth Speed Weeks* in 2002, the majority of which use surface piercing systems.

'At Speed Week 2002 Joddy Chapman brought Ceres, she proved to be the fastest boat of the week by a considerable margin.' [Pictures from Weymouth Speed Weeks website]

As is the case with the surface piercing systems, transducer – actuator based control uses the free surface of the water and its relative position to a datum on the craft to control the flying height of the craft. Transducers that plane, float or respond to the pressure step across the free surface can be used to activate a change in the lift of the submerged foil through a passive mechanism (hydraulics, push rods etc.) or through a powered electronics based system (motors, solenoids).

Ride height sensor and lift variation actuator methods are explored in the Technical Report, Chapter 10.4, although this only touches the surface of the wide variety of engineered solutions that might be applied to the problem.

4.4 Foil arrangement

In order to provide a craft that competes with the current dinghy sailing market segment, as stated in the project aim, the foils have been arranger such that they offer a similar style of sailing. Although the boat is unlikely to feel like a traditional dinghy when sailing, certain features will remain so that the sailor / pilot can become quickly accustomed to the craft. The rear foil sits in the centre of the craft at the stern (back), in the same position as a traditional rudder, utilising the strut of the foil to perform the task of a rudder.

Similarly, the struts of the front foil pair replace the job of a traditional centreboard, providing resistance to lateral motion and aiding steering. Whilst the arrangement is dissimilar to a standard monohull craft, the front struts will perform the task in a way that a catamaran would instead. Figure 18 shows the arrangement in plan form.

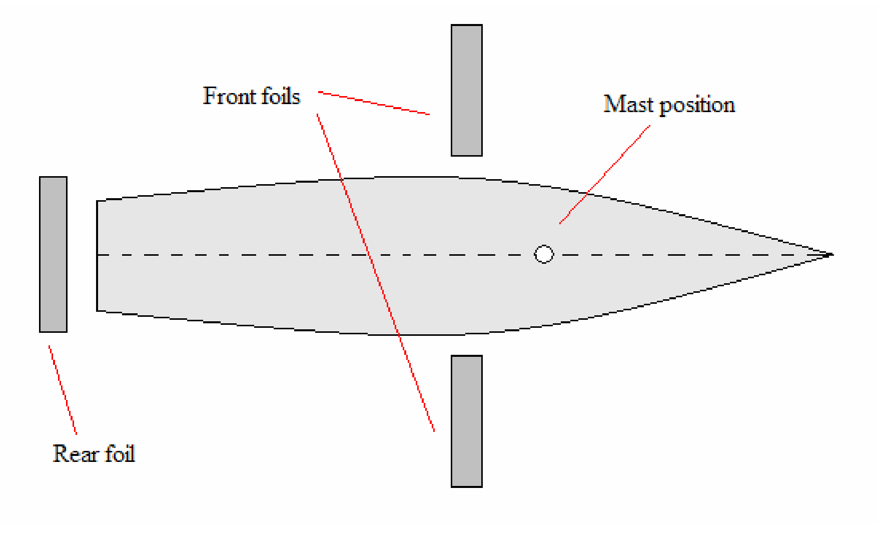


Figure 18 - Showing the arrangement of the three lifting foils

Three foils have been used to create a stable, user friendly platform for the sailor, enabling them to concentrate on the sail and steering without too much concern for weight distribution and lift control.

4.5 Introduction to Prototype Foil Design

The following section covers the decisions and design process undertaken to produce the foil assemblies for the craft. This constitutes the design of the struts and lifting foils of the front foil pair (considered identical) and the rear foil, with consideration for the integration of the control system and the attachment to the hull. The profile, dimensions and method of manufacture are considered and decided in this section.

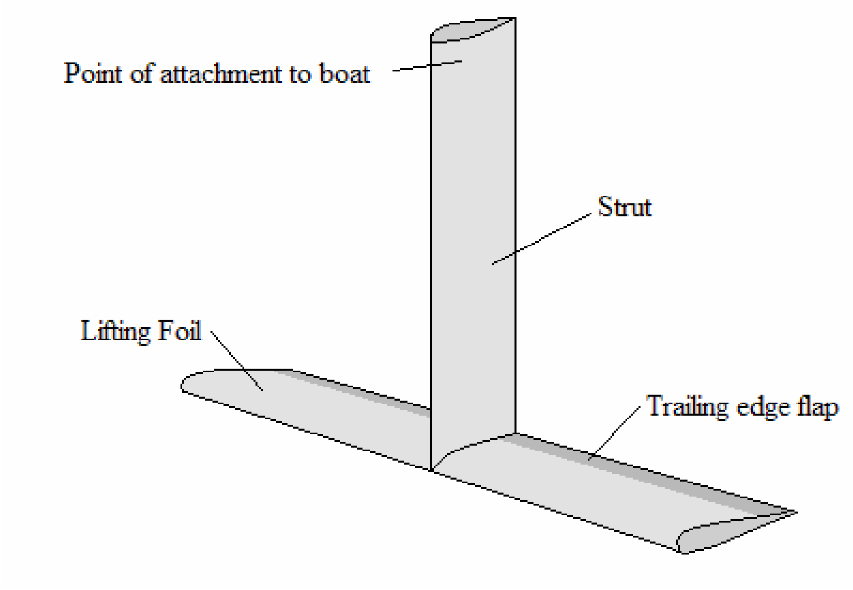


Figure 19 - Inverted T-foil arrangement chosen for the prototype boat

The design of a hydrofoil is a very broad engineering problem, dictated by a wide variety of factors. As this area of the project is perhaps one of the most critical topics, a large amount of time and design effort have been spent trying to get the craft's hydrofoils right. Without functional hydrofoils that give a notable benefit over a traditional sailing dinghy, the craft is very unlikely to draw a market from the existing sector.

In order for the foils to perform their task in a way that increases the performance of the craft and sailing experience, rather than diminishing it, the following primary and secondary principle criteria need to be fulfilled.

Primary principles: so that the boat will perform…

- The foils must provide and overall increase in speed in one or more of reaching, close to wind, or running sailing modes.
- The foils must not present an excessive increase in drag such that they stop the craft from reaching a speed at which they can become fully operational (flying).
- The wholesale increase in drag must not be such that the performance of the craft is unduly reduced when the craft is not in flying mode.
- The foils must integrate with the hull and the control system.
- The foils must double up on performing the tasks of the conventional rudder and centreboard.

Secondary principles: so that the design begins to work towards a commercially viable boat…

- The added weight, width and more complex 'setting-up' of the craft should be worth it, for the increase in performance.
- The durability of the foils should be such that under normal operating conditions they should last for a minimum of five years.
- The foils should be removable to aid transport and so that the craft can be customised, changing the type of foil to suit the sailors experience / leisure requirement (kids, racing, cruising, etc.)
- The foils should be designed such that the manufacturing process can be simplified for larger scale production, without unduly compromising the performance of the foils.

As the concern for this year is to produce a prototype, the primary principles have been the major concern, and the secondary principles have been addressed where possible and practical.

4.6 Design Specification

The following numerical specification is based on initial design estimates to set the iterative numerical design process going. The final output values are taken from the total boat model – Chapter 13.

Flying height - **0.5 m** between hull underside and free surface at cruising speed.

Take off speed - **5 - 8 knots** (2.5 – 4ms^{-1}).

Cruising speed - **15 knots** (7.5ms^{-1}) i.e. a competitive speed in comparison to competitor performance craft.

Maximum speed - **25 knots** (12.5ms^{-1}); any greater than this and a crash from flying mode could severely compromise the safety of the sailor.

Worst case lift - **2000 N** per foil; i.e. the estimated total weight of the boat (hull, rig, foils, etc) and sailor.

Width - **Less than the length of the boat.** In order to provide a race worthy boat, this has been taken as a basic dimension condition.

4.7 Foil design

The foil design process has been broken down into the following sections aimed at satisfying the specification set out above:

1. Foil profile selection.
2. Theoretical design
    a. Required lift and lift variation
    b. Cavitation considerations
3. Integration with a lift control system
4. Design for loading – the foil as a structural member

This set of requirements gives rise to an inherently iterative design process with a number of optimums arising based on the design weightings of these factors. This iterative design element means that the above sections do not strictly represent a chronological break down of the process.

4.7.1 Foil profile selection

The design process was initiated by considering the type of wing and foil section that might be appropriate for the task. Based on advice, research and available data, the design process started at this point. [Li, 2001, and personal discussion; Joddy Chapman's article and personal discussion; International hydrofoil society website]

For the purposes of this project, the choice of foil section has been limited to those available in *Visual Foil*, as profile designs cannot be input to the program. Whilst perhaps this places a limit on finding the optimum solution, it means that detailed CFD modelling can be used to model the chosen foil.

In order to minimise the width of the assembled craft, asymmetric foil sections have been explored to increase the circulation over the foil and minimise the required span. As four digit profiles are more suited to symmetric profiles and commonly produce concave (see cavitation material, section 4.7.6) surface region on the lower surface, the five-digit database was explored for the appropriate section.

The foil section must adhere to the following design criteria:

- The upper surface of the foil must be such that the profile distributes the lift generating pressure over as much of the surface as possible.

- Sharp peaks in the pressure profile should be avoided, minimising the possibility of premature flow separation and cavitation generation.
- The foil should not respond too severely to changes in angle of attack in order for account for the likely unpredictable incident flow.
- The profile should provide the above points whilst maximising the lift to drag ratio.

The last of these points represents the efficiency of the foil and hence the essence of the design.

Visual Foil gives the opportunity to change the first three digits as a fixed group and the second two as another group. After extensive work within the program NACA 25014 was chosen as the optimum design based on the criteria above.

Although all the work undertaken to select NACA 25014 cannot be detailed here, the foils close to the chosen profile can be used to show the reasons for this final choice. NACA Permutations 21014 to 25014 (second digit varies in integer steps) and 25008 to 25018 (the last two digits vary as a whole number in steps of 2 from 08 to 18) have been used to illustrate the choice of 25014.

A more detailed explanation of the affects these changes have on lift, drag, flow transition, surface pressure and variation in performance relative to changes in angle of attack, can be found in graphical form and explained in the Technical Report, section 12.1.

Changing the first three digits of the NACA code defines the position of maximum camber, whilst the last two, define the thickness ratio of the foil (thickness to chord). The camber of the foil defines the curvature of the form: increasing the camber causes the lower surface to flatten out, whilst the curvature of the upper surface increases.

The magnitude of the camber of the foil can be modified separately within the program, but has been left at the suggested default value (2.3% of the chord) to maximise circulation around the foil whilst minimising sharp jumps in surface pressure.

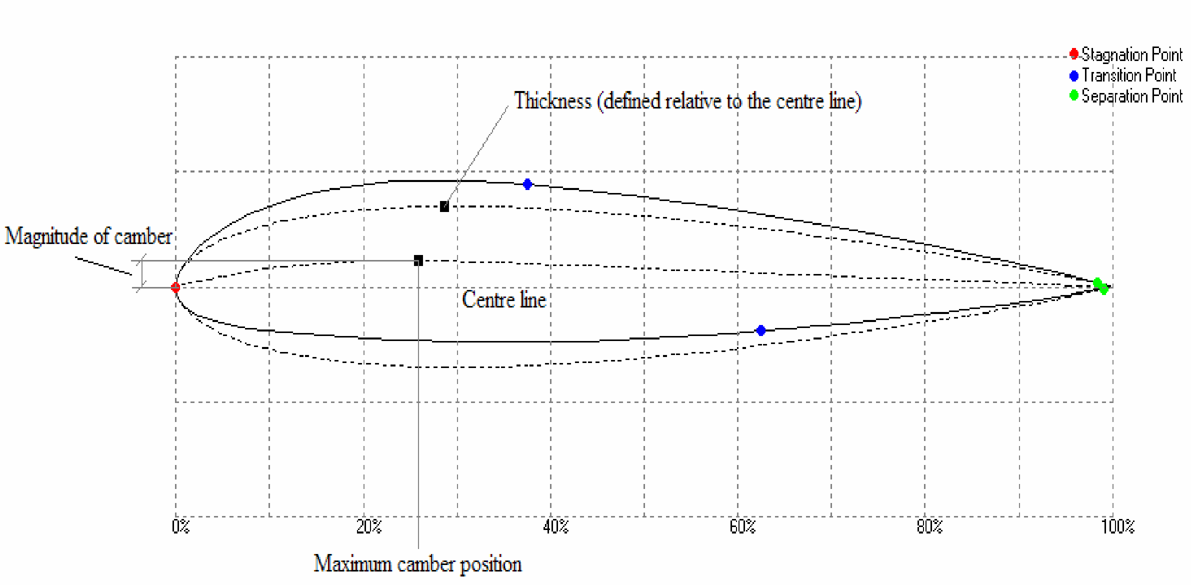


Figure 20 - Design parameters that define the foils profile.

4.7.2 Theoretical design

As covered in Chapter 2.1, the theoretical lift produced by a foil can be defined using a lift coefficient, foil dimensions and a set of operating / environmental parameters. Theoretical proof yields an equation where these factors are incorporated in a form that is difficult to apply directly, not knowing the value of a (see Equation 3, Chapter 2.1).

For design purposes, we take into consideration the lift per unit plan area *A* (Chord × Span) of the foil and use a coefficient specific to the foil profile C_l:

Lift: $$L = C_l \, A \rho \frac{v^2}{2}$$ **Equation 34**

Where ρ is the density of the fluid in which the foil is acting and v is the velocity of the foil through the fluid. The fluid density can be considered as a constant (incompressible flow) for design purposes, and for has been modelled as fresh water for the purposes of the prototype (to be tested in fresh water).

4.7.3 Lift Coefficient C_l (and drag coefficient C_d):

The foil design/CFD package used for the design and theoretical modelling of the foils *Hanley Innovations* ***Visual Foil Lite version 4.1*** was used to generate a variety of NACA profiles from the four and five digit series. The program outputs a value for the lift coefficient of each given design generated.

Visual foil uses a CFD method based on the linear strength vortex panel method, placing model singularity vortices at evenly distributed points along the wing surface to model the circulation over the total foil. The method computes the inviscid outer flow field, whilst standard boundary layer equations for laminar and turbulent flow are used to compute the viscous layer at the surface of the foil. Further detailed explanation of the source of C_l can be found in the Technical Report, section 12.2.

4.7.4 Plan area and aspect ratio

The plan area of the foil is taken as the multiple of the chord and span. Finding the correct span to chord ratio (aspect ratio) for a foil is one of the key areas of design when choosing the appropriate foil for the task.

Visual Foil assumes an infinite wing model, meaning that although the span can be inputted for a lift estimate, the program does not account for the loss of lift associated with the reality of a wing of finite length. This means that lift outputs from the program, and equation 34, give the same lift for two very different wings (short and wide and long and thin) as long as the plan is the same.

In reality, vortices exist at the tips of a foil and extend onto the top and bottom surface of the wing in a pattern similar to that shown in Figure 21. For this reason, wing tips commonly have a rounded end (in plan profile) to improve lift to weight efficiency, and to reduce drag and energy lost in the generation of the vortex.

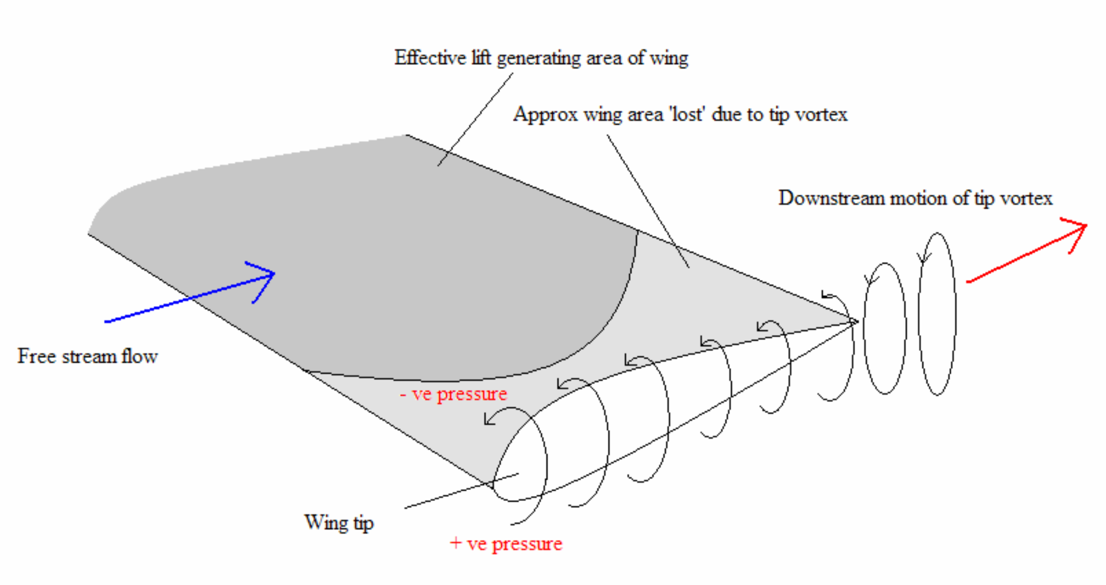


Figure 21 - Loss of wing efficiency as a result of wing tip vortices

However, rounded wing tips significantly increases the design and manufacture complexity, and eliminates the possibility of constant section design and associated manufacture productions such as extrusion and pultrusion. A simpler method of minimising this area of energy loss is to use a device to minimise the strength of the vortex, by providing a barrier between the two areas of pressure. Bulbs and wing end plates are two such devices and can have a marked improvement on the performance of the wing.

A simple model for the efficiency of the plan area of the foil has been used for the design of the foils to account for the area lost to tip vortices. The formula [Marchaj, 1991] is such that at an aspect ratio of 1 (span = chord) two thirds of the wing surface area is ineffective at producing lift:

Real Lift: $$L_R = \frac{LR}{2+R}$$ **Equation 35**

By designing a constant section wing carefully, wing tip vortices can be kept to a minimum. As the aspect ratio (span / chord) of the foil increases (a longer thinner wing), so the lifting area lost to wing tip vortices as a percentage of the total plan area reduces resulting in a more efficient wing. However, as the aspect ratio increases, so the does the structural slenderness ratio, reducing its resistance to bending and buckling.

As the thickness of a foil is directly proportional to the chord of the foil, an increase in aspect ratio also results in a thinner, weaker foil. The optimum compromise between the two has been modelled in Appendix 9 - Optimising Aspect Ratio - Foil Design and explained in the Technical Report, section 12.3.

4.7.5 Foil Velocity *v*:

The speed of the boat and hence foils is a function of the predicted velocity of craft in typical operating conditions, including wind speed and consistency, free surface conditions (chop and waves), craft direction relative to wind and indeed sailor competency. As these factors are beyond the realms of valid theoretical prediction, the speed of the craft has been taken as a conservative estimate of the operating speeds of similar sized dinghies through consultation with experienced sailors.

Rough computer based velocity prediction programs (VPP's) can be generated through empirical data and estimates of drag, but have been left out of the design process for this early stage of the project. Instead, it is hoped that our data logging system (see Chapter 7) will provide the necessary data to build a model of the boats typical performance and potential in various sailing modes (reaching, running, close to wind etc.) and conditions.

For design purposes the operating velocity envelope for the hydrofoils has been modelled for **0 knots < speed < 25 knots** (12.5 ms^{-1}) with an estimated functional (flying) envelope starting at **5 – 8 knots** (2.5 – 4 ms^{-1}). This is further described in the modelling section 12.3.

4.7.6 Designing against cavitation

Although not a direct factor in the design formulae discussed above, cavitation represents a very important boundary condition in practical hydrofoil design. Cavitation is the formation of bubbles of air or water vapour in close proximity to a submerged surface. The phenomena can only occur in liquids, as the bubbles form as a result of areas of tension in the fluid generated in areas of between very high and very low pressure which would not be possible in a gas due to the weak intermolecular bonds of the fluid.

Cavitation exists in two main forms, of varying strength and type of affect on hydraulic machinery performance. i) **Cavitation** in the strict sense of the word occurs when a region of low pressure fluid drops below the vapour pressure of the given fluid at the immediate ambient temperature. This action causes the fluid to vaporise spontaneously, generating bubbles in the flow field. As these bubbles travel back into an area of higher pressure, they collapse very rapidly, creating a shock wave in the fluid powerful enough to damage even high-grade steel machinery. The process also generates noise, vibration and deterioration in machinery performance and enhances the effects of silt erosion and chemical corrosion.

When designing for the relatively low speed foils being considered in this application, this form of cavitation is unlikely to be a direct problem. The fluid velocities required to generate areas of sub-vapour pressure are not likely in the context of small-sail powered hydrofoil use, although it is would be an essential design consideration and boundary condition when designing foils for use on engine powered craft exceeding 30 knots ($15ms^{-1}$).

The method by which the pressure field can be modelled and checked for possible cavitation is explained in the Technical Report, section 13.1

ii) **Artificial Cavitation**, also known as ventilation; this form of cavitation occurs when a low-pressure region of fluid causes the entrainment of air into the fluid from a nearby free surface or submerged source. Whilst the effects of the generated bubbles are not damaging in the extensive way described above, the entrained air can result in a dramatic loss of lift on a hydrofoil.

Instead of the pressure drop across the depth of the wing serving to generate lift, the negative pressure region on the wings upper surface is satisfied by the generation of a air cavity. The effect is to the wing into a planning plate with a theoretical loss in up-thrust of fifty percent (see Chapter 2.1).

Ventilation can be brought on by a variety of factors that have been addressed in the design of the prototype foils:

- Poor surface finish and abrupt features on surfaces crossing the free surface boundary.
- Lifting surfaces crossing the free surface boundary.
- Tight convex and concave curves on the profile of the wing causing peak locations of negative pressure on the upper surface.
- Large angles of attack causing the flow to separate at the leading edge of the foil.
- Interruptions on the surface of the foil, such as sharp corners, trailing edge flaps and other lift control devices.

In aerofoil design, surface features are commonly used to enhance performance; however, the 1000 fold increase in fluid density with hydrofoils necessitates the use of simpler streamlined forms and more subtle methods of flow control.

4.7.7 Integrating foil design and control

In order generate a profile that performs well over a varying lift, the control system must work well with the main lifting body of the wing increasing circulation without interrupting flow over the rest of the wing. This can be achieved through variation in the angle of attack, foil section shape, the use of a trailing edge flap, or by supplementing the base circulation using an auxiliary foil. These ideas are discussed in applied form in Chapter 6.4. In most cases, the added shape complexity has the potential to cause ventilation by introduction of localised peaks in dynamic pressure.

For the prototype hydrofoils, a trailing edge flap system has been incorporated. Although the join between the flap and the main body of the wing presents a possible site for ventilation, the flap angle of attack has been kept to a minimum by using a flap takes up a nearly a third of the main body of the wing. The trailing edge flap system has chosen for simplicity of design and predictable performance output from *Visual Foil*.

4.7.8 Design for loading – the foil as a structural member

In order to maintain the lift to drag efficiency of the foils the inverted-T prototype foil assembly needs to be able to take the worst case and constant load without an external support structure. This design issue discussed in brief above plays a key factor in deciding the chosen profile of the foils.

In order to retain the correct shape, the centre of flexure (CF) of a wing must match up with the centre of pressure (CP), the point through which the lift force can be considered to act. By designing to keep these points in the same position, the torsional load on the wing can be minimised.

Visual Foil gives an output value for the centre of pressure, which can then be used to design the internal load structure of the wing such that the CF then exists at this same point. The CP is commonly modelled for simple wings by the quarter chord rule, i.e. the CP exists a quarter of the total chord from the leading edge.

This places the requirement on the foil section design that at the quarter chord position, there must be enough internal space to place a load member capable of taking the worst-case lift from the foil. This factor is explored in conjunction with the aspect ratio optimisation in Appendix 9.

4.8 Foil Design output

The following design outputs are taken from the NACA foil selection process and Appendix 9:

Struts: (all three are the same)

NACA	**0018**
Length	**1.4m**
Chord	**0.18m**

Wing structure: box section square steel 25mm at 3mm wall thickness (the nearest stock commercial product – 1 inch linished bar was used and checked and confirmed suitable). The three-millimetre GRP wing skins will be made up from the layered glass structure as described in the manufacturing process decided subsequently.

Foils:

Front:	**NACA**	**25014**
	Span	**1m**
	Chord	**0.18**
Rear:	**NACA**	**25014**
	Span	**0.8m**
	Chord	**0.18m**

Wing structure: as above, but using 19mm (3/4inch stock) box section steel bar and the GRP skin structure described above.

4.9 Design for Manufacture

In keeping with the aim of producing a commercially viable hydrofoil craft, the methods and ease of manufacture and the types of material used also need to be incorporated in the design of the foil system.

One method explored in the prototype foils is to use an asymmetric foil section for the lifting foils, whose upper surface profile doubles up as both sides of a symmetric foil for the struts. As the profile of the lifting foil is more critical, this was set first as NACA 25014 and then a symmetric four-digit foil found to fit the upper surface geometry of the five-digit foil. A very close correlation was found to be NACA 0018, a profile that is commonly used for the rudder and centreboard tasks that the strut sections are replacing.

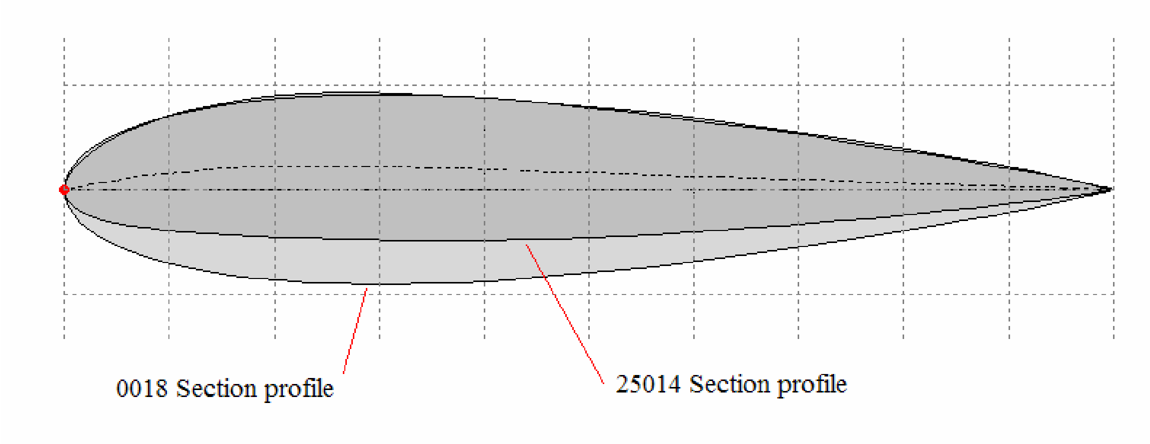


Figure 22 - Correlation of NACA 25014 and 0018 for manufacture.

This cuts the number of moulds required for the prototype production to two from a possible three or four. Although manufacture time is potentially increased, the method is cheaper.

4.10 Foil production process

As stated in section 4.5 Introduction to Prototype Foil Design it is imperative that the foils are precise and accurately manufactured. With the foil measuring [180mm by 1000mm] and following a detailed construction method it is vital that each feature is carefully accomplished.

The key area of a foil is the trailing edge. If this area creates turbulence the hydrofoil will not work as efficiently as necessary.

After designing the foils, it was decided that by manufacturing the foils in two halves would be the most practical way of creating an acceptable trailing edge. By creating two halves of a foil, a top and a bottom, then attaching them at the front and rear ends would allow a simple manufacturing process, as well as being precise.

With two halves of a foil, it allowed a greater amount of flexibility when inserting internal beams, needed for both strength and rigidity. A large amount of work was required to uphold the strength of the foil; therefore having an open section from which to work was vital.

Due to the precise curvature of the foil surface it was agreed that a wooden mould, similar to that used in the hull manufacture, would not provide the necessary accuracy from which to work.

A mould from which the foils could be made was the best solution for the problem. A plaster mould was therefore agreed upon, because of its strength, ease of manufacture and the ability to be repeatedly reused, with no change in dimensions.

4.11 Manufacture of moulds

Cut the top and bottom halves of the wing profile into a piece of Perspex and polish in order to create the perfect foil shape. This will be used to shape clay, placed in a box, from which a cavity mould is generated. Build a high-sided box that will house the clay, the width of the box must be equal to the width of the Perspex profile.

Figure 23 - Mould Manufacture, Step 1

Fix 10mm wooden rails into the base of the box parallel to the sides, such that the distance between these rails is a little more than the length of the wing, from the leading edge to the trailing edge.

Soft clay was then placed into this box, and when shaped using the Perspex the plaster could be poured over in order to form the cavity mould. Dragging the Perspex through the clay, and removing excess clay with successive passes generated the final mould shape. Using a lightweight oil spray, WD40, when finishing the shaping left a high surface quality finish.

Figure 24 - Mould Manufacture, Step 2

Figure 25 - Mould Manufacture, Step 3

Before the clay dries and shrinks, pour mould making plaster into the top half of the box and leave to set on a level surface.

When the plaster cavity mould is dry, a process that lasted two weeks at room temperature; it was necessary to ensure all the moisture was removed from the plaster. The tool could then be removed from the mould, and was ready for use in the manufacture of the foils.

Before the resin could be painted into the moulds it was imperative to firstly cover the surface in a waxing agent, this ensured no damage was done to the moulds so they could be reused throughout the foil making process.

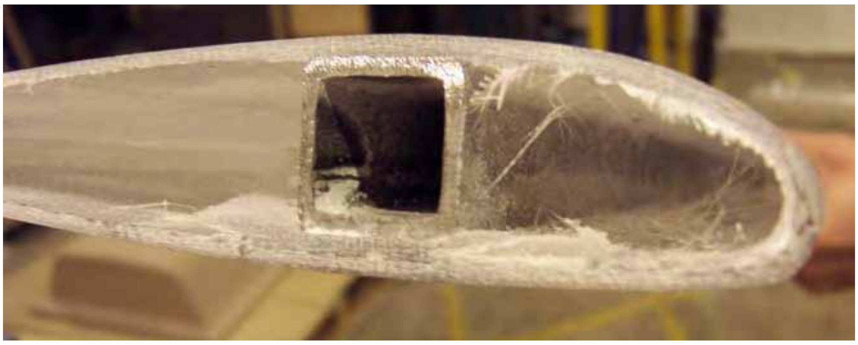
Wax the surface of the mould using a toluene free, clear, canuba based wax, such as Briwax. Use two layers of Briwax to seal the plaster and finish with two layers of mould release agent such as ambersil release agent 1.

Figure 26 - Foil Manufacture

Allowing the wax to dry was very important, as was putting on a continuous layer across the whole foil mould. Paint polyester resin into the moulds and layer two layers of random fibreglass scrim cut to fit the profile as near as possible. Add more resin and lay two layers of full chord coverage glass fibre, followed by two shorter layers at the quarter chord position.

For the foils that were to be used in the upper foil surfaces a steel beam had to be fixed to the surface of the foil. Therefore, more resin was applied to the wing skin, and a layer of 25mm wide thick-chop strand matt was laid along the quarter chord position. The steel member was placed on the wet chop strand glass, and again, further layers of lightweight glass fabric were placed over the steel member to hold it in place.

5 THE PROTOTYPE FOIL ASSEMBLY



6 CONTROL SYSTEM DESIGN AND BUILD

6.1 The function of the control system

The foil control system is a vital part of the project. The control system is necessary to keep the boat stable whilst in flying mode and to prevent the boat from pitching and heeling excessively when lifting.

6.1.1 Foils for Stability

With a simple, uncontrolled foil, the up-thrust generated increases as a function of the square of the velocity of the foil. As the lift increases it reaches a point where it becomes greater than the weight of the boat and causes the craft to rise out of the water. Although this is the desired effect, if the foils have no means by which to change their lift coefficient, as the boat accelerates the foils will continue to increase their lift force until the foils reach the surface of the water, aerate and fail. The result will be a boat that rises quickly onto the foils and then crashes back down to displacement sailing. The boat needs to remain in flying mode over a range of velocities. In order to do this, the lift from the foils must remain constant and equal to the weight of the craft, adjusting accordingly to the velocity, to keep the craft stable and level.

6.1.2 Foils to reduce pitching and Heeling

With the varying hull altitude along with motion and direction of the sail, the load distribution between the three foils varies significantly. In order to keep the craft performing as designed, in a near level flying mode, it is important that the system of foils adjusts individually accordingly to these varying loads.

As the load increases on a foil, as a result of changing moments about the mast foot, a simple foil will begin to sink into the water. In a controlled system, this sinking motion should result in an increase in lift from the foil, finding a new point of equilibrium.

6.2 Methods of Control

The control could be a manual system, requiring a skilled 'pilot', or a passive system, which responds to the foils' depths below the water surface. This will prevent the boat lifting in and out of the water constantly as the control system will ensure that a steady lift, appropriate to the current condition, is generated.

As the hydrofoiling boat is to be a single-handed craft, it is preferable for the foil system to be self-adjusting, leaving the sailor to be concerned with the standard elements of piloting the craft: controlling sail attitude and the position of the rudder. In order to generate this element of performance; a simple and effective passive feedback system is needed.

In other hydrofoil dinghy designs the foils are generally either fixed or capable of varying their angle of incidence, thus changing their lift coefficient.

Fixed foils may be angled to be part submerged, and part above the water surface, so that as they rise, the submerged area of foil decreases, and equilibrium is achieved.

However, foils that break the surface cause wave drag and suffer from ventilation, which is the pulling down of air to the upper surface of the foil due to a decrease in pressure. Thus, fully submerged foils, with some means to prevent them reaching the surface, are potentially more efficient. More detailed reasoning for this can be found in the Technical Report, section 13.3 Final Design.

6.3 Design Specification

The control system must have the following features:

- Passive control - To allow the dinghy to ride stably on the foils with no additional input from the sailor.
- Height detection - It must be able to determine when the hull is in or close to the water so it can increase lift and when the foils are close to the surface of the water in order to decrease lift.
- Capacity to vary lift - in order to maintain a balanced flight.
- Real time input - It must detect and respond to the conditions instantly.
- Transducers close to foil - The height detectors that control each foil must be close to that foil. If the front foil detector trails behind close to the rear foil, when the boat pitches backwards, (the bow points upward), the front foils will be too high but their transducers will be pushed up towards the hull and will detect that the lift needs to increase, thus magnifying the problem.

- Ease of manufacture - The prototype must be made with the resources available in the University workshops. The final design will need to be mass-produced so needs to be simple to construct.
- Simplicity - Require minimum amounts of technology and moving parts so it is simple to attach, maintain and repair.
- Tuning capability - Once the system has been fitted to the dinghy it will need adjusting to calibrate it to the exact weight and dimensions. A commercial product will need to have this facility so it is suitable for sailors of all sizes and weights.
- Durability - The nature of sailing requires the control system to be strong enough to withstand high forces and impulse forces.

It would also be desirable to have the whole system incorporated in the foil and strut assembly. This would allow future development of the product to include different types of foils that can be attached. For example, there could be a range of learner, cruising and racing foils so that buyers can change the foils on their boat to suit their needs. If the control system uses a complicated system of pulleys and rods it will be difficult for owners to fit their own foils.

6.4 Design Process

Many design possibilities were identified in the preliminary stages of design, most of the ideas didn't get developed beyond the initial concept, but four systems emerged as realistic possibilities. They are introduced here, with further development of two of them detailed in the technical report.

6.4.1 Design Concept 1: Aerated Flow Control System

The aerated flow control method is based on the concept that aerated flow over the surface of a hydrofoil has an adverse affect on lift as explained in section 4.2. By passively controlled introduction of air cavities into the flow at the leading edge of each foil, lift can be destroyed in that section of the wing. By placing a series of holes along the leading edge, the lift can be progressively (in discrete steps) varied from wing tip to root.

The system uses the negative pressure peak generated at the leading edge of the foil to draw air down from above the free surface. A network of tubes connects inlet holes on the strut to corresponding holes on the leading edge. Figure 27 shows a simplified system diagram of the concept.

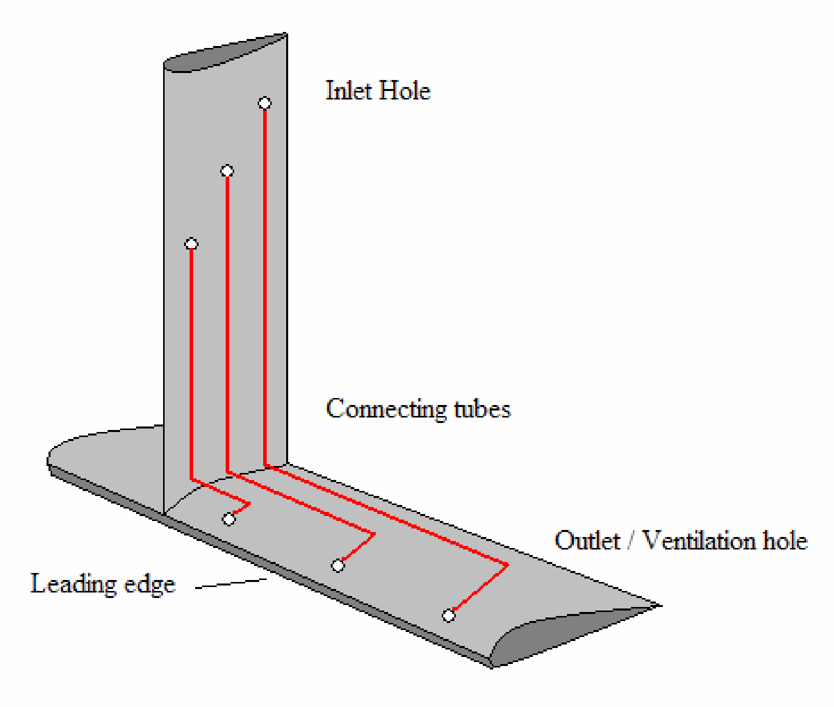


Figure 27 - Aerated Flow Control System

As the uppermost hole on the strut breaks the free surface, the change in viscosity of the surrounding fluid causes air to be drawn into the connecting tube and fed to the leading edge of the wing. The vented air destroys the lift over the end section of the wing, returning the foil to state of equilibrium. If the foil rises to close to the free surface, the total lift of the foil could be removed entirely, by aerated the whole upper surface.

In a prototype design version, more holes would be used to increase the sensitivity of the system. The system has the beneficial features of being entirely self-contained within the volume of the foil, and having no moving parts. If proved as a successful working system, the control method could provide a major advantage over competitor craft.

Insufficient test material and theoretical work was produced for this years prototype, but further work is suggested in Chapter 8. The test material and a brief technical summary of the system is given in the Technical Report, section 13.1.

6.4.2 Modelling of the Aerated Flow control system

In order to design the control system effectively it is important to know how we need them to behave. When the boat is foiling the lift from the foils will need to be equal to the total weight of the boat and will also need to balance the moments from the sailor and the wind load on the sail. The programme in Appendix 5 models how the aerated flow control system should work. For an inputted wind speed it calculates the total length of foil that is needed to make the boat stay above water and also calculates the effective length of each foil to make the boat balanced about all axes; so the downwind foil gives more lift than the upwind foil to compensate for the heeling moment from the wind. This model would have enabled the design of the foils and struts including spacing of holes. Once the holes spacing was designed the model could have then been modified to predict the height above water and the heeling angle of the boat for any wind speed.

The spreadsheet starts with the inputs, such as the dimensions of the boat and the foils, including the total length of the foils. It then uses an iteration approach to calculate the speed of the boat with respect to the wind speed.

The wind speed has to be set in the spreadsheet. The speed of the boat is predicted by balancing the forces. It must first be guessed at to allow the driving and drag forces to be calculated. Then it is repeatedly changed until the forces balance.

The driving force of the boat comes from the wind on the sail and the opposing force comes from the drag on the hull and foils. Other forces such as the aerodynamic drag on the hull and sailor are assumed negligible.

Marchaj [1991] gives the driving force for a dinghy as

$$F_D = \frac{\rho_a A V^2 C_D}{2}$$

Where

ρ_a = Density of air

A = area of sail

V = apparent wind speed

C_D = driving coefficient of sail

The driving and heeling coefficients are properties of the sail shape. When each is multiplied by half the area of the sail, the density of the air and the wind speed squared, they give the driving and heeling forces on the sail respectively.

The values for the sail used in the final design were are not known. The only data available was from a graph in Marchaj [1991], which is can be seen in section 13.1 of the Technical Report. The graph is for a Finn-type dinghy and the wind speeds are not stated. However, the model is to be used as a guide to the speeds achieved and is not expected to be precise.

The apparent wind speed is made up of the actual wind speed and the rush of air as the boat moves through it. The angle of attack, β, actual wind speed and the boat speed are all inputs for the model so the apparent wind speed can be calculated by vector addition.

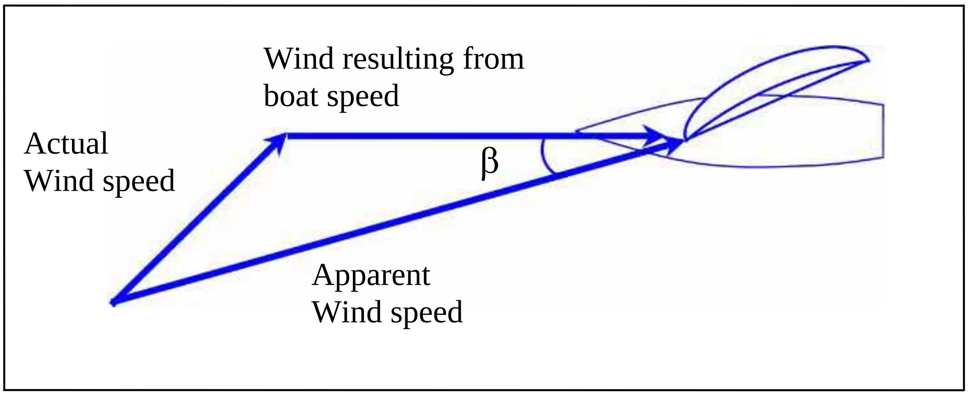


Figure 28 - The apparent wind speed is found by vector addition of the boat speed and the actual wind speed.

The sail area was determined by adding up the areas of each section. The sail is divided into sections by the battens and the spaces between the battens were considered to be rectangular. The distance from the mast to the centre of each rectangular section was multiplied by the area of the section, and the sum of these results was divided by the total area of the sail to find the centre of effort of the whole sail.

The drag on the foils was calculated from the drag equation:

$$F_d = \frac{\rho_w A V^2 C_d}{2}$$ **Equation 36**

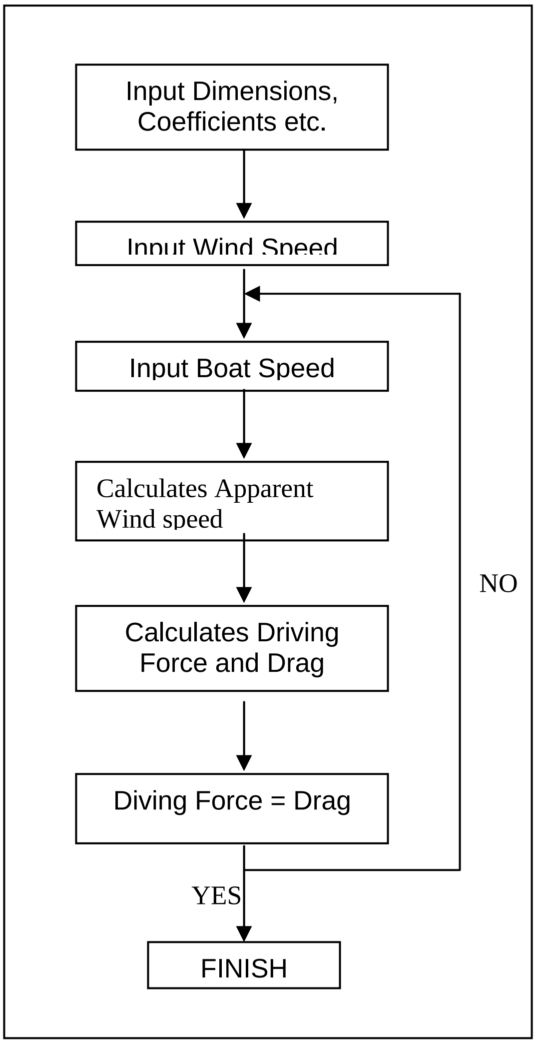
A = Area of foil = span × chord

$$F_d = \frac{\rho_w s c V^2 C_d}{2}$$ **Equation 37**

The drag coefficient, C_d, is found using Hanley Innovations, Visual Foil. The drag acts on the whole length of each foil and not just the sections that are providing lift.

The drag on the struts was found using the same formula, as the struts are also foil shaped.

Figure 29 - Flowchart to show how to use the spreadsheet model.



The boat will travel at a constant velocity when there is a net force, in the direction of the boat, equal to zero. In practice the wind will not stay perfectly constant and the waves in the water will vary the drag on the boat but for the sake of modelling we will assume that these factors have no effect and at a set wind speed the boat will reach a steady speed and continue to travel at that constant speed until the wind changes or the sailor changes direction or decides to stop.

The model then adds up the drag and compares it to the driving force. If the driving force is greater than the drag, it displays “increase boat speed” and the operator must return to the boat speed and increase it. If the driving force is less than the drag it displays “decrease boat speed”. If the drag is less than 1% different from the driving force the model displays “OK”. The operator can then be satisfied that the forces balance and the boat will travel at that speed.

With the known wind speed the spreadsheet then goes on to calculate the heeling moment from the wind and the opposing moment from the hiking sailor. With the net heeling moment the programme calculates the required lift from each foil by balancing moments. The final outputs for each wind speed are the three required effective foil lengths and the boat speed.

6.4.3 Design Concept 2: Trailing Wand

To date, the most commonly used system, and that incorporated on the successful Windrider RAVE and Ceres trimarans, is the ‘trailing wand’:

The crossbeam supports two-inverted "T" shaped hydrofoils at the front of the boat. There is a further foil in place of the rudder. The two front foils are linked to trailing wands, which adjust the foils.

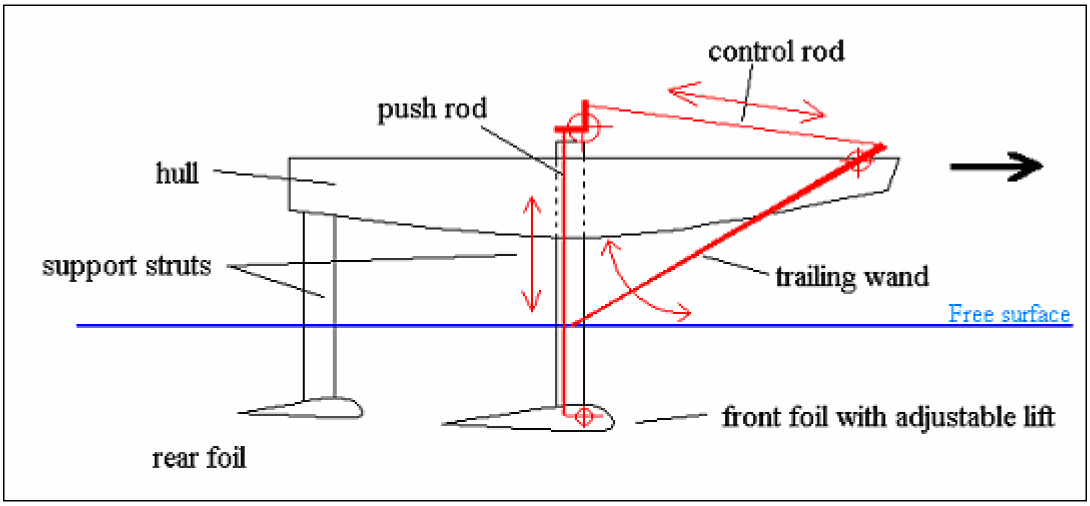


Figure 30 - Trailing Wand Control System

The trailing wands skim along the surface of the water, with their tips positioned near the leading foils (Figure 30). By means of a system of linking control rods, the varying height of the wand tips relative to the hull adjust either the angle of attack, (Ceres) or trailing edge flaps, (RAVE) on the main lifting foils, increasing lift if the foils sink too far into the water, and reducing lift if the foils rise too close to the free surface.

The rudder foil can be designed in two ways:

1. Fixed Stock Rudder Foil

The stock rudder foil is a neutral, following wing. As the front foils rise, the angle of incidence increases giving the rudder foil lift to raise the boat completely out of the water. Once the boat is foil borne the rudder foil returns to near neutral. The system is designed to be neutral at the design/optimum flying height, with minimum drag in ideal conditions.

2. Adjustable Rudder Foil

The adjustable rudder foil has the same design as the front foils, using either variable pitch or trailing edge flaps. Moving a control arm on the side of the cockpit can control lift and drag. This can assist when becoming foil borne and in controlling the boat when flying.

6.4.4 Design Concept 3: Free Surface Planing Floats with Variable

This concept uses a planing float, attached to the foil strut that skims on the surface of the water, connected to the foil by a mechanical linkage. Foils are adjusted, according to the ride height that is measured by these planing floats, and ensure a constant height.

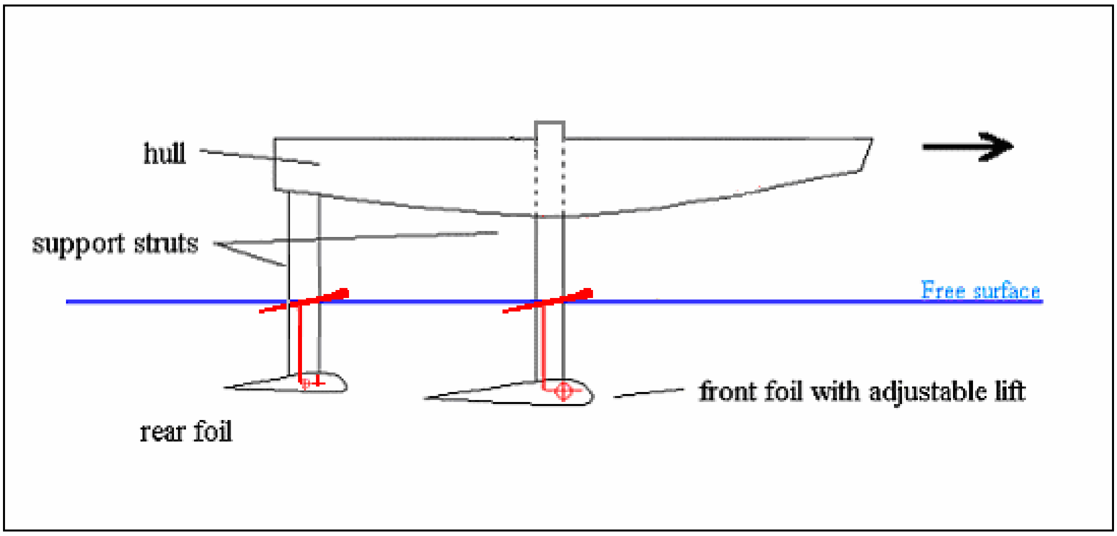


Figure 31 - Adjustable Wing Control System

The foils are either variable pitch or have trailing edge flaps, as in Design Concept 2 above. Figure 32 shows a possible arrangement for the linkage between the planing float and the trailing edge foil flap. This arrangement keeps the mechanism to a minimum so will be simple to construct and maintain. Fewer moving parts reduce the possibility of the mechanism breaking down.

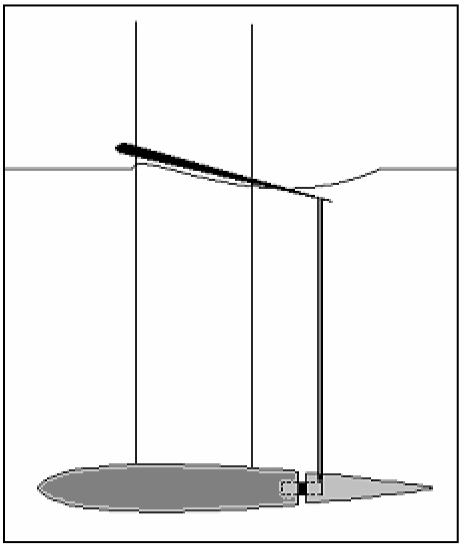


Figure 32 - Planing float control with trailing edge flaps

This is a variation of the system used on the hydrofoil catamaran, the Trifoiler, which uses a more complicated system to adjust the foils.

6.4.5 Design Concept 4: Dual material foil

This fourth design exploits the varying pressure distribution over the foil. If a different material is used in the critical section, (the trailing end) the foil could change shape purely by the pressures exerted on it through movement in its current environment, without any additional input.

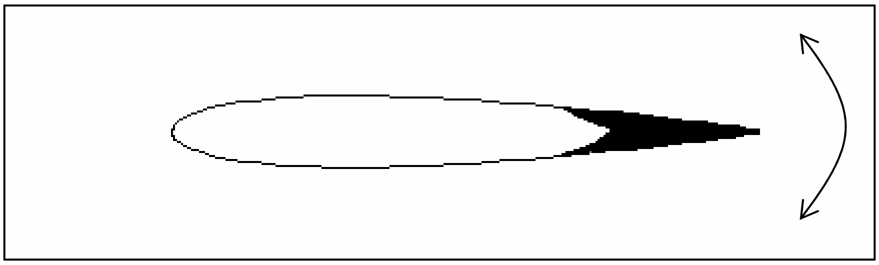


Figure 33 - View of foil made from 2 different materials

By using solid rubber that only flexes when undergoing considerable pressure changes the foil could alter form, and hence alter the amount of lift provided.

The wings of birds inspired this concept. The feathers are structured in such a way that if the wing experiences a drastic change in air speed, the feathers blow open and spill the lift, rather than turn the burst of air into a burst of lift.

The problem lies in finding a material that has the exact properties that are needed. The design would be difficult to adjust.

6.5 Final Design Outputs

The preferred method of control was the aerated flow control system because of its simplicity and originality. However, the tests concluded that this control method could not be made to work, so an alternative method was needed.

The Free surface adjustable wing was not used because it would require a calm water surface to plane on and would also not allow any heeling. One of the advantages of hydrofoiling boats is that they are not affected by the water surface conditions, so a control system that could only be used on a calm day is not appropriate.

The dual material concept was also rejected because certain properties, such as the young's modulus, would have to be perfectly suited to the foil. It would also be very difficult to fine tune and adjust for different circumstances. A mechanical system is therefore preferred.

Consequently the trailing wand concept emerged as the best solution. It is a tried and tested method that has been proved to work well.

Within the trailing wand concept there are design choices to be made. The first is whether to use variable pitch foils or trailing edge flaps. Variable pitch foils require hinges at the connection points between the foils and struts. These hinges have to transmit the entire lifting force of the foils to the struts. They would have to be extremely durable and strong whilst also being easy to rotate.

Figure 34 - Adjusting Flap System

Trailing edge flaps allow fixed joints between the foils and struts. These joints will transmit the lifting force to the struts while the flaps adjust the lift. Fixed joints are generally stronger and more durable and the same results are achieved by using the flaps. Therefore the flaps were identified as the most suitable method of adjusting the lift.

The next decision is whether to have a fixed or adjustable rudder foil. A fixed foil has the advantage of simplicity while the adjustable foil offers greater control. The adjustable foil requires a trailing wand with its tip directly above the foil. This presents the problem of where to mount the wand.

The adjustable foil is not necessary. When the front foils lift the hull the boat will pitch backwards so the bow points upward. This will automatically change the pitch of the rudder foil so it will increase its lift. If the boat decelerates the front foils will begin to reduce lift, pitching the boat forwards and changing the rudder foil pitch angle to reduce lift. The rudder foil can be designed to be at the correct pitch relative to the hull so that it will adjust the boat to an equilibrium state automatically for a range of speeds. It means that the boat will pitch slightly so at low foiling speeds the boat will pitch backwards and at high speeds the boat will pitch forwards.

The fixed stock rudder foil will be used because of its simplicity and because the adjustable foil is not necessary.

6.5.1 Wand Attachment

The trailing wand is the ride height measurement device. On existing foil boats the wands are mounted on the bow of the hull so their tips are level with the foils. They are then connected to the foil flaps by a system of rods. To cut down on the complexity of the system the initial design had the wands mounted on the beam above the foils. However this left the wand tips trailing behind the foils. If the wands trail behind the front foils, when the boat pitches backwards the rear of the boat will be too low while the front foils are too high, but the tips of the wand will detect that the boat is too low in the water and increase the lift of the front foils. It follows that to be most effective; the wand tips should be measuring the ride height directly above the foils.

The trailing wands will be attached to additional beams extending from the front of the main foil beam so their tips can still be in line with the foils.

6.5.2 Foil Adjusting Rod

The planning floats on the wand tips must move through a certain range as the boat lifts and drops in the water. This range of movement must translate to move the foil flaps through their range of movement. This is done by a mechanism of rods and pivots shown in Figure 35.

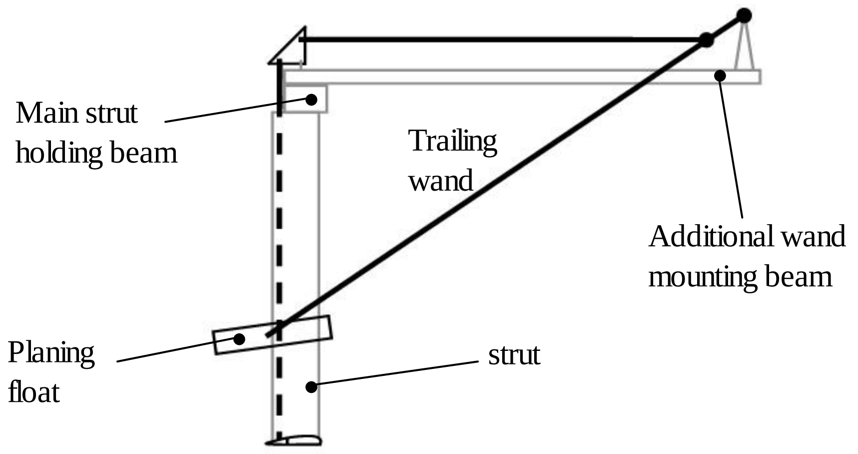


Figure 35 - Trailing wand mounting arrangement

The foil has a plastic hinge to attach the flap to the main body of the foil. The flap is manipulated by a push rod that travels up the inside of the rear edge of the supporting strut see Figure 35. It is attached at the top to another rod via a triangular pivot that translates horizontal motion to vertical motion. The horizontal motion comes from the rod being attached to the trailing wand between the float and the pivot. The dimensions of the system are explained in the Technical Report, section 13.1.

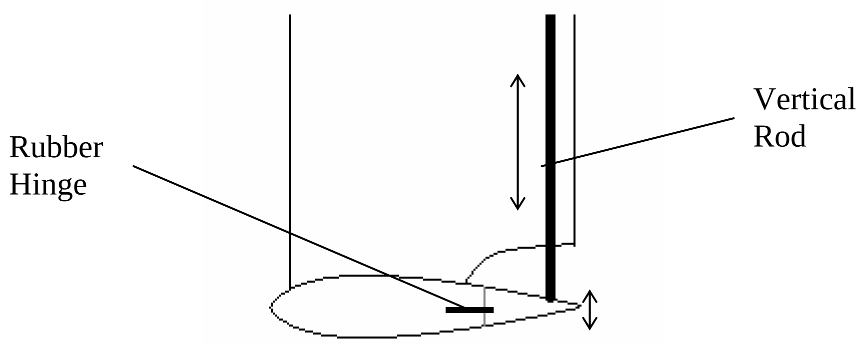


Figure 36 - Side View of Foil and Strut

6.5.3 Modelling of the Control System

Another spreadsheet programme to predict the performance of this control system is included in Appendix 6. The programme is based on the programme in Appendix 5, which models the aerated flow control system.

Visual foil gives lift and drag coefficients for different flap angles. The lift coefficient stays almost constant with varying speed (within the speed range of the boat) for a set flap angle. However, the drag coefficient decreases as the speed increases. This phenomenon complicated modelling because the coefficient is a function of both flap angle and speed. To simplify the model it was assumed that the drag coefficient was constant for each flap angle and the average coefficient was taken within the range of 6 to 20 knots. Investigation shows that the maximum error that this assumption gives is 19% for the range of flap angles used and the speed range given.

Formulae relating the average flap angle to the lift and drag coefficients were calculated, using the data from visual foil, and used in the spreadsheet model. The data and calculations for the average lift and drag coefficients can be found in Appendix 7.

The model works in much the same way as the aerated flow control system model. It uses an iteration to predict the boat speed and foil angles for a given wind speed. Once the wind and boat speeds have been put in to the spreadsheet it calculates the force on the sail and the required lift from each of the foils. Using the required lifts the programme then calculates the lift coefficients and the angles of the flaps required to produce those coefficients. Once the flap angles are known the drag is calculated and the model can instruct the operator to increase, decrease or leave the boat speed as it is.

The outputs of the model are the required angles of each of the foil flaps and the speed of the boat for each set wind speed.

A more detailed, row-by-row, explanation of the programme is included in section 13.1 of the Technical Report.

Appendix 7 shows the spreadsheets for a flap that is 20% of the length of the foil. They were both repeated for a flap of 30%. The 30% flap was found to be more suitable because it allows a greater range of lift coefficients and a larger flap is also easier to manufacture.

The 30% flap programme predicts that with an 80 kg passenger the boat will be able to foil at a speed of 8.9 knots (4.6 ms^{-1}), in a wind speed of 6.4 knots (3.3 ms^{-1}). This does not mean that it will take off at this wind speed because when the hull is submerged in the water the boat will travel slower because of the extra drag of the hull. It means that once the boat has risen onto the foils it should be able to stay foiling if the wind drops to 6.4 knots.

It was not possible to create a model that incorporates hull drag because there are no available methods of calculating the drag coefficient of the hull. Once the boat has been tested it will be possible to measure the drag coefficient of the hull. This will allow development of the programme to incorporate the hull drag to predict when the boat will actually rise onto the foils. This will be useful if the boat does not perform perfectly and adjustments are needed.

6.6 Evaluation

The final control system design achieves all of the targets set out in the specification. It has:

- Passive control
- Height detection
- Capacity to vary lift
- Real time input
- Transducers close to foil
- Ease of manufacture
- Simplicity
- Tuning capability
- Durability

It is not all incorporated into the foil and strut but this was only a desirable feature and is not essential for the prototype.

The aerated flow design concept that was investigated in detail did have this final desirable feature along with all of the other necessary features. Although the tests concluded that it would not work there is no theory to suggest that it cannot work. This is an area for further work. If the concept can be made to work it offers greater simplicity, durability and potentially greater ease of manufacture.

7 ELECTRONIC MEASUREMENT DESIGN AND BUILD

7.1 Introduction

The electronics aspect of the project is concerned with data collection and processing. The performance of the boat is to be measured so as to assess the success of the design and to assist with the boat testing and development. Collecting this information electronically provides a lightweight and flexible solution. Values must be stored for Apparent Wind Direction, Boat Speed, Height Above Water, and the output from strain gauges. The budget limit for the electronics is set at £150 this is low for such a system but is realistic given its context in the project.

7.2 Specification

- The device should collect and log data from sensors placed on the boat.
- The sensors must include Apparent Wind Direction, Apparent Wind Speed, Boat Speed, Height Above Water, and the output from strain gauges.
- The data should be able to be downloaded to a PC for processing and viewing.
- Enough data should be storable so as to give a good picture of overall performance for each excursion.

7.3 Design

7.3.1 System Design

Three basic system architectures are possible.

1. A remote datalogging system onshore with data sent wirelessly to a PC
2. Onboard datalogging to internal storage for later retrieval onshore
3. A hybrid system where performance can be monitored wirelessly with an internal storage backup

Remote data logging would require a transmitter receiver pair to a data collection system onshore. The easiest and most flexible way would be to use a laptop on the shore to collect and process the data from the receiver, using a program such as MATLAB or Labview. The advantage of this method is it provides real-time values for the shore team and could be integrated with a custom graphical display to provide a real time visual display of sensor outputs. Using a laptop would produce a virtually infinite data logging time as there would be no problem with running out of data memory.

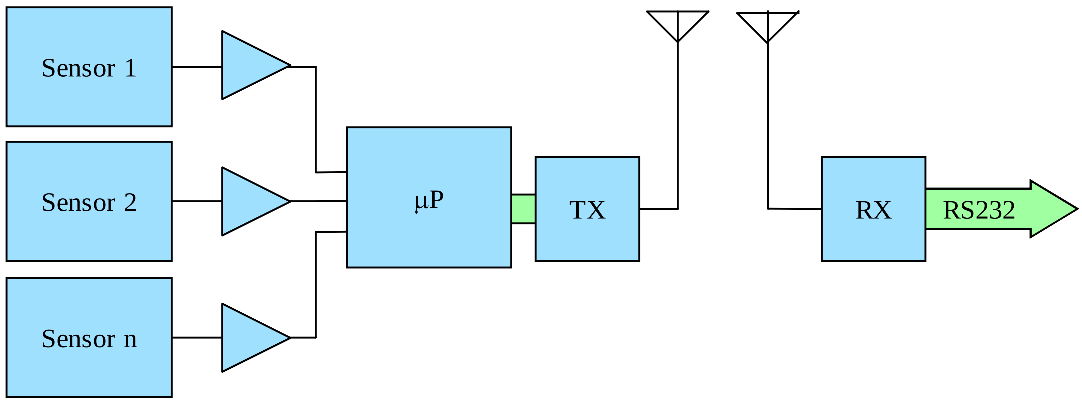


Figure 37 - Remote Wireless Data Logger

Logging for later retrieval onshore prevents the data being available immediately and limits the time and sampling rate for which data collection can be performed. However it should be more reliable than wireless transmissions as there will be no gaps in the signal due to loss of data. This design is also likely to have more environmental resilience due to less exposed parts.

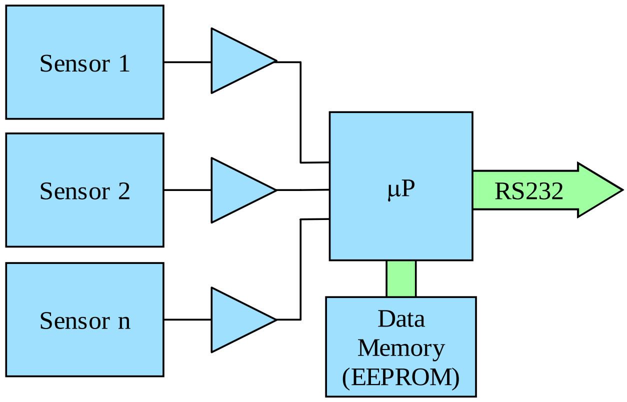


Figure 38 - Storage Data Logger

The hybrid system combines the advantages of both systems while elimination a large proportion of the problems. This would therefore be the most flexible, reliable and hence desirable option.

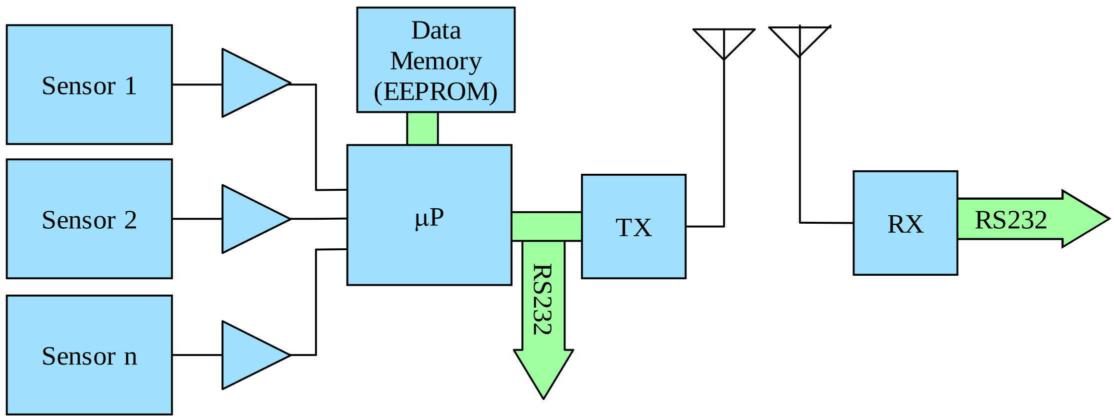


Figure 39 - Remote and Storage (Hybrid) Data Logger

It was agreed with the group that a wireless system would be the most desirable and so a feasibility study was undertaken. A range of a few km (distance across a typical lake/reservoir) with a data rate of only a few kbits/s is required since the sampling rate will only need to be around 1-2 times per second. Many wireless systems were considered but current wireless standards e.g. WiFi and Bluetooth were too expensive to implement and/or too short range. Therefore the use of a custom serial wireless modules was the obvious solution. This would allow the microprocessor to use its onboard serial to send the data wirelessly direct to the serial port of a laptop on the shore. Some of these were found to give a suitable range and data rate. The TX1 and RX1 modules were considered from radiometrix. These were priced at £60 for the pair, and hence considering the budget of £150 for the entire system were considered too big a drain on resources. Other modules were found to be of a similar price.

The alternative system, onboard datalogging to internal storage for later retrieval onshore was then considered. This would provide a lower cost alternative while maintaining all functionality apart from real time data processing. Such a data logging system is ideally suited to a microprocessor based design. Microprocessors designed for handling data, memory, peripherals and interfacing with a PC via RS232 for data transfer. The data required can be safely stored in low cost battery backed RAM or EEPROM for retrieval onshore. 8-bit data values would be sufficient for this application, allowing 256 levels per signal. This will simplify the system, and save storage space. The storage system was chosen over the wireless system primarily due to cost considerations.

7.3.2 Choice of Chip

The 8051 family of microprocessors seems ideal for this application. The 8-bit 8051 microcontroller is very well established in industry and much literature and software is available. The exact choice of chip was greatly influenced by the availability of a low cost development board. The 80C517a microcontroller was chosen for the system. This is a 100% 8051 compatible microcontroller with additional features. The main features of the microcontroller are shown below:

- Up to 18 MHz operation frequency
- ROMLess
- 256x8 on-chip RAM
- 2Kx8 on-chip RAM (XRAM)
- Superset of SAB 80C51 architecture:

  – 1 ms instruction cycle time at 12 MHz

  – 666 ns instruction cycle time at 18 MHz

  – 256 directly addressable bits

– Boolean processor

– 64 Kbyte external data and program memory addressing

- Four 16-bit timer/counters
- Powerful 16-bit compare/capture unit (CCU) with up to 21 high-speed or PWM output channels and 5 capture inputs
- Fast 32-bit division, 16-bit multiplication, 32-bit normalise and shift by peripheral MUL/DIV unit (MDU)
- Eight data pointers for external memory addressing
- Seventeen interrupt vectors, four priority levels selectable
- Genuine 10-bit A/D converter with 12 multiplexed inputs
- Two full duplex serial interfaces with programmable Baudrate-Generators
- Extended power saving modes
- Fast Power-On Reset
- Nine ports: 56 I/O lines, 12 input lines

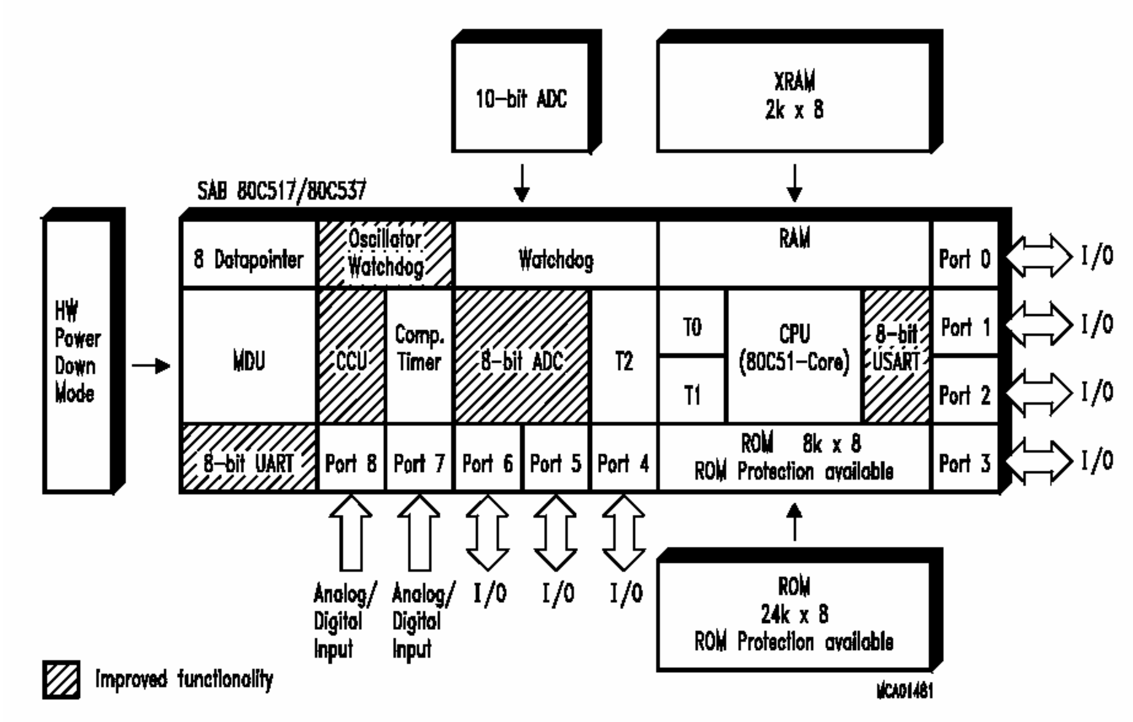


Figure 40 - Chip Block Diagram

Since a data logger is required with analogue inputs the most important features of this chip are the 10-bit A/D converter with 12 multiplexed inputs and support for 64k of external data memory. A 12 input A/D converter would be ideal for this application, allowing 12 separate inputs with no additional hardware required. It will not be necessary to use the full 10-bit sensitivity of the ADC since only 8-bit (1 Byte) values will be recorded to simplify the code and optimise storage space usage. The chip can support up to 64kbytes of external data memory, without the need for the coding of additional device drivers. This should be plenty for it's required application. Using all 12 input lines with a sampling rate of 0.5s per line gives only 24bytes per second and hence allowing the system to be run for (64x1024)/24 = 45 minutes, plenty of time to record a satisfactory set of results. In practice all 12 input lines will not be needed so a longer measurement time or a higher sample rate are possible. It may be necessary to increase sampling rate for some trips where accurate strain gauge or height above water is required. This would be achieved by reprogramming the data memory. It would be possible to have a switch to set sampling rate as high or low or two chips containing higher and lower sampling rate programs, for easy switching in the field. The microcontroller and memory can easily handle greater sampling rates than the maximum that would be required though any increase in sampling rate would obviously reduce the recording time and hence would only be required when this type of data was being collected.

A simple system block diagram is shown below:

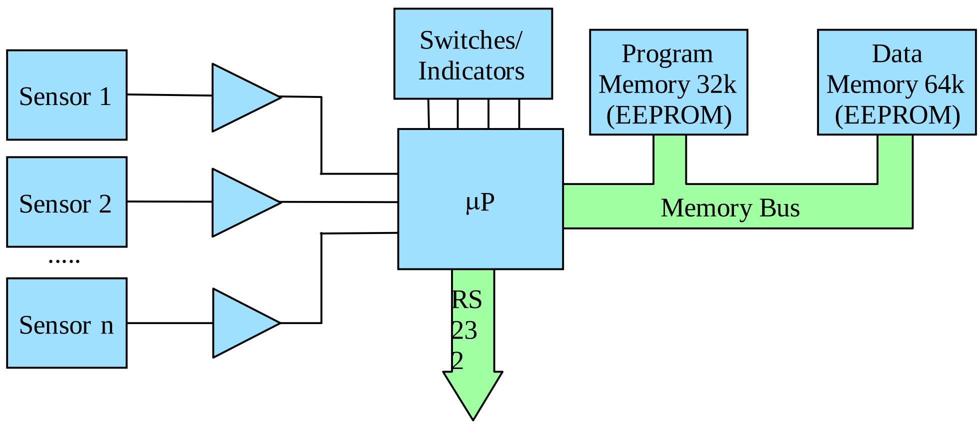


Figure 41 - System Block Diagram

The chip will be programmed in C, a much easier method than directly programming in assembler, and a more flexible one than BASIC. There are many software development environments available for embedded systems, supporting many chips and features, often including simulation and debugging. Of these Keil is a very popular program and directly supports the 80C517a including simulation of many of the features such as the ADC and additional arithmetic unit. Keil supports simulation debugging and compiling the developed programs, ready for upload to the program memory (external EEPROM).

7.4 Sensors

7.4.1 Wind Direction

Apparent wind direction can be simply measured using a multi rotational potentiometer with a wind vane attached. With a voltage applied the output form the potentiometer will vary linearly from between 0V and V_{cc}, ideal as input to an ADC for digitalisation. By setting the orientation of the potentiometer and measuring the output voltage, it is possible to calibrate the sensor in relation to the boat to give an angle of zero when head-to-wind.

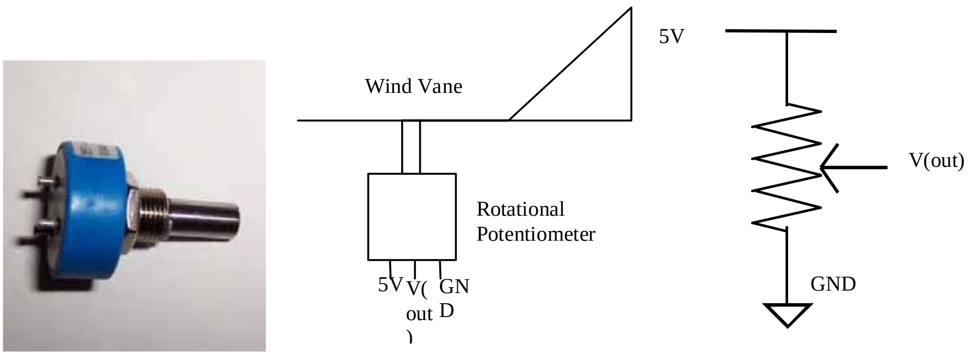


Figure 42 - Wind Direction Measurement.

7.4.2 Height above Water

The measurement of height above water is very similar to the measurement of wind direction in that a potentiometer is again used. The boat control system requires a trailing wand device to adjust the foils mechanically. This device can be modified to enable and electronic reading of this height to be taken. A potentiometer is added to the axle of the trailing wand and using a 741 op-amp with variable gain to attenuate/amplify the signal as required, the output voltage can be made to vary from 0-V_{ref} (ADC Maximum Voltage). The stored byte value represents the angle of the trailing wand between minimum and maximum values. The actual height above water is calculated by further processing after the data has been retrieved. Further details are given section 7.8 Data processing and presentation, and in the Technical Report, section 14.4.

7.4.3 Boat Speed

The measurement of apparent boat speed is achieved using a small impeller bought as a spare from the Nielsen-Kellerman range of sailing and rowing instruments. This is fixed near the bottom of the strut supporting one of the main foils. This is to ensure it remains in the water while foiling and does not interfere with the flow over the foils.

The impeller contains a magnet allowing a nearby pickup coil to detect the magnet's movement and produce a sinusoidal voltage. The pickup coil used is a solenoid from a 9V relay. A voltage with an amplitude of a few millivolts is produced whose frequency and amplitude are proportional to speed.

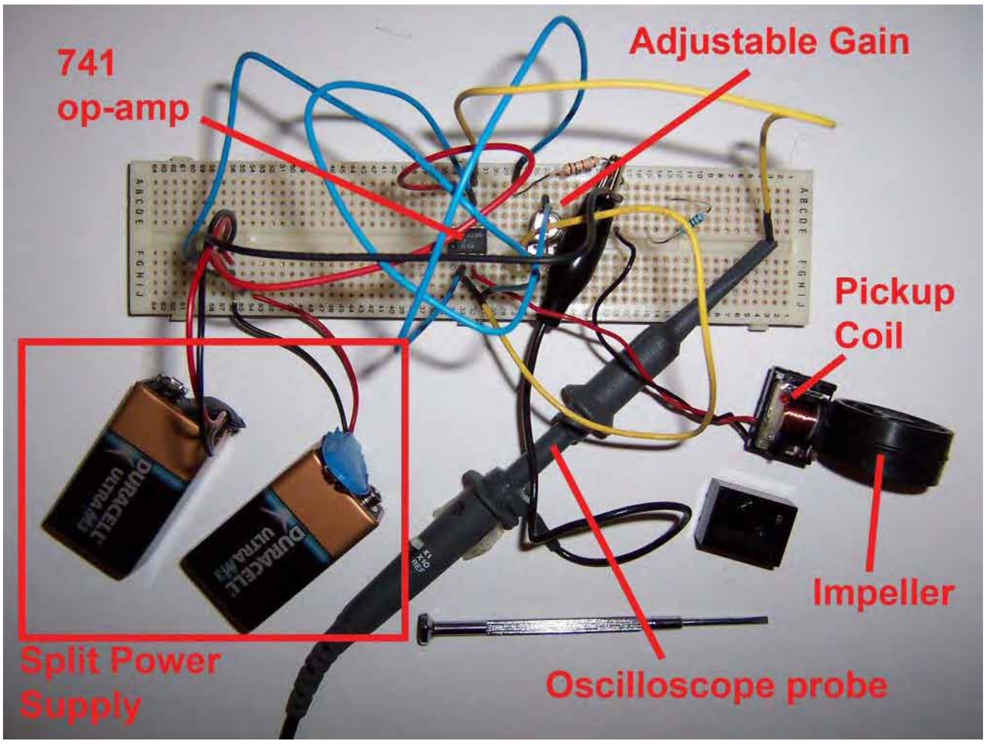


Figure 43 - Impeller Test Circuit

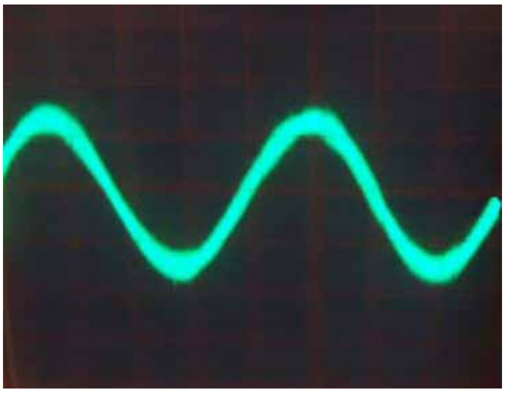


Figure 44 - Impeller Waveform

Although it would be possible to produce a reading using the amplitude, the frequency of the signal provided a more accurate method as this does not change due to sensor/pickup separation. The signal is then amplified and converted to a constant voltage using a frequency to voltage converter (tachometer). The output from the frequency to voltage converter is a voltage proportional to speed for input into the ADC of the microcontroller. Further Details are included in the Technical Report

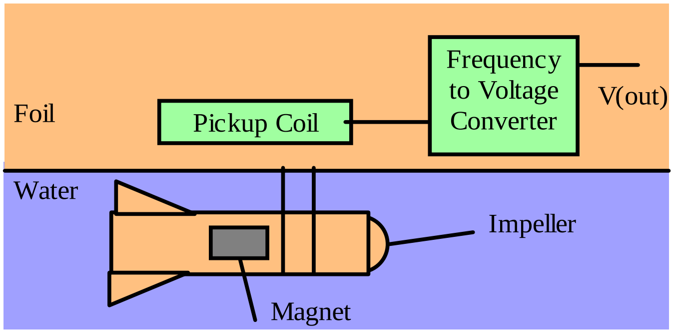


Figure 45 - Boat Speed Sensor

7.4.4 Wind Speed

The measurement of apparent wind speed also uses an impeller from the Nielsen-Kellerman range of sailing and rowing instruments. The impeller is fitted on the wind vane as shown so as to keep the sensor pointing into the wind:

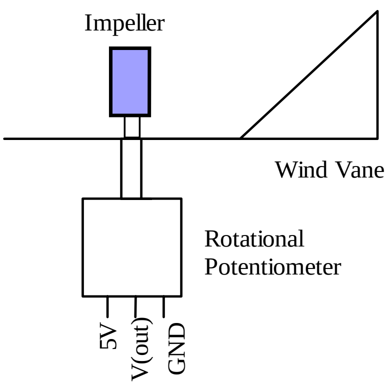


Figure 46 - Impeller position for wind speed sensor and impeller

The same impeller was used as for the water speed sensor for testing. The circuit is identical except for a reduced gain due to the impeller’s higher speed in air.

7.4.5 Strain Gauges

Strain gauges are used to detect a change in strain of a material and hence determine the mechanical stress that the material is subject to. Strain gauges are produced from a piezoresistive material, typically thin metal foil, although silicon based strain gauges are also available. The strain gauge is bonded onto the surface in which strain is to be measured, typically with an epoxy or other strong adhesive. Accurate installation is very important to minimise error due to misalignment or bad adhesion. Gauges are commonly available in 2mm and 5mm sizes. Advantages of using a longer gauge include greater grid area for better heat dissipation and easier handling and installation. They also have improved strain averaging which is especially useful for inhomogeneous materials such as fibre-reinforced composites. Generally a smaller strain gauge will only be used in cases where space is limited. Metal foil strain gauges generally have gauge factor of 2.00 and a low resistance of 120Ω to minimise noise effects. These are the type chosen for this application.

The strain gauge circuit takes the form of a bridge circuit input to a differential amplifier based on an op-amp. An additional variable gain op-amp based amplifier is used for calibration. A single active strain gauge is used due to difficulties in mounting dual strain gauges on the foils/struts. Further details are provided in the technical report.

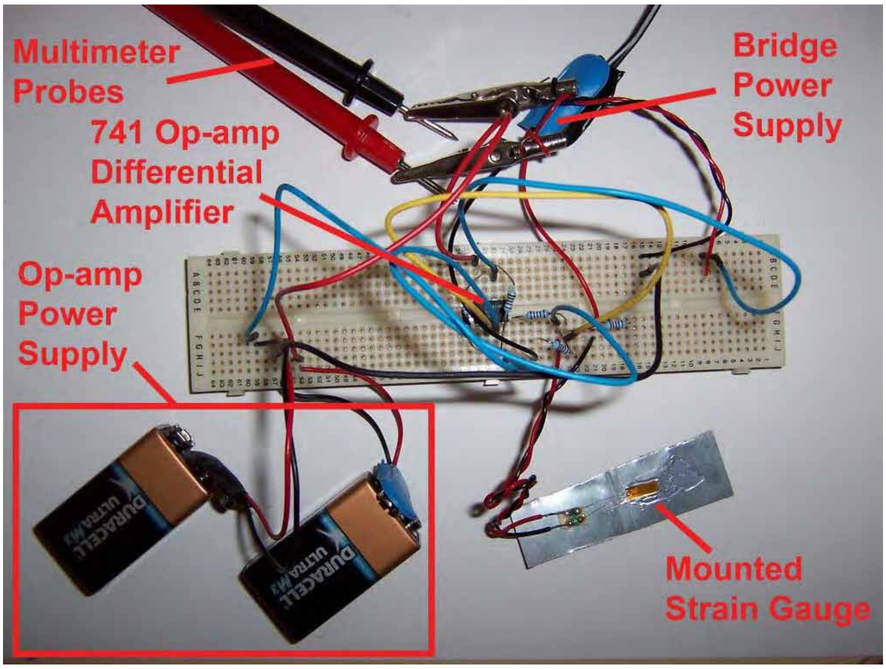


Figure 47 - Strain Gauge Testing

7.5 Hardware Design

The initial design is based on the development board that provides access to all ports, in addition to program memory, RS232, LEDs and switches. The development board is provided as a kit and was assembled. Full details of the development board are provided in the Technical Report, section 14.2.

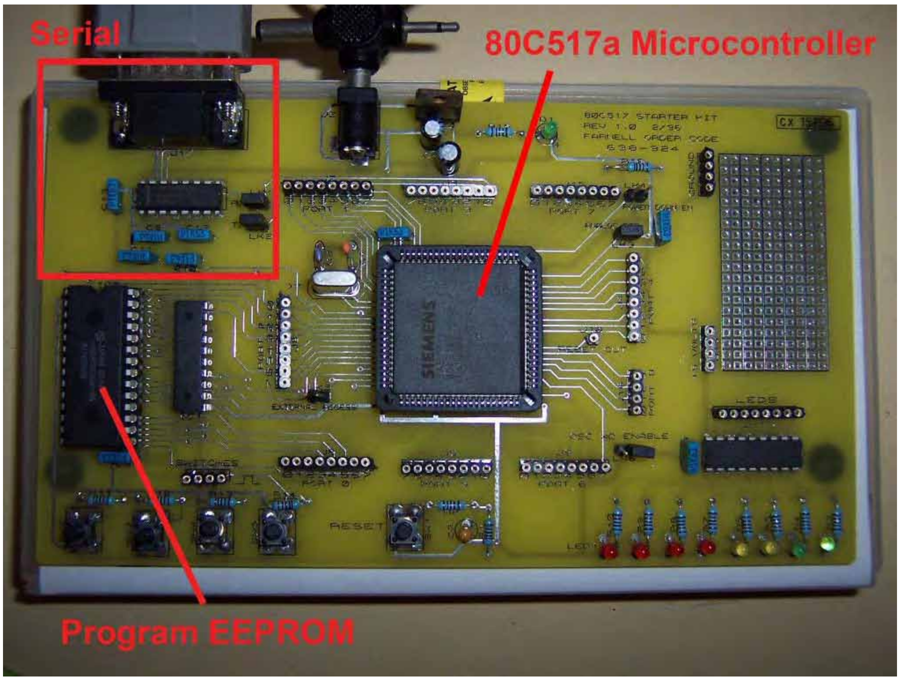


Figure 48 - Assembled Development Board

The main addition to the development board circuit required for the final system is the inclusion of an extra data EEPROM on the bus (i.e. duplicating the connections of the current EEPROM). This is required to store to collected values and the inputs to the ADC from the various sensors to port 3. The final circuit does not need all the features of the original board so a simpler, more compact circuit board may be produced.

7.6 Code Development

7.6.1 Program Specification

The final program should:

- Sample analogue data from multiple input lines.

- Store the sampled data in data memory for later retrieval.
- Dump the recorded data to serial for retrieval via a PC when triggered. The data should be formatted for easy processing.
- Record data only when enabled by an input line.
- Include status indicators as required

The c code was developed in the Keil IDE. This allows simulation of all used functions of the microprocessor. The development of the program was split into sections which were independently simulated in Keil before the main program was assembled.

First a routine to read from the ADC was developed. This simply performed a digitalisation of each of the input lines in turn and outputted the results sequentially to the serial port where a PC could receive them.

The second program tested methods of writing to XRAM (or external data memory). This is vital for correct writing and reading of the sampled values. This program was designed only for simulation and hence no real world output was produced.

The main program was designed according to the specification. Recording was performed when P1.0 was high with a sampling rate per sensor of 0.5s though this is adjustable by changing a constant. When not recording if P1.1 was taken high the data would be written to the serial port, formatted for import into MATLAB. P1.2 and P1.3 were used as status outputs to LEDs to show when the datalogger was recording or outputting data.

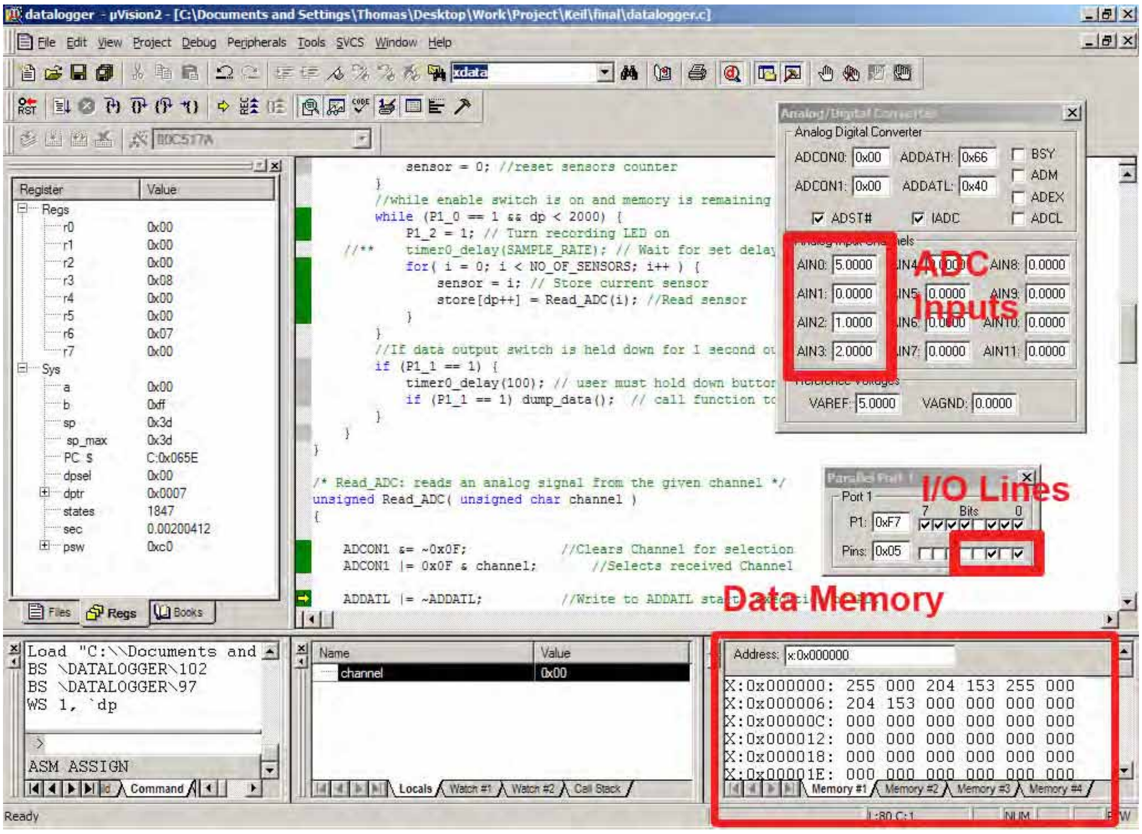


Figure 49 - Program Simulation in Keil

Although most of the program simulates correctly the program output function does not currently function as required and further debugging and simulation are necessary. Full Details of the programs are given in the technical report and the program listings are displayed in Appendix 15.24

7.7 Testing and System Installation

7.7.1 Testing

It is possible to test the operation of the datalogger external to the boat by providing test signals to the ADC inputs using, for instance, potentiometers. The correct operation of the data logger will therefore be verifiable before its use in the system. Similarly the operation of the majority of sensors is testable without installation although most calibration must be done in situ. Certain sensors such as strain gauges and height above water, although testable removed from the boat, require development in conjunction with it. Strain gauges are nearly impossible to calibrate without using the actual mounting and the height above water sensor calibration depends strongly on the trailing wand design.

7.7.2 System Installation

The datalogger is designed to be removable from the boat for download of data and to prevent water/dust damage. The sensors and their associated wiring are not offered the same protection. The datalogger is to be housed in one of the waterproof compartments under the foredeck. A hatch will allow access to this compartment.

A boat is a harsh environment for electronics. Boats are subjected to sand, high pressure water, occasional brief immersion and strong sunlight. Where external connections are required it would be pertinent to use Ingress Protection (IP) certified connectors. Of these standards IP66, which states that connectors are dust proof and protected from strong water jets, is the most suitable for the boat. These connectors are expensive, typically £1-3 each but for a semi-permanent or permanent installation they will be required. Some sensors, e.g. Strain gauges and boat speed sensor, require installation in struts or foils, and hence will need to be included during final assembly where required. The advantages of including electronics internally include protection from accidental damage and waterproofing.

7.8 Data processing and presentation

The purpose of the data collection is to determine the performance and operational envelope of the boat in different wind speeds and different positions of sailing.

The data output by the program is to be captured using a serial link by the program LookRS232. The output is arranged as an array of unsigned byte values (in ASCII) separated by a carriage return after each set of samples. This results in a set of samples per line with each sensor's data arranged in columns. This data can then be imported into MATLAB for further processing. MATLAB was chosen due to its widespread use and acceptance although other software, including custom written software could be used. Labview by National Instruments provides a simple way of displaying information in real-time/pseudo real-time using custom graphics, and therefore could be used for a playback of trip data or for real-time instrument positions using a wireless system.

An initial MATLAB program is used to process the input data and provide real world values for apparent wind speed, apparent wind direction, true wind speed, boat speed and boat height above water. Full details are given in the Technical Report, section 14.4.

Graphs can be plotted of this calculated data using MATLAB. A simple plot of the data with time will be of some interest but will not be of much use in assessing the boats performance. By plotting boat speed values vs. apparent wind angle as a polar plot (polar command in MATLAB) a performance envelope can be created. Performing multiple tests in different wind strengths will enable performance envelopes to be produced for a set of wind strengths. Although height above water is of some interest by itself, this value can be thresholded producing a simple foiling/not foiling value. Integrating this with the performance envelope diagram by using different colours for foiling/non foiling points will enable the boats foiling performance at all points of sailing to be displayed.

7.9 Future Modifications and Upgrades

- **Wireless Telemetry –** This would allow the shore team to receive collected data in real time and allow higher sampling rates and longer recording durations due to the higher storage capacity of a PC over EEPROMS. The program would also be simplified and it may even be possible to replace the microcontroller with a suitable PIC. The cost of serial transmitter/receiver pairs is constantly falling. Indeed a new low cost 1km-range transmitter/receiver pair from Rfsolutions is now as little as £45.
- **Storage Upgrade** – Although the 8051 can only directly access 64kbytes of external data memory it is possible, using custom written drivers and additional address lines to access larger memories. The low cost of flash memory means that it would be possible to upgrade to say 2Mbyte storage for little extra cost but at the expense of program simplicity.
- **LCD Display –** A simple LCD display can be bought for around £15 this could be used on either the storage or wireless based systems and could help with diagnostics and calibration, and show status information such as recording time remaining.

- **Sensor Network –** Although the current system design is sufficient for the current number of sensors, increasing the number of sensors would require much extra wiring. Using a bus-based sensor network such as CAN (Controller Area Network) would reduce the required wiring and allow nodes to be closer to the sensors. This would reduce the distance between sensors and an ADC, especially important when using susceptible sensors such as strain gauges.
- **Power Requirements –** Although not measured the maximum power consumption of the entire system is likely to be as high as 300mA. This is in part due to the high power requirement of the development board and strain gauge circuits. Disconnecting the strain gauges when not required and producing a custom circuit board to remove some redundant features on the development board can produce a lower power design allowing battery life to be increased.

7.10 Conclusion

The electronics section of the project ran alongside the main project with a transfer of ideas between the two. The electronics was not intended to influence the initial boat design but was designed as a method of testing the finished boat to enable adjustments and alterations to be made as necessary. The electronics system consisted of two main areas, the sensors and the datalogger. The sensors were designed but assembly and calibration has not taken place since the boat is not yet complete. The datalogger was designed but a working version has not, so far been produced or tested. The main problems delaying full system production have been with the testing of programs on the development board and the, as yet, non-completion of the boat. It should however be possible to have a system working before the testing of the boat commences.

Completing such a project on a very tight budget is not easy, but even though the data collection system is not operational, the electronics work during this first year of the project provides a firm foundation for future years.

8 OVERALL EVALUATION

8.1 Conclusion

The future foils project has seen a successful pilot year, and although not all of the objectives have been met, a great deal of ground work has been provided with the theoretical, design and build of a hull, foils, and electronics testing system. Research into materials and manufacturing methods suitable for the production of a concept prototype craft have been covered in depth, enabling future work to focus in more detail on the possibilities of commercial based materials and production methods.

The extensive design and practical work covered has only been possible thanks to a very hard working and dedicated team. The groundwork for next year will be completed over the summer, with extensive testing of the boat and data-logging system.

8.2 Evaluation of Objectives

In order to evaluate the project, the original objectives have been assessed. The objectives were:

- Researching and evaluating theoretical background
- Investigating possible arrangements (foils, control system etc.)
- Investigating materials and manufacturing processes for prototype development.
- Addressing issues of commercial viability

- Producing a working prototype
- Providing performance data through the use of an electronic testing and data-logging device.

The theoretical background behind boat hulls and hydrofoils has been thoroughly explored. The information was used to carry out the mathematical justification of design decisions.

The number and position of the foils were studied and through a variety of combinations the final design was reached. Various foil control system concepts were explored. Some of these have not been included in the report because they were not developed past the initial concept. The ones that were have been included and the reasoning behind accepting or rejecting the ideas have been given.

Materials for the production of the boat were investigated and the most suitable identified. These were not necessarily used, as the materials and tooling available to the group were limited.

All design decisions were made with the image of the final commercial product in mind. The boat hull was designed to look like a popular existing product in order to encourage interest. The ease of sailing the boat was a major consideration throughout the design process.

A prototype has almost been completed but has not yet been tested. Theoretical models predict that the prototype will work but due to time restraints it has not been possible to complete and test the boat.

The electronic testing and data logging devices have been designed, but as the boat has not yet been tested this equipment has not been used to get the required data.

8.3 Further Work

The prototype will be completed in the near future and will be tested to provide data for the next group that take on the project.

Although theoretical models predict that the boat will work it may still need altering next year. It will almost certainly need fine-tuning to make it perform as desired.

If the boat does hydrofoil as planned, the main work for the following year will be in making it more commercially viable. Market research needs to be carried out to find the public opinion of the design and to find a realistic retail price in order to determine if production of the boat can be cost effective.

The prototype has taken excessive manpower to manufacture and a commercial product would not be fabricated in this way. Less labour intensive methods of construction need to be explored if the boat is to be mass-produced.

The aerated flow control system explained in section 13.1 is a novel and interesting way to control the lift from the foils. Theory suggests that the concept could work but without conclusive test data, use on a full-scale prototype is not yet appropriate. Further theoretical and test work on the system could yield a project in itself, and may provide Future Foils with a competitive edge in terms of innovation.

In order to develop the system further, the inlet and outlet ventilation holes need to be designed more carefully so as to only disturb the flow over the wing when in active mode. The tubing system between the holes needs to be designed carefully so as not to impede the performance of the control mechanism.

In order to produce conclusive test data, a smaller prototype system that could be tested in a tow tank or water tunnel needs to be undertaken, so that the system can be observed closely.

Hydrofoil Sailing

Technical report

FUTURE FOILS

THE HIGH SPEED FUTURE OF SAILING

THE UNIVERSITY OF WARWICK

9 BACKGROUND THEORY

9.1 Displacement Boats

There are three main sources of the drag on a displacement boat hull,

- Skin friction, due to the roughness of the hull surface
- Form drag, due to the effort required to force the flow apart, as the hull moves through the water
- Wave drag.

Wave drag is very different from the other two sources of drag. Skin friction and form drag can both be measured by the loss of energy to turbulence. Wave drag however, is due to energy being radiated away in the form of surface waves generated by the hulls motion. [P Rye Of Boats and Waves website]

With a displacement hull, the bow and the stern each produce their own wave. The frequency of these waves is constant based on the properties of water. The wavelength depends on the speed of the boat. The faster the boat moves, the longer the waves become, until eventually the bow and stern waves are of the same frequency. When the waves are of the same frequency, the boat rides in a trough between the waves. This speed is the theoretical maximum speed of the boat. To go faster, the vessel must start to drive over its bow wave, lifting itself out of the water, obviously requiring a significant increase in power. [Kite sailing Progress website]

The basic equation of a surface wave can be written as:

$$v^2 = \lambda\left(\frac{g}{2\pi}\right)$$ **Equation 38**

Where;

v = velocity of boat

λ = wavelength

g = acceleration due to gravity

The drag a displacement boat produces is therefore very simple to calculate. For simplicity, only the longest wave along the hull is considered. The height of the wave relates to the pressure applied by the bow of the hull, to the water through which it moves. Bernoulli's Law tells us that the pressure, and so the height of the water which forms the wave, depends on the square of the hull speed. As a result, the height of the wave depends on the square of hull speed.

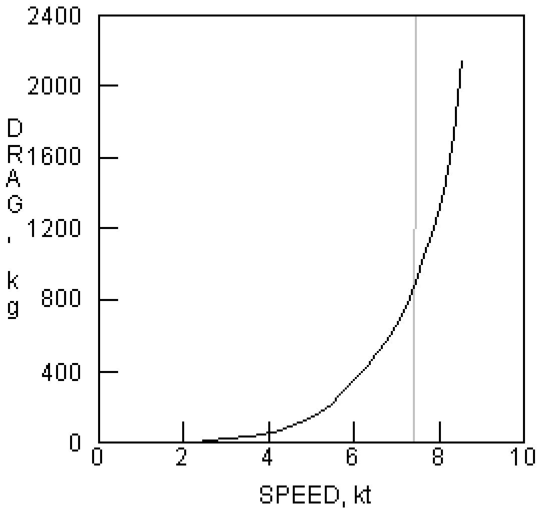


Figure 50 - Drag vs. Speed for a displacement hull

Figure 50 above is one example, for a heavy-displacement, 10-metre long hull, showing the relationship between drag force and hull speed. This was calculated using Hullform's "Gerritsma" drag scheme [P Rye Of Boats and Waves website]

‘If the speed is such that the forward wave is at its highest point when the wave formed at the stern is at its lowest it will have the effect of neutralising the drag caused by the wave set up from the stern so that this is the most efficient condition for propelling a boat through the water.’ [P Rye Of Boats and Waves website]. These optimum conditions are as a rule achieved when

$$\frac{V}{\sqrt{L}} = 1 \qquad \textbf{Equation 39}$$

Where;

V = speed

L = length

Equation 39 provides an approximation to show that a 16 ft boat will most easily travel at 4knots. Beyond this point a larger fraction of power will have to be used to generate waves of such form that the whole weight of the hull is lifted relative to the trim line. This will consist of the back lowering and the front rising out of the water.

9.2 Lift on a Planing Surface

The total lift of a planing surface is obtained by considering the momentum vector changes in the system. In order to calculate the mass of water involved a streamline infinitely far below the surface has to be considered. The line is sufficiently below the surface so as to avoid distortion from a straight line. [Pierson & Leshnover]

The principle of linear momentum may be applied to the mass of fluid, which at time t_1 occupies the volume bounded by the free surfaces, the solid boundary, some streamline ψ_1, and the lines AB, CD and EF - Figure 51. The fluid bounded by these coordinates is M_1.

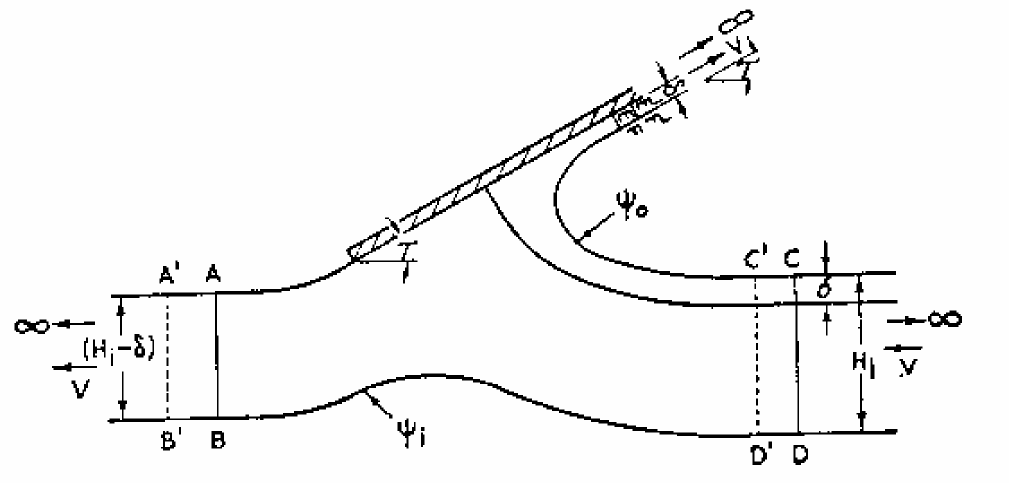


Figure 51 - Flat plate planing model

At some later instant t_2, this same mass of fluid will have moved under steady-state conditions so that it will then be bounded by the same streamlines, but AB will have moved to A'B', CD to C'D' and EF to E'F'. Meanwhile the momentum of this fluid will have changed in both magnitude and direction to some value M_2.

The vector rate of change in momentum between M_1 and M_2 will be due to the contributions from the fluid ABB'A', CDD'C' and EFF'E' during the time period t_1 – t_2.

Using the principle of linear momentum the rate of change of linear momentum $\frac{dM}{dt}$ of a mass is equal to the vector sum, R, of the external forces on that mass.

$$|\Re| = \frac{dM}{dt} = \left[\frac{\overline{M}_2 - \overline{M}_1}{t_2 - t_1}\right]_{t_1}^{t_2} = \rho(H_i - \delta)\overline{V}^2 + \rho\delta\overline{V}^2 - \rho H_i\overline{V}^2 \qquad \textbf{Equation 40}$$

In order to avoid having to take into account the horizontal component of the external force on the 'bounded' fluid due to the pressure distribution along the ψ_1 streamline, the line is infinitely far below the free surface where it approaches a straight horizontal line. Thus by denoting this particular streamline by ψ_∞ and the corresponding infinite distance Hi by H_∞ then equation 41 becomes:

$$|\Re| = \rho(H_\infty - \delta)\overline{V}^2 + \rho\delta\overline{V}^2 - \rho\overline{H}_\infty\overline{V}^2 \qquad \textbf{Equation 41}$$

Since $\Re$ is the resultant of the external forces on the bounded fluid mass, it equals the vector sum of the normal reaction, F. It also equals P, the vertical force on the fluid due to the integrated pressure distribution over the entire ψ_∞ streamline.

Equation 41 can therefore be written as

$$|\Re| = (-\overline{F}) + \overline{P} \qquad \textbf{Equation 42}$$

Adding the horizontal components of these vectors gives;

$$-\overline{F}\sin\tau = \rho(H_\infty - \delta)\overline{V}^2 + \rho\delta\overline{V}^2 - \rho\overline{H}_\infty\overline{V}^2$$ **Equation 43**

And hence,

$$\overline{F}\sin\tau = \rho\delta\overline{V}^2(1+\cos\tau)$$ **Equation 44**

This is the equation for the drag produced by a planning surface.

The lift generated by the planning surface is given by

$$\overline{F}\cos\tau = \rho\delta\overline{V}^2 ctg\frac{\tau}{2}\cos\tau$$ **Equation 45**

Equations 41 and 42 combine to give the momentum equation, which is defined as;

$$M = -\rho|V|^2\left[\frac{\delta^2\sin\tau}{\pi(1-\cos\tau)^2}\right]\times\left[L+\cos\frac{\tau}{2}+\frac{\pi}{2}\sin\tau+2(1-\cos\tau)\ln 2\right]$$

Equation 46

The dimension δ is the thickness of the jet of water moved forwards. This is undefined and a difficult dimension to compare with those calculations made for the foil. Therefore an expression must be found that includes the term l, so that a direct comparison can be made.

$$l = \frac{\delta}{\pi}\left[\left(\frac{1+\cos\tau}{1-\cos\tau}\right)+\pi\left(\frac{\sin\tau}{1-\cos\tau}\right)+\ln\left(\frac{2\cos\tau}{1-\cos\tau}\right)\right]$$ **Equation 47**

As τ tends to zero, the previous equation can be simplified to;

$$l = \frac{4\delta}{\pi\tau^2}$$ **Equation 48**

By substituting this term into the lift and drag equations (40 and 41) it is possible to provide equations that are more applicable in the analysis of a planing surface.

Lift:

$$\boxed{L = \frac{\rho v^2 l}{2}\pi\tau}$$ **Equation 49**

Drag:

$$\boxed{D = \frac{\rho v^2 l}{2}\pi\tau}$$ **Equation 50**

10 HULL DESIGN AND BUILD

The following ratio calculations were used when choosing which hull design would best meet the project's needs.

10.1 Hull Design

10.1.1 Sail Area / Displacement Ratio, SA/D

$$SA/D = \frac{SA}{\left(D/64\right)^{2/3}}$$ **Equation 51**

Where: SA = sail area (m^2)

D = hull displacement (m)

This ratio is a power to weight indicator, comparing sail area to hull displacement. A higher SA/D ratio indicates faster acceleration, and the boat will need less wind to reach top speed. Therefore a high SA/D ratio is required as it will be a better performer in lighter winds.

10.1.2 Displacement / Length Ratio, D/L

$$D/L = \frac{D/2240}{\left(0.01 \times LWL\right)^3}$$ **Equation 52**

Where: LWL = Waterline length of hull (m)

This ratio is the measure of speed potential a boat has. For displacement sailing (when the boat is not foil-borne), speed potential is a function of waterline length. A longer waterline length means the boat can go faster. Lighter boats accelerate faster, reaching hull speed with less wind. Therefore, the design with lower D/L ratio will be a better performer in light winds.

A limiting factor is that lower displacement will also make the boat more sensitive to loading. This has to be considered when choosing the overall boat design.

10.1.3 Waterline Length/Beam Ratio, LWL/B

$$LWL/B = \frac{LWL}{B}$$ **Equation 53**

Where: B = beam width (m)

This ratio gives a measure of speed: the larger the ratio the faster the hull.

These ratios were then weighted and put into a decision matrix with boat designs with decreasing beam, to see the effects of these ratios and use the results to decide which design is most favourable.

It was decided all 3 ratios used were important, and hence were weighted equally. The outcome of the decision matrix (see Appendix 1 – Hull Design Decision Matrix) was to design a hull with a narrow beam.

The final hull design resulted in a 30% decrease of beam width, reducing weight and thus increasing displacement speed. The beam could have been reduced further, but it was decided for stability reasons to only decrease by 30%, giving a beam width of 0.997m. Overall length was kept to that of a Laser sailing dinghy to make the boat appeal to sailors, that is 4.396m.

The deep vee front and high rise back as discussed earlier can be seen in the *Hullform* picture of the final design, Appendix 2.

10.2 Explanation of Mast Position Spreadsheet

Section 3.4 'Hull Design Output', in the Summary report explains how the mast should be positioned. It refers to the spreadsheet in Appendix 4. This section shows how the model works by explaining each row.

Row 3 The length of the boat is entered as an input. This is the distance from the bow to the centre of the rear foil, so includes the length of the rudder attachment.

Row 4 The longitudinal distance from the mast to the centre of effort of the sail is calculated by multiplying the distance from the edge of the sail to the centre of effort of the sail by the cosine of 45° to find the average distance. In normal sailing the sail can be at any angle between zero and ninety degrees to the direction of the boat so 45° will find a rough average.

Row 5 The lead of the centre of effort to the centre of lateral resistance is 13% of the length of the boat. Refer to section 3.4 'Hull Design Output'

Row 7 The distance from the bow to the front foils is entered here increasing in steps of 0.1 metres across the columns.

Row 9 The centre of lateral resistance of the boat when it is foiling is found by finding the average distance of the foils from the bow. There are two front foils and one rear foil. All the struts are the same dimensions so their actual lateral resistances are not needed. The distance from the bow to the front foils is multiplied by two (because there are two front foils) and added to the length of the boat (which is the distance from the bow to the rear foil), and the result is divided by three (because there are three foils).

Row 10 The centre of effort of the sail must be 13% of the length of the boat in front of the centre of lateral resistance found in Row 9. Row 9 finds the distance from the bow so 13% of the length of the boat is taken from this to give the distance from the bow to the centre of effort of the sail.

Row 11 The mast must be the value of Row 4 in front of where the centre of effort should be in order to get the centre of effort in the correct place so Row 4 is taken from Row 10.

Row 14 The centre of lateral resistance of the hull is an input and is determined by inspection of the profile area of hull below the waterline shown in Hullform.

Row 15 Hullform gives the hull profile area below the waterline.

Row 16 The centre of lateral resistance of the foils has already been found in Row 9.

Row 17 The area of each strut below the waterline is the chord (0.18m) multiplied by the length under the water (1m). There are three struts. So the total area under the water is $0.54m^2$, (0.18 x 1 x 3).

Row 18 The total centre of lateral resistance is the weighted average of the centres of the foils and hull. So the profile area of the hull under the water multiplied by the distance from the bow to the hull CLR is summed with the total area of struts under the water multiplied by the strut CLR, and the sum is divided by the sum of the hull and strut area under the water.

Rows 19 and 20 The centre of effort and the mast position are found in the same way as for the foilbourne boat.

Row 22 If the position of the mast for the foilbourne boat is within 1% of the position for the displacement boat the display shows ‘yes’, otherwise it displays either ‘no’ if the foilbourne boat mast position is in front of the displacement sailing position, or ‘NO’ if it is the other way around. The different ways of displaying ‘no’ were included in case the mast positions were never within 1% of each other. The operator would then be able to see clearly where they swapped position and could change the foil position steps in that region.

10.3 Hull Materials

The aim of this section is to give the reader some knowledge of the wide variety of materials that are available, and have been used for boat building. These materials range from wood in its simplest form, with people in Goa hollowing out tree trunks, to exotic composites used on the most expensive racing yachts.

The information presented has been gathered from numerous sources and some is people’s personal opinions, rather than solid technical data. Each material is examined individually; the section then moves on to look at cores and resins.

10.3.1 Wood

Wood has been used in boat building for many years. From a ‘structural and economic standpoint, wood remains the most efficient engineering material’ (why wood). Wood is still used in modern boats for individual components, it offers good floatation, but poor rot resistance so is usually treated in some way, or encapsulated in one of the modern boat building materials. With the introduction of modern materials such as glass fibre the number of wooden boats produced dropped to ‘a small fraction of total production’ [Pascoe, 1998].

One of the advantages of using wood is that it is lightweight and stiff, this gives good performance when used in hulls. However, when it gets wet these properties are reduced.

To work with wood is relatively cheap, as only simple tools are needed. The downside is that highly skilled people are needed to work and shape the wood; this causes an increase in labour costs. Many man made materials have been used instead of, or as well as wood.

10.3.2 Aluminium

Aluminium is used to make the hull of the boat. It is a monocoque hull, deck and keel, because it is welded as one structure there are no joins, and hence no leaks. Care must be taken if any riveting is used on the boat hull to avoid any leakage. A major advantage of aluminium is that it is corrosion resistant; all that is needed to be done after manufacture is an application of an anti fouling treatment. It has been reported of some aluminium boats have been sailing for years, without being painted.

Aluminium is not as resistant to abrasion, and does not have the high impact resistance, like steel. However, it is easier to shape than steel, and allows smooth, soft shapes to be produced.

The abrasion and impact resistance are higher than fibre reinforced plastics and traditional strip built wooden hulls. Aluminium hulls require fewer bulkheads than FRP and wooden hulls; this means that the interior space can be more open, allowing greater flexibility in fitting out the interior. This greater flexibility allows more customisation of the interior, attractive to the consumer, and beneficial when adding additional structures to the boat.

Aluminium hulled boats can reach the performance levels of fibreglass boats, but at this level of performance they are not 'economically advantageous over fibreglass hulled boat' [Anon, 2003G].

10.3.3 Steel

Like aluminium hulls, steel hulls are made in a monocoque construction; this gives the same advantages of no joints to leak. Similarly minimal, or even no bulkheads are needed, allowing great flexibility in fitting out the finished hull. A downside of using steel is that highly skilled labour is needed to form the sheet into the correct shapes to produce the hull.

10.3.4 Glass Reinforced Plastic (GRP)

Moving from metal construction, another material that may be used is fibreglass. Fibreglass has been used in boat building since the 1930s, the first reinforced plastic boat was built by Gar Wood in 1936 [Pascoe, 1998]. Many modern boats use fibreglass, and it has become extremely popular as a boat building material. Often it is not used alone, and tends to be used with wood providing some stiffness to the structure. The wood is encapsulated in the fibreglass to protect it from the environment.

Fibreglass comes in a range of varieties and is a relatively inexpensive cloth when compared to alternative materials, such as carbon fibre and Kevlar. S Glass has 15 to 30% better performance relating to shear strength than ordinary glass cloth. It is used where weight and stiffness are a big concern, such as racing yachts.

Fibreglass itself is very rot resistant; this is obviously a benefit in the marine environment. It also does not need sanding and painting every year, which wooden boats require.

The nature of fibreglass allows it to be moulded into many shapes. This is useful when adding deck fittings such as locker boxes, which can be moulded in to the deck of the boat.

As with aluminium and steel the fibreglass hull has no joints, which can leak, which is obviously beneficial in a marine environment. Unlike wood it does not shrink when removed from the water.

There are some disadvantages to using fibreglass. Firstly it is very labour intensive, needing to be laid by hand, however, after basic training it is possible to produce a satisfactory product. This means that quality can vary between a production run of the same boat. The second disadvantage is that fibreglass can be very heavy if used in the thickness needed to produce a strong, stiff hull. To get round this problem of weight cores are often used between two sheets of the laminate.

10.3.5 Carbon Fibre & Kevlar (FRP)

Moving to more exotic materials, carbon fibre and Kevlar have been used in boat building. Using these materials is expensive and they tend to be used in small areas of boats, or where cost is not a problem.

Kevlar has very high shear strength and elongation properties. It does not absorb as much resin as other lay up materials, this makes it '30% lighter per layer' (Anon, 2003C) when used in manufacturing the hull, compared to fibreglass. Kevlar performs badly when in compression, because of this it tends to be used on the inside of the hull, or where areas will be in tension. It is also not UV stable; meaning exposure to sunlight will cause some degradation of the material.

Carbon fibre cloth contains up to 95% carbon. This cloth ‘has the highest strength and stiffness to weight ratio of any cloth’ [Anon, 2003C]. However, it can be brittle when an impact is applied to the material.

Carbon fibre is used all over racing yachts, with a wide range of applications. It has been ‘proven against material fatigue and vibrations’ [Anon, 2003E].

The reduction in weight that both these materials give is useful due to the less power required to move the boat.

As mentioned earlier in the fibreglass section, cores are used with various materials to allow better material properties to be obtained.

10.3.6 Cores

‘In theory, the stiffness of a laminated panel will be determined by the third power of its thickness. Seeing it in this way, a core material adds to the strength and stiffness of the laminate.’ [Anon, 2003E].

Many boat builders were increasing the stiffness of their boats by simply adding greater thickness to the laminate they were using, it is reported that some fibreglass boats were up to one inch thick. This simply added more weight to the boat impacting negatively on the performance.

During the 1960s and 1970s after the space missions, cored structures were being used in aviation to reduce the weight and increase the performance of certain materials. Boat builders began to look at how they could use these new materials and ideas in their boats.

There were many obstacles to using these materials; these included the expense of the material and the lack of knowledge of how the material worked. Some individuals tried to use the materials, but the lack of knowledge of the material behaviour led to many boats falling apart. The idea of using cores in the early days was simply to stiffen up the structures and thereby improving performance. Nowadays however, they are used to replace ‘more costly material with less costly material’ [Pascoe, 1998].

Many small boats used a material called CoreMat, this was a foam material, with many small holes. These small holes cause the material to absorb water; this causes the boat to blister. These thin cores do not create a structural advantage as the laminates are still close together; a core increases stiffness by increasing the distance between the two laminates. Therefore to achieve a significant increase in stiffness the core must be thick. The increase in stiffness reduces the hydrodynamic drag of the boat, increasing performance. The reduction in weight means there is less weight to move through the water, hence increasing speed.

The behaviour of the core-laminate construction allows thinner laminates to be used. The laminates experience the tension and compression forces exerted on the hull, the core takes the shear forces. As the laminates do not experience the shear forces they can be made thinner than would be possible with a single laminate structure, reducing the weight further. Care must be taken not to use a laminate that is too thin as the resistance to minor impacts reduces.

The core must be thicker than the single laminate to take the shear forces, this creates a stiffer structure, but with less weight. The stronger and stiffer the core, the thinner the laminate that may be used.

The most common core materials are ‘balsa wood, PVC foam, SAN foam, and honeycombs made from aramid, plastic, and paper’ [Sponberg, 2003]. In most cases, all cores can be made to do the same job. ‘The choice as to which core is best for a particular design is usually reduced to which core is the least expensive for the greatest strength and stiffness’ [Sponberg, 2003].

10.3.6.1 Balsa

The simplest core material is balsa wood. Balsa wood is very common in yachts as a core material. It is used around the dagger board casing, and on areas of the deck.

Sandwiching end grain cut balsa between two layers of laminate provides a truss between the panels, and significantly stiffens the panels. Balsa wood core is very useful in areas where high mechanical properties are needed with a lightweight core.

As balsa is a wood it will absorb water. Therefore care must be taken to ensure that no fasteners pass through the balsa, otherwise it will be exposed water. This absorption property also causes problems when resin is applied to the wood. Under a microscope balsa wood looks very like the honeycomb core materials. When resin is applied it soaks into this honeycomb structure increasing the weight of the material, hence losing its lightweight property. However, this effect can be utilised beneficially. When the resin soaks into the balsa it creates a very strong bond. This effect is not apparent in foams.

10.3.6.2 Foam

The foam used in boat building has a very coarse texture. Therefore foam will not soak up the resin and the resulting bond is not very strong. This is because the foam cells 'are round, and not tubular like balsa' [Pascoe, 1998]. This means a much thicker resin is needed that will flow into the round cells.

PVC foam comes in two main varieties – cross-linked and linear. Cross-linked foam is brittle and if bent too much will break easily. However the rigid cross-linked foams are preferred as they compensate for the thinning of the laminate sheet.

Foam will also suffer from water ingressing into the structure. Once the water has penetrated the foam will break down quickly, resulting in a loss of stiffness to the structure. This ingress of water will still happen with 'closed cell' foams.

Foam cores are extremely vulnerable to impact damage, and can be 'highly prone to core separation' [Pascoe, 2003]. This is where the core begins to pull away from the laminate that has been applied to it.

There are several advantages to using PVC foam in boats. One of the best features is that it will not rot; this is a big advantage when operating in a damp and warm environment. As with most cores it will reduce the weight of the structure in which it is used. Wood core strips tend to vary in how they change dimension when exposed to warmth and dampness, foam does not suffer from this problem.

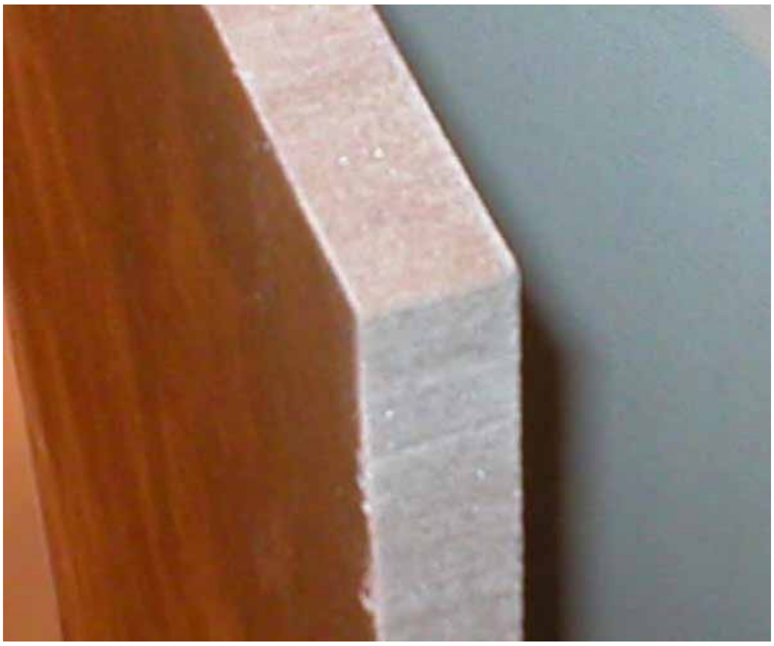


Figure 52 - An example of foam core

10.3.6.3 Honeycomb

The final core material that we will look at is honeycomb material. Honeycomb cores have been tested since the 1970s, when there was a paper honeycomb and an aluminium honeycomb.

The paper honeycomb suffered problems when water entered the structure, causing the paper to degrade. The aluminium honeycomb used very thin aluminium to make the structure. When water got into the structure, it broke down nearly ‘as fast as with the paper core’ [Pascoe, 2003].

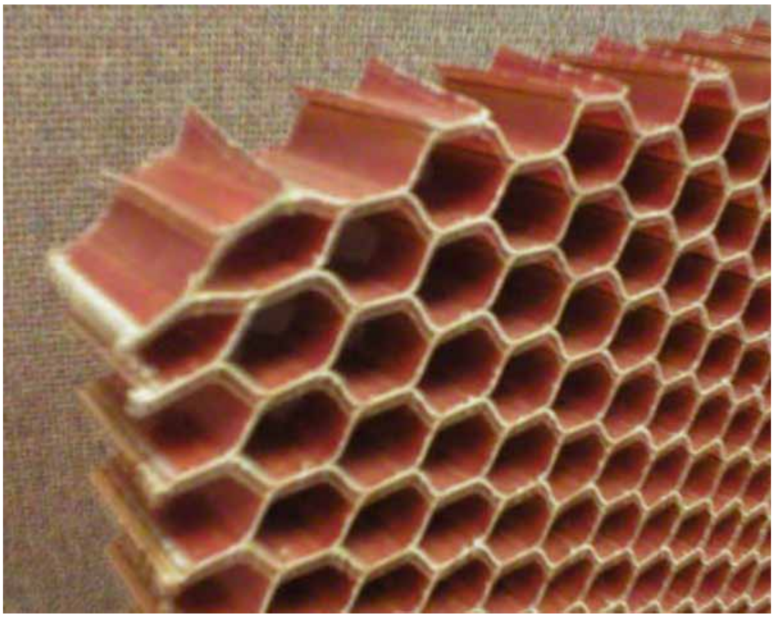


Figure 53 - An example of honeycomb

When first introduced honeycombs were very expensive, some still remain expensive. The structures are extremely light and resemble a bee honeycomb. One misconception with the early use of honeycomb materials was that builders felt that they could reduce the framing system in the hulls. When parts of the honeycomb failed the structure could not support itself and failed. This would have been ‘far less dramatic’ [Pascoe, 2003] had the framing system been complete.

There are several types of honeycombs, each suitable for use in different areas of the boat.

Nomex is a structure with aramid fibres and is mainly used in custom boats. Plastic honeycombs are used in the deck, hulls, and interior joinery. Paper honeycombs are used in interior joinery, but should not be used in the hull and deck, due to its poor performance when in contact with water.

As with foam honeycombs can have problems with the bond they form with the resin. The resin is in contact with only the edges of the honeycomb, these could be paper-thin and to ensure a good bond lots of resin is needed. This resin will seep into the cells of the honeycomb, filling them and increasing the weight of the structure. Nida-Core has solved this problem by fixing a polyester scrim to the edges of the honeycomb, giving a large area for the resin to bond to.

Following are several graphs showing the physical properties of the various core materials mentioned above. All charts are from Sponberg [2003].

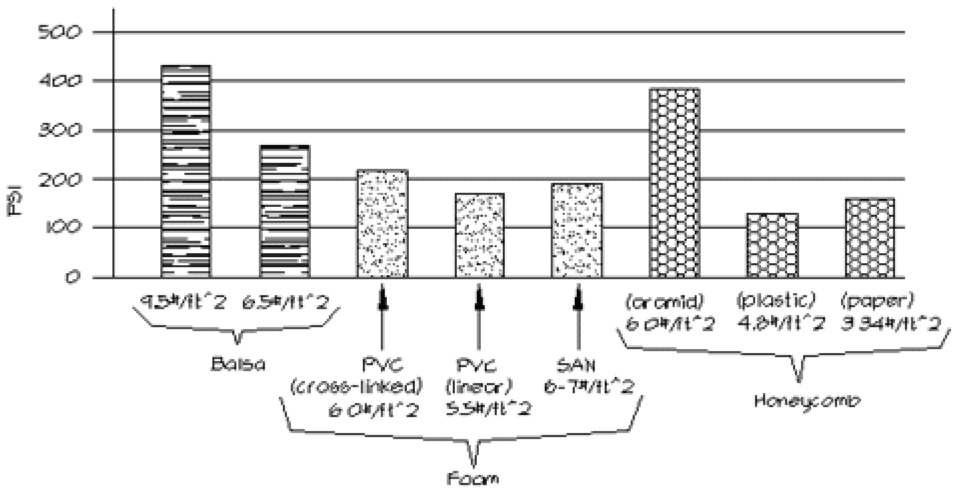


Figure 54 - Shear Strength of Various Core Materials

As can be seen from Figure 54 previously, the balsa wood outperforms the majority of the other cores, except the aramid honeycomb. The performance of the foams is very similar to the honeycomb structures.

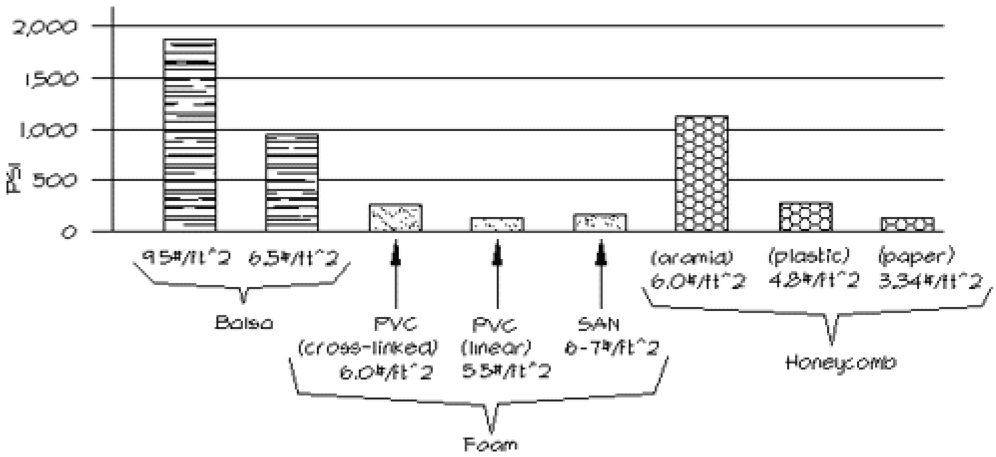


Figure 55 - Compression Strength

High shear modulus is needed to take the force of various fixings being attached to the hull, such as winches, and bolts passing through the core. Again balsa appears to be a high performing core, with the aramid honeycomb similar to the least dense balsa. The foams do not perform well in this area, having the lowest shear modulus.

Obviously cost is a major factor when the material choice is made, Figure 56 depicts the relative price of each of the core materials.

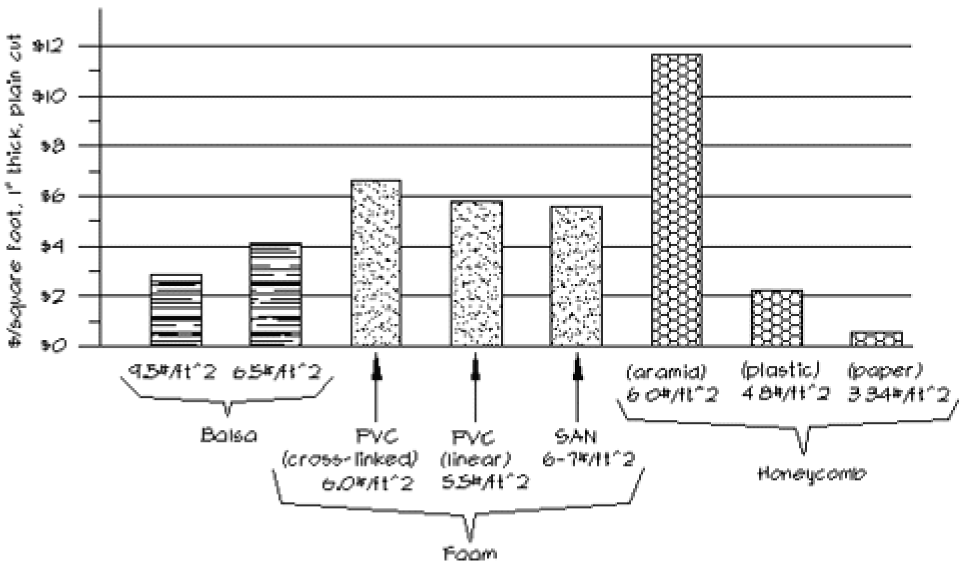


Figure 56 - Costs of Various Core Materials

The prices for this data are November 1999 prices.

Throughout this section on cores, there have been various requirements of resins for the material being used for the core. Therefore the next section looks at the various resins that are available.

10.3.7 Resins

10.3.7.1 Polyester

One of the most common resins is polyester resin. This is ‘the cheapest and most readily available’ [Anon, 2003C]. ‘Most production boats use polyester resin, combined with vinylester resin in structurally important areas, or in the very outer skin’ [Anon, 2003D]. The elongation properties of vinylester exceed those of epoxy, and is ideal for boats exposed to white water [Anon, 2003C].

Polyester resin comes in two types, stiff and flexi, usually a mixture of the two is used. Polyester resin tends to be stiff, making it suitable to use on boat decks. As with all materials it has several disadvantages. Polyester resin does not bond well with aramids, such as Kevlar, or with synthetics like polyester. Impact can cause the layers of the laminate to separate, much more readily than with other resins.

Polyester resin is susceptible to water penetration by osmosis through the molecular structure. ‘Experiments have shown that a polyester laminate possesses about 65% of its outer skin protection after 12 months immersed in water’ [Anon, 2003E].

Osmosis causes blistering of the boat hull. To reduce the osmosis extra coatings will need to be applied to the hull, this can include a coating of epoxy resin.

Epoxy resins are typically only seen in high end racing boats due to its costs and difficulty to work with. It gives the highest strength with the least number of layers. However, its impact resistance is relatively poor as the resin is quite stiff and cannot disperse the energy over a large area. Epoxy resins perform well with the stress and tension experienced as the hull moves through the water. Tests have shown that epoxy handles this stress and tension better than the polyester and vinylester resins.

The bonding strength is far better than that achievable with polyester and vinylester resins. Due to this bonding strength it is possible to get a better fibre percentage in the laminate.

10.4 Hull Manufacturing Process

10.4.1 Laminate production

The material used in these methods is investigated in the material section of the technical report.

10.4.1.1 Single skin laminate production

The core is shaped in an open mould and then the reinforcement and resin is added to provide the laminate. Depending on the size of the item in consideration, the laminate may not need stiffening with internal structures due to the hull curvature and strength of the skin laminate.

10.4.1.2 Double or sandwich skin laminate production

Certain sections of the hull may require high rigidity such as the outside skin of the hull, decks and bulkheads. This can be provided by two thinner skins of laminate separated by a lightweight core of foam (or similar material). The core is laid on a female mould and layers of reinforcement and resin are applied to form a solid bond. Once this has cured the lamination process is continued on the exposed outer side of the core.

10.4.2 Ferro-cement production

Ferro cement is constructed with hydraulic cement mortar reinforced using small diameter wire mesh. The wire mesh is usually made out of metal. It is a highly versatile form of concrete, which has relatively thin walls allowing freedom in design. Weight is the major disadvantage especially in smaller vessels with small amounts of water displacement. However, the boat will last a long time, as they are tough and easy to repair. This production method is suited to one-off boat building and is usually cheaper than most other methods due to the low material cost.

10.4.3 Wood construction methods

Wood can be shaped relatively easily and its stiffness, low weight and resistance to fatigue make it good method for making a boat. However, wood is subject to rotting when water is absorbed and the temperature changes causes the material to swell and shrink. This problem can be rectified with the application of epoxy resin. All the joints and the pieces of wood are bonded with resin, which means no water or air can be penetrate into the material. Kevlar is sometimes used on larger vessels for increased impact resistance.

The fastest method of wood hull manufacture is the stitch and glue technique:

1. Develop the correct panels using CAD
2. Draw the panels on the plywood and cut to shape
3. Assemble the panels and then join by stitching, taping, stapling etc.
4. Fillet and glass tape the seams
5. Install bulkheads, floors and frames
6. Paint

Copper wire can be used to stitch the two ends of wood together usually starting from the centre of the boat. The plywood should be saturated with epoxy resin before and after assembly. Fillet bonding is then used on the inside and glass tape is applied on both the inside and the outside to reinforce the boat structure.

A number of layers of wood can be applied which are usually at ninety degrees to each other to increase the strength of the vessel. There are three basic methods of laminating these boats:

1. The mould method
2. The strip plank method
3. The stringer frame method

10.4.3.1 Mould method

A plug/cavity mould is produced in the shape required which can be used to diagonally lay the plywood on top.

Advantages: Repeatability, sound base for large pressures (usually provided by staples).

Disadvantages: Slow and costly for one-off production, interior fittings and bulkheads cannot be installed until after the boat is taken out of the male mould.

10.4.3.2 The Strip plank method

In this method, the mould becomes part of the hull, which then provides a strong monocoque design. Diagonal veneers are laminated over the mould.

Advantages: With the mould the basis of the lay up, interior fittings and bulkheads can be installed during set up.

Disadvantages: Minimum skin thickness is now 22mm, which means that weight can be a problem, not a fast production method.

10.4.3.3 The Stringer frame method

The most widely used method of wooden hull production.

Advantages: Interior fittings and bulkheads can be installed during set up, best strength and stiffness to weight ratios.

Disadvantages: Have to laminate the wood in what is an inadequate mould.

10.4.4 Steel and Aluminium production methods

The marine industry has widely used aluminium for commercial operations and now it is used in the yacht industry. Aluminium vessels can be manufactured and assembled quickly and maintenance is also easy. Usually CAD is used to generate designs and send them to a computer-assisted cutter, which cuts the required shapes out of flat sheets of aluminium. These are then welded together. The process for steel is very similar to the aluminium method however; it is easier to weld.

10.5 GRP Production Considerations

10.5.1 General Precautions

Fire risks

The most critical hazard is the risk of fire when mixing the resin and the catalyst. If incorrect quantities are mixed together an explosive mixture called a hot mix is created from the exothermic heat. There is also the danger of cleaning solvents and cleaning cloths soaked in flammable materials being ignited. Small fires can be handled with carbon dioxide or dry powder fire extinguishers.

Health risks

The majority of the materials used in composite production are toxic if ingested, especially the catalyst which causes burns when in contact with skin or the eyes. Eye wash should be present when handling these chemicals and the correct safety clothing should be worn. Ventilation is also required to remove the smells and vapours produced in this process.

10.5.2 Production Sequence

The basic process of composite hull production is detailed in the hull production section of the summary. The material discussed in this section has been detailed in the material earlier in the report. A step-by-step record of the manufacturing process used to build the hull for this project is presented in the next section.

Step 1 – Generating the profiles

The first step was to printout 8 profiles of the boat from Pro-desktop. These profiles were generated from the original hull design from Hullform. The profiles were cut to shape and size with scissors and a guillotine.

Step 2 – Adhering the paper profiles to the plywood

3 sheets of Far Eastern plywood were ordered. This was the cheapest and most suitable material for the hull tool as it was easy to machine and screw into and was strong enough to support the manufacture of the hull. The paper profiles were then adhered to the plywood sheets using diluted PVA adhesive that was mixed to the specification of

the product. The accuracy of the placement of the profiles on the plywood was crucial as this determined the shape and accuracy of the completed hull. Measurements were taken with care using metre rules and tape measures and the profiles were smoothed down to avoid distortion from the wet glue. Each upright on the plywood sheets was labelled with the appropriate number for identification purposes. The sheets with the profiles attached were then left to dry over-night.

Step 3 – Shaping uprights

The plywood sheets needed cutting into 8 different uprights for the hull form tool. Again accuracy was imperative here so the carpenter was used to cut the sheets on a bench saw when it was evident that the band saw could not accurately produce the cut. See layout of profiles and cutting paths for the carpenter, Figure 57. Combining the accuracy of the bench saw and experienced operator ensured that the uprights had true parallel sides.

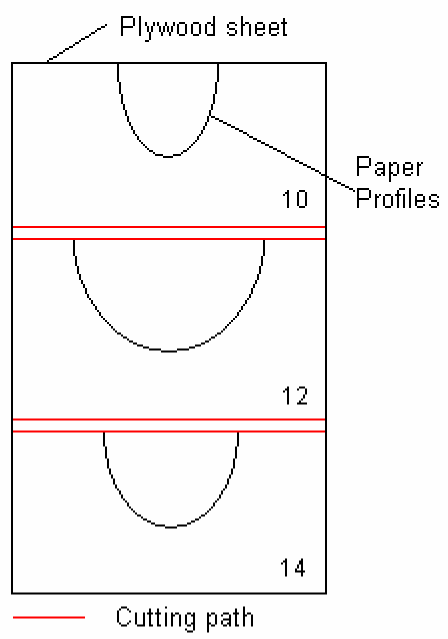


Figure 57 – Layout of uprights and cutting paths for carpenter

Step 4 – Cutting base frame parts to length

The uprights needed a frame to be mounted on to keep them all in the correct position. Four 2500mm long beams of (50mmx50m) softwood were cut to length (squaring off the ends with a mitre saw for a true fit). The off-cuts from the Far eastern plywood will also be used to brace the lengths of softwood.

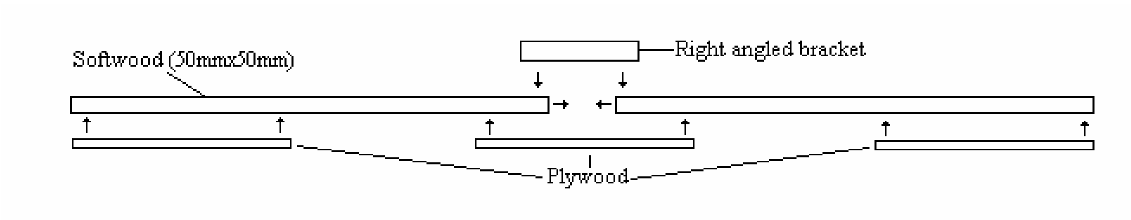


Figure 58 – Schematic of base frame assembly

Step 5 – Assembling base frame

The plywood was screwed to the beams using 1” woodscrews. A right-angled metal bracket was also inserted to strengthen the connection of the two beams (see right and above). This provided a rigid base for the uprights to be attached to.

Figure 59 – Assembling the base frame

Step 6 – Cutting the profiles out of the uprights

The profiles represented by the glued paper templates on the uprights needed cutting out to provide the external shape of the hull. A versatile machine was required that could cut 18mm thick plywood. After consideration and tests, a jigsaw was used to cut the eight profiles using a cutter designed for machining wood and a slow feed rate. An extraction device in the form of a vacuum cleaner was used to remove the dust and cuttings produced from the jigsaw. The uprights were located on a workbench to hold the work piece firmly while cutting.

Figure 60 – Using the jigsaw to cut out the profiles

Step 7 – Attaching uprights to base frame

Right-angled brackets and strips of softwood were used to locate the uprights at the correct height see Figure 61. 16 softwood supports were cut by the carpenter as the band saw could be set to a specific length of cut and process all the supports which increased repeatability and productivity.

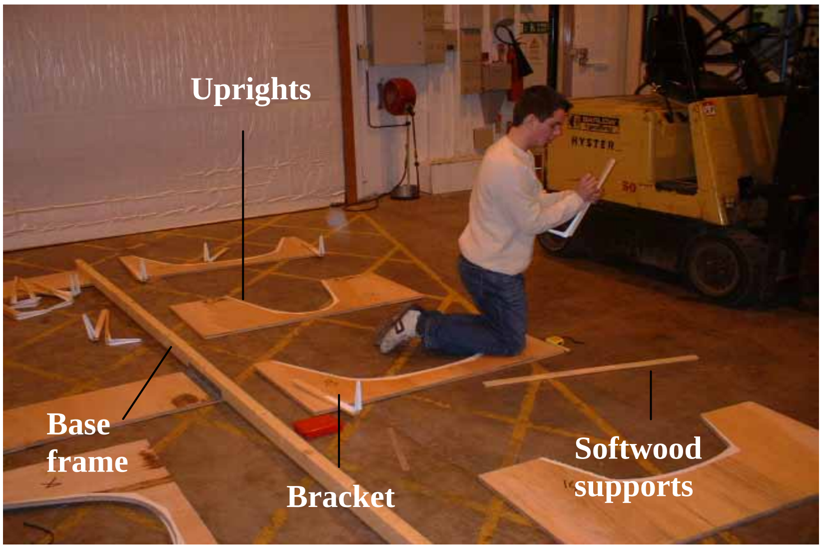


Figure 61 – The components used to attach the uprights to the base frame

16 right-angled brackets were used to attach the softwood to the base frame. Pilot holes for the screws were drilled and then the brackets were screwed to the base a measured distance apart. The uprights were then clamped to the soft wood supports, a pilot hole was drilled and then the uprights were screwed in at the appropriate height. This process was completed for all 8 uprights see Figure 62 for the assembly. The progress of installing the uprights to base frame is detailed in Figure 63 and Figure 64..

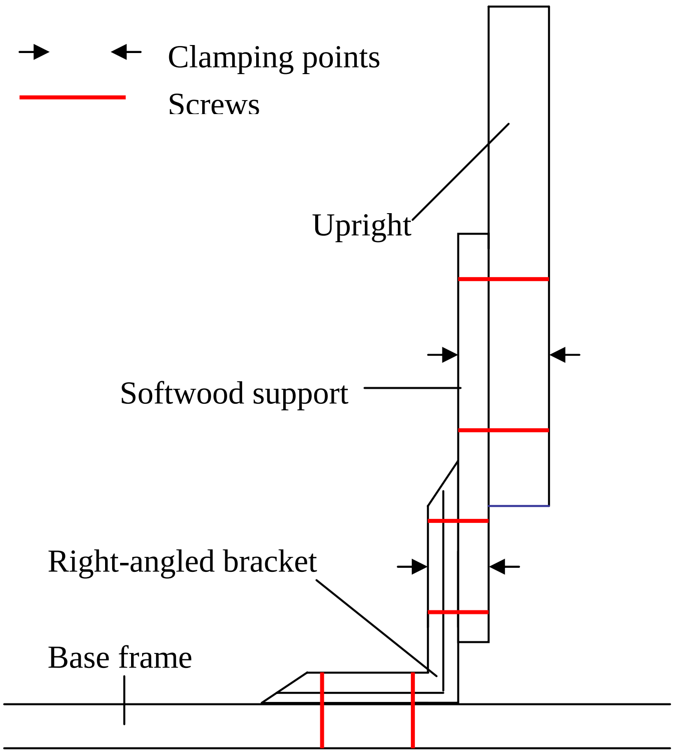


Figure 62 - Schematic of upright attachment to base frame

Figure 63 – Screwing the brackets to the base frame

Figure 64 – Clamping the uprights to the softwood supports to insert screws

Step 8 – Fixing stringers to uprights

The stringers were cut to size by lying the plywood on top of the uprights and using a hand saw to cut off the excess. Each stringer was one complete piece of material to provide the smoothest and truest surface for laying up the honeycomb.

The plywood stringers were located onto the uprights in the correct position and the pilot holes were drilled with a 3mm drill. Each stringer was then screwed to the profiles of the uprights in a symmetrical arrangement creating the shape of the hull. Figure 65 shows the stringers attached to the uprights and Figure 66 illustrates the symmetrical pattern used to locate the stringers.

Figure 65 – Attaching the stringers to the uprights

Figure 66 – Location of stringers in a symmetrical pattern (left)

Step 9 – Relocating stringers

It was apparent after attaching the stringers to the uprights that the plywood had bowed in places and come out of alignment at the bow of the hull. To rectify this problem, two right-angled brackets were screwed to the uprights and then bolted to the relevant stringers, see Figure 68.

Figure 67 – Right angled brackets used to locate stringers (right).

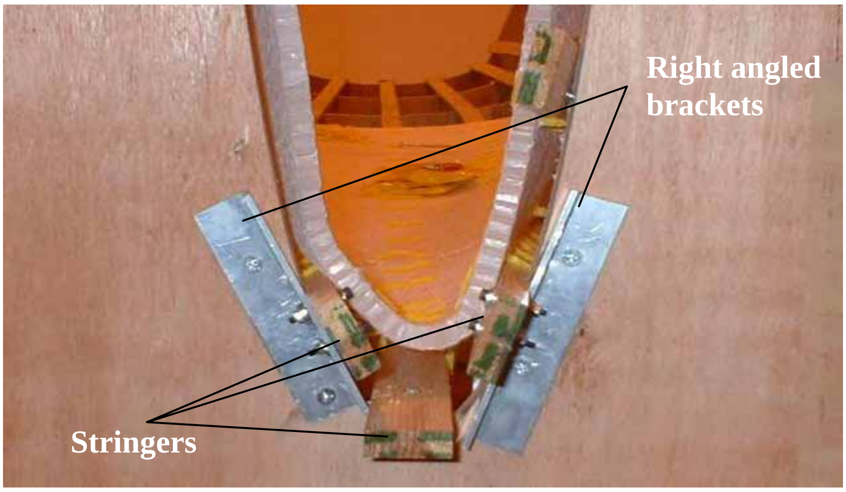


Figure 68 – The hull tool in its completed form

Step 10 – Laying the honeycomb on the hull tool

The next phase was laying the honeycomb. Calculations were completed using Pro-Desktop to ascertain how much honeycomb was needed to cover the inside surface area of the hull. The honeycomb was cut to the appropriate dimensions using a handsaw and a Stanley knife. Honeycomb areas above $2m^2$ were difficult to mould into the correct shape so thinner strips were used.

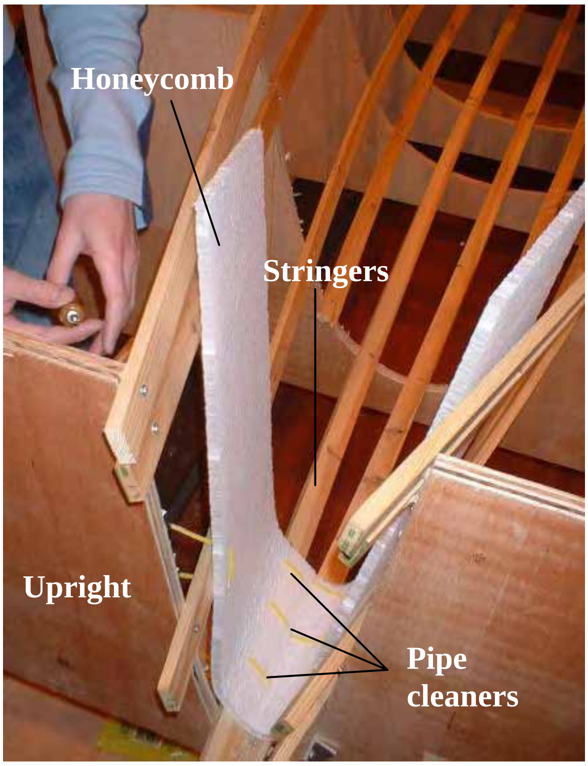


Figure 69 – Attaching the honeycomb to the stringers using pipe cleaners

Step 11 – Inserting the pipe cleaners

The honeycomb was then attached to the stringers of the hull tool by piercing it with a bradle and passing a pipe cleaner through the hole, round the stringer and then back out the hole, see Figure 70. The pipe cleaner was then tightened up with pliers to ensure the honeycomb was located in the correct position and was against the stringer. Pipe cleaners were used as they absorb the resin thus becoming part of the hull and can be tightened up easily by hand. Figure 70 shows the progress of laying the honeycomb on the hull tool.

Figure 70 – Laying the honeycomb

Step 12 – Locating internal bulkheads

After the honeycomb was in place in the inside of the hull the next step was to locate the internal bulkheads. Cardboard templates were cut out (using the profiles cut out from the uprights) to the correct shape by compensating for the thickness of honeycomb.

Thicker honeycomb sections were used where extra support was required (50 mm for the rudder support and underneath the hydrofoil mountings). The bulkheads were cut with a handsaw and Stanley knife as before. An orbital sander was used for small shape changes and to make the adjoining surfaces smooth. These bulkheads were not fixed at this stage as the inside of the hull and the bulkheads need to be glassed before assembly. The figure below shows the bulkheads in position prior to the glassing process.

Figure 71 – Hull tool with honeycomb and bulkheads inserted

Step 13 – Laminating the inside of the hull

The glass mat was placed over the honeycomb with the excess cut off and smoothed to lie on top of the honeycomb sheets. The glass mat was removed before the glassing process started. The resin was mixed by weighing the amount needed and adding the catalyst (1% of resin mass) into a plastic beaker. The exothermic reaction between the catalyst and the resin happens immediately so there is only 20 minutes to apply the mixture to the core. The mixture was applied with a brush until the honeycomb was completely wet. The glass was laid on top of the wet resin and smoothed down to remove any trapped air. Resin was then applied to the glass sheet until all areas had been completely penetrated. Two layers of glass cloth were used to provide a strong laminate.

Figure 72 – Glassing the inside of the hull

Step 14 – Glassing the bulkheads

The bulkheads were glassed one side at a time to avoid any running or distortion in the glass / resin structure. The same glassing process as described in step 16 was applied to the bulkheads. The bulkheads were left over night to cure before glassing the other side (see Figure 73).

Figure 73 – Glassing the internal bulkheads

The excess glass and resin was cut off using a band saw and orbital sander. This provided a clean and smooth surface to locate into the hull. The top surfaces of the bulkheads and hull were all shaped with an allowance of at least 100mm to minimise delamination. This excess will be cut of with a circular air powered saw after the outside surface of the hull has been glassed.

Step 15 – Locating the bulkheads in the hull form

Once the bulkheads and the inside of the hull had been cleaned to remove dust and any dirt they were prepared for assembly. The bulkheads were placed in the designed locations using spirit levels and tape measures to increase accuracy, see Figure 74.

Figure 74 – The bulkheads in place in the hull ready for filler application

The arrangement of bulkheads is shown in Figure 75.

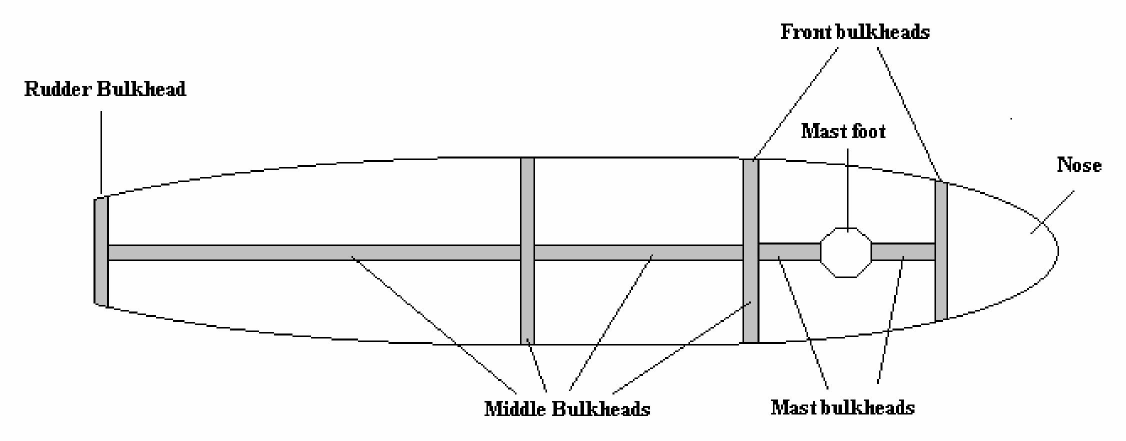


Figure 75 – Location of bulkheads

The joins of the bulkheads were then lined with resin putty (P38 Car body filler) to ensure a tight fit and to fill any between the two parts. The filler and hardener were mixed to the specifications given by the product (2% hardener). If too much hardener was inserted into the mixture the filler would set before application could be completed, conversely if insufficient amounts of hardener were used then the filler would not set. A 10mm layer of filler was applied to each edge, by wearing gloves, the excess filler could then be smoothed into a radius using the operator's fingers, see Figure 76.

Figure 76 – Filler applied to the bulkheads and inside of the hull

The filler could be sanded down after it had cured to produce an even smoother finish. This minimised the amount of cavitation in the resin and glass composition when applied on top of the filler.

Step 16 – Glassing in the bulkheads

Three different widths of glass mat were used to attach the bulkheads to the hull in an arrangement shown in the schematic.

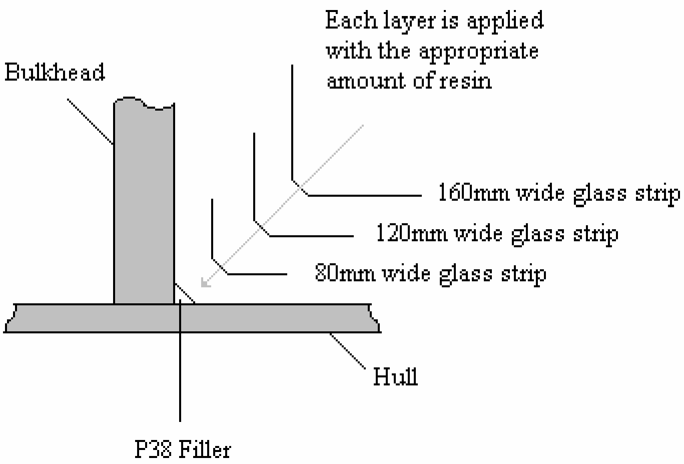


Figure 77 – Schematic illustrating how the bulkheads were attached to the inside of the hull

The different widths of glass mat were used to ensure a close fit in the corner of the joints and to increase the amount of surface area incorporated in the joint thus increasing the strength. This process was used to fit all the bulkheads into the hull.

Step 17 – Mast foot

The carpenter was used to machine plywood into a hexagonal column to support the mast. Using a skilled operator increased the accuracy of the cutting and decreased the time spent on this element of production.

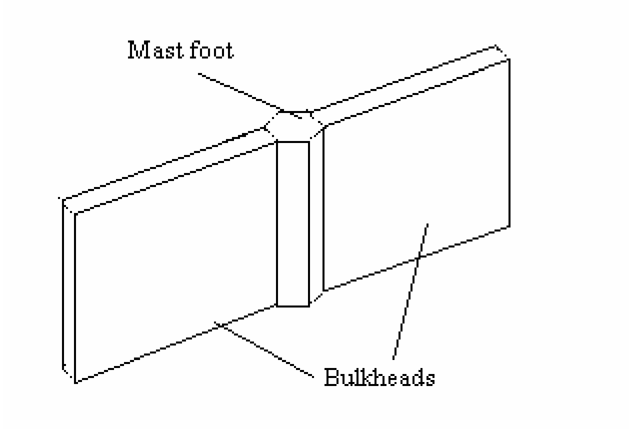


Figure 78 – Location of mast foot

A hexagonal shape was used to provide faces on the column to attach aluminium supports and to accommodate the two bulkheads.

The mast foot was glassed to the bulkheads and inside of the hull using 120mm and 160mm wide strips of glass mat.

Step 18 – Supporting the mast foot

Square aluminium lengths were used to brace the mast against the bulkheads because of the good strength to weight ratio. The ends of the aluminium were cut with a hacksaw and filed down to remove the sharp edges. Filler was applied to the end of the supports and they were then glassed in using small strips of glass mat. The arrangement can be seen in the following figures.

Figure 79 – Mast support arrangement

Figure 80 – Location of mast and aluminium supports

Step 19 – Locating beam supports

The hydrofoils will be attached to the hull using a 3m long aluminium hollow beam. This beam will be supported on one of the bulkheads using four plywood blocks and stainless steel brackets see Figure 81.

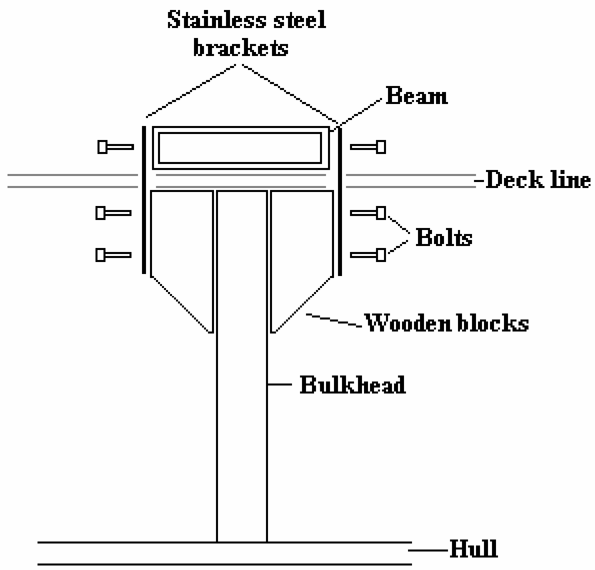


Figure 81 – Schematic of beam support assembly

The wooden blocks are shaped to fit on the bulkhead behind the aluminium support. These angles on the plywood were cut by the carpenter who set the bench saw to a 45˚ angle, again saving time and effort. The blocks were varnished and left to dry before attaching them to the bulkhead. P38 Filler was applied to the flat side of the wooden blocks to ensure a secure fit between the two surfaces. The blocks were then clamped onto the bulkhead and the filler was smoothed around the perimeter of the block, see Figure 82.

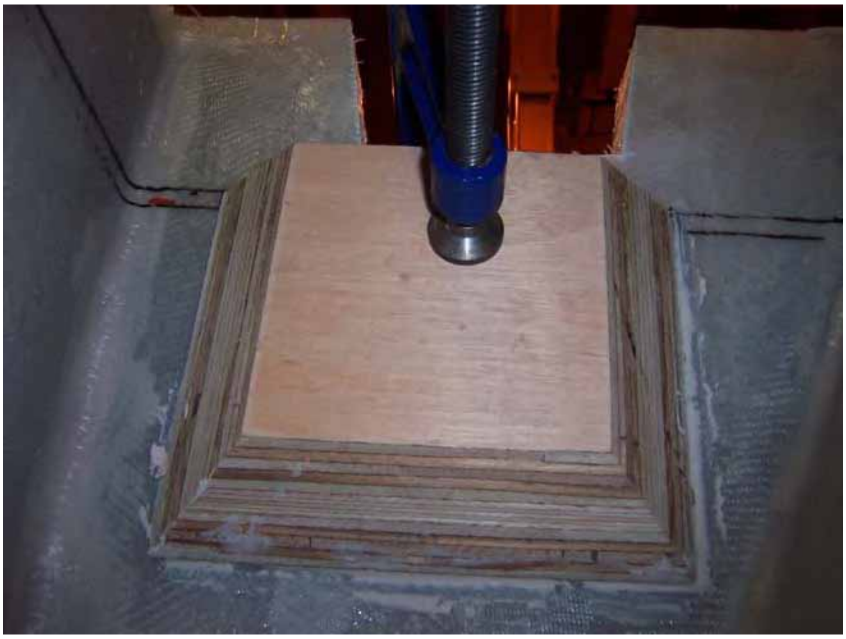


Figure 82 – Beam supports being clamped on to the bulkhead

A section of the excess of the bulkhead had to be removed to locate the clamp as can be seen in Figure 83. The blocks were glassed in using 80mm and 120mm wide strips of glass in the same manner as described earlier.

Figure 83 – Beam mountings bolted to the bulkhead via wooden blocks

The stainless steel brackets were guillotined from the sheet to the correct size by a technician. The holes for the bolts were then drilled on a pillar drill using coolant/lubricant and increasing the diameter of the drills in 4mm increments to minimise wear on the drills.

Three holes 10mm in diameter were then drilled into each of the wooden blocks to house the bolts that secure the stainless steel brackets. The hole could not pass through both blocks and bulkhead so another method of attaching the metal brackets was required. Araldite® was used on the threads of the bolts to secure them into the wooden blocks.

Figure 84 - Internal View of Hull

Step 20 – Shaping the nose

The nose of the hull will be shaped from a foam block as the honeycomb was difficult to lay right at the bow of the boat. Blocks of foam were adhered together to form a block large enough to shape the nose from. The nose will be cut roughly with a handsaw and then smoothed into shape with an orbital sander. The nose was located into the hull to make sure the outside of the hull matched the shape of the nose, see Figure 85.

Figure 85 – Shaping the nose

The nose once finished (see Figure 87) was coated with resin to make it waterproof and to provide a surface, which could be glassed to the hull.

	
Figure 86 – Applying resin to the nose	**Figure 87 – The nose located in the hull**

Step 21 - Glassing the outside of the hull

The outside of the hull was laminated using the same method and principles as detailed in step 13. Before this took place, the outside surface was sanded and cleaned to remove any surface roughness or impurities. The pipe cleaners that were attached to the wooden mould frame were cut off and hammered into the hull to provide a smooth surface.

Step 22 – Cutting the hull to size

After the outside skin of the hull had cured completely, an air powered circular saw was used to cut down the excess laminate, see Figure 88. The shape of the hull was now apparent as can be seen in Figure 89 and Figure 90.

Figure 88 – Cutting off the excess material on the hull

Figure 89 – Hull shape (front view)

Figure 90 – Hull shape (rear view)

It was evident after cutting off the excess how effective the fillet joins were between the bulkheads and hull, see Figure 91 below.

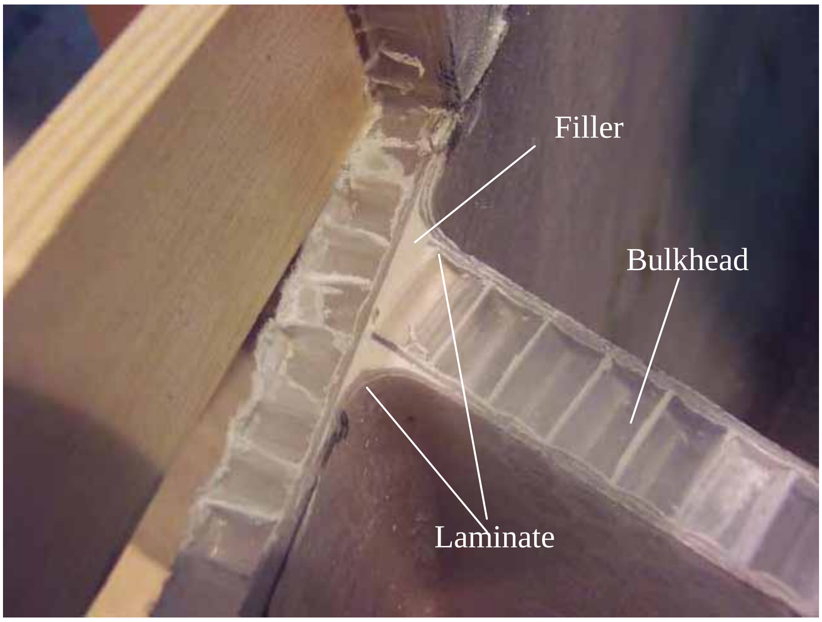


Figure 91 – Fillet join at hull / bulkhead interface

Step 23 – Attaching the deck to the hull

Sections of deck were cut from 10mm thick honeycomb core with a Stanley knife. These sections were then laminated using the same method as the bulkheads on side. Once this side of the deck had cured completely, it was still flexible and could be formed into the curved shape at the rear of the boat. The excess was cut off using a band saw and resin putty was then applied to each of the contact faces on the hull and deck panels. The deck panels were then placed into position and left to dry other night with weights placed on top to add pressure to the joins. The other side was then laminated using the glass cloth to join the deck to the hull. These joins were then laminated again using 80mm and 120m m strips of glass.

Figure 92 – Rear view of the deck attached to the hull

Step 24 – Manufacturing the beam

An aluminium hollow beam will be used to connect the hydrofoil supports to the hull. The beam is bolted to the hull using the stainless steel brackets that can be seen in the right of Figure 92. Wooden blocks were glued inside the aluminium beam to provide a solid material to attach the hydrofoils supports and bolt into. The wooden blocks located at the end of the beam were grooved to provide a recess for the glue to settle. A profile was cut out with a band saw to locate the hydrofoils support into. The beam can be unbolted from the hull and hydrofoils can be released from the beam to make transportation easier. See Figure 93 for a schematic of the beam arrangement.

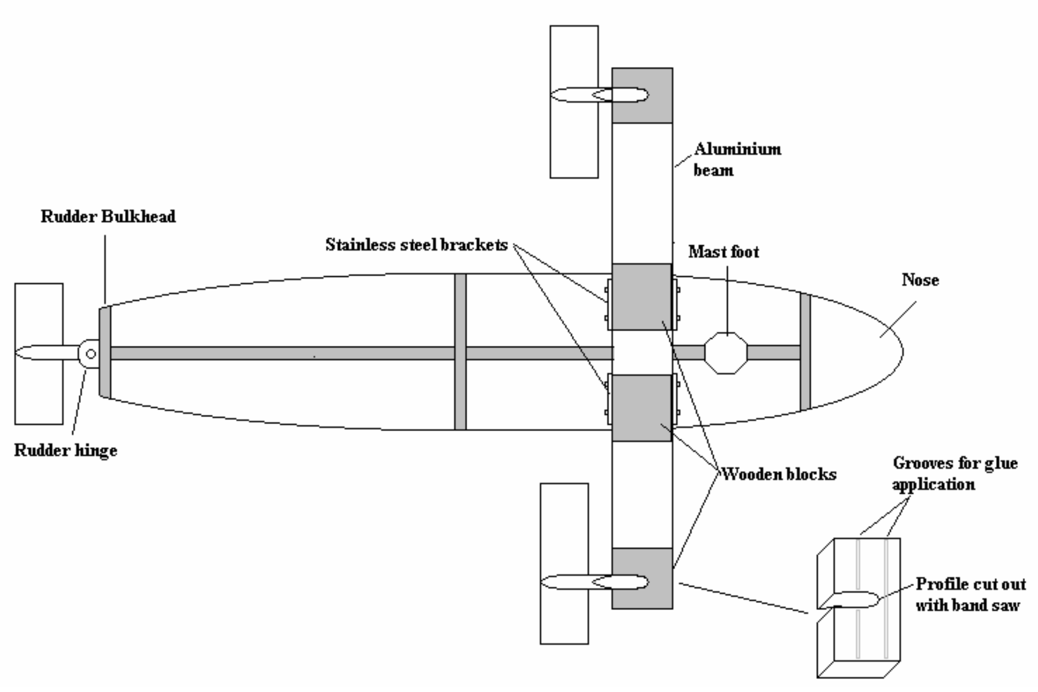


Figure 93 – Beam attachments

Step 25 – Rudder Attachment

The rudder will be connected to the hull using a hinge system machined from stainless steel. The components for the rudder attachment were machined at a local manufacturing firm and then welded to a pre-drilled stainless steel plate. The holes were then used as a template to drill through the stern of the hull in the appropriate places. Araldite© was then applied to both connecting surfaces before attaching the stainless steel sheet to the hull with bolts to increase the strength of the join. The rudder attachment located on the hull is shown in Figure 94.

Figure 94 – Rudder attachment

The two bolts that fix the rudder to the hinge can be removed so that the rudder can be taken off to make transportation easier.

Step 26 – Rigging Attachments

Most of the brackets for the rigging attachments can be screwed into the hull directly. A layer of filler is applied to both contact faces and then the component is screwed into a pre-drilled hole in the hull.

11 THE PROTOTYPE

12 FOIL DESIGN AND BUILD

12.1 Foil profile study

As discussed in section 4.7.1 Foil profile selection, the choice of profile NACA 25014 for the prototype foils can be validated by considering those NACA profiles close to the chosen design. Foils 21014 to 25014 (Group 1) and 25008 to 25018 (Group 2) have been modelled in visual foil and used to draw the following conclusions based on the profile criteria specified in section 4.6 Design Specification.

12.1.1 Surface pressure profile

In the design of a hydrofoil in particular, it is the pressure surface over the upper surface of the foil that is of most concern in terms of performance. It is in this negative pressure region that cavitation and ventilation will occur if the foil is incorrectly designed.

Group 1 – By moving the point of maximum camber further back along the length of the foil, the point of peak negative pressure is also brought backwards and its magnitude reduced (Graph 1 – Appendix 3). The pressure peak is also stretched across a greater portion of upper surface, providing greater lift and reducing the likelihood of cavitation. NACA 25014 represents the greatest distance of the maximum camber point from the leading edge that Visual Foil will generate.

Group 2 – Although the pattern is not regular, it can be seen that the magnitude of the total negative pressure over the upper surface of the foil, and hence lift (effectively the integral of the pressure profile) increases as the thickness of the foil is increased (Graph 2). Without then moving the point of maximum camber back further, it can be seen that the pressure field begins to creep back into an unwanted sharp pressure peak. NACA 25014 gives a good intermediate performance without generating too thick a foil – see Lift to drag ratio below.

12.1.2 Lift to drag ratio

The defining performance feature of hydrofoils is there ability to produce a much greater lift force than drag force. By studying the variation in C_l , C_d ratio with change in foil profile, the optimum section can be found.

Group 1 – Graph 3 shows how the ratio of C_l to C_d varies with the angle of attack of the foil (Appendix 3). In order to maximise the potential of the foil, an angle of attack of three degrees has been chosen for the fixed angle of attack of the lifting foil. This value is set such that with the trailing edge flap in the neutral position, the main body of the wing will provide sufficient lift to carry the boat. The angle is also safely within the angle at which ventilating flow is likely to occur on the leading edge.

The increase in lift from a 21014 foil to a 25014 foil of identical span and chord is approximately 20%, a notable beneficial increase in performance.

At three degrees angle of attack, the lift coefficient for the foils in Group 1 and 2 falls near the 0.5 mark. At this point, a small although barely significant improvement can be seen in the lift to drag ratio of NACA 25014 over the other foils. The difference in performance does however increase with angle of attack.

Although not an apparently extensive performance improvement over the other foils in group 1, if the data is considered numerically, the increase in lift from NACA 21014 to 25014 is greater than 20% for a 2% increase in drag, representing a very valid argument for the use 25014.

Group 2 – Graph 4 shows the disadvantages of using thicker foil sections, represented by the greater drag for the same lift than the thinner foils. This loss of performance is justified by the observation that thinner foils respond more rapidly to changes in angle of attack, and are more prone to pressure peaks and ventilation.

12.1.3 Transition from laminar to turbulent flow

Although very much subject to factors such as the surface and build quality of the prototype foils, the point at which the flow over the surface of the foil switches from laminar to turbulent as an output from Visual Foil, can be used as a performance assessment factor (Graph 5 and 6) to aid selection of a profile. The data gives an indication of the sensitivity of the foil to changes in angle of attack.

However as a prediction of performance, the data has very little value. As the boat will inevitably be used on a windy day, the body of water in which the foils are submerged in (particularly during flying) will be very turbulent, and hence the flow over the foil is likely to be turbulent at every point.

Group 1 – It can be seen from Graph 5 that the further the point of maximum camber is placed from the leading edge, the smaller the response to angle of attack beyond two degrees angle of attack. This gives the foil an advantage when required to perform in the unpredictable flow that it will be subject to as an operational prototype, where sudden changes in performance will not make for a comfortable ride on the flying boat.

Group 2 – A similar relationship to Group 1 can be seen for Group 2, where, an increase in thickness results in the transition point occurring further back down the foil. The correlation is less prominent for this case however, and has very little affect in the predicted angle of attack operating range designed for.

12.2 Finding lift coefficient C_l

Visual foil uses a CFD method based on the linear strength vortex panel method, placing model singularity vortices at evenly distributed points along the wing surface (the number of points can be increased for a more accurate model). The method is used to compute the inviscid outer flow field, whilst standard boundary layer equations for laminar and turbulent flow are used to compute the viscous layer at the surface of the foil.

The method generates a 2D model for the flow over the wings surface from which a velocity profile for the wing surface can be produced. From this discrete step velocity profile, the dynamic pressure at these points along the wings surface can be found through the formula:

Dynamic pressure: $$P_D = \frac{\rho v^2}{2}$$ **Equation 54**

The lift generated by the foil is also found using the vortex panel method to calculate the net circulation over the foil:

Lift: $$L = \rho \Gamma V_\infty$$ **Equation 55**

The lift coefficient can now be calculated using the lift and dynamic pressure approximations and the area of the foil over which the lift coefficient is being calculated (the reference area A_{REF}):

Lift Coefficient: $$C_L = \frac{L}{P_D A_{REF}}$$ **Equation 56**

12.3 Optimizing foil design for structural integrity

12.3.1 Design against lifting foil failure

As mentioned in section 4.7.8 Design for loading – the foil as a structural member there are a number of physical limits that confine the design of the foil, and define its final size (span and chord). Design optimisation spreadsheet 1 (Appendix 3) has been used to assess these limits to find the near optimum foil dimensions for the given NACA code. Having set the shape of the foil based on its potential to generate lift and minimise the possibility of cavitation, and given that the chosen design is constant section, the only dimensions left, required for manufacturing the foil are the span and chord.

The spreadsheet begins by assessing the worst-case load condition that wing is likely to be under. The chosen safety factor makes the assumption that the total weight of the craft, rigging, foils and sailor all act on one foil at once. This total weight has been estimated and rounded up to 2000N.

Using the infinite wing model of lift outputted from *Visual Foil* the plan area for the wing is set by looking at the minimum area of wing required to produce 2000N of lift. If the plan area is known, choosing the correct aspect ratio will yield the span and chord dimensions.

The aspect ratio (as mentioned in section 4.7.4

Plan area and aspect ratio) of the foil affects the performance of the foil such that the amount of lift lost as a result of wing tip vortices decreases as the aspect ratio increases, i.e. a long thin wing will be more efficient:

Real Lift $$L_R = \frac{LR}{2+R}$$ **Equation 57**

However, as the aspect ratio increases, so the further the centre of pressure moves from the base of the strut. If we model each side of the wing as a uniformly loaded cantilever beam where the fixed end is at the base of the strut, we can express the bending moment generated in the wing as a function of the lift and the span of the foil:

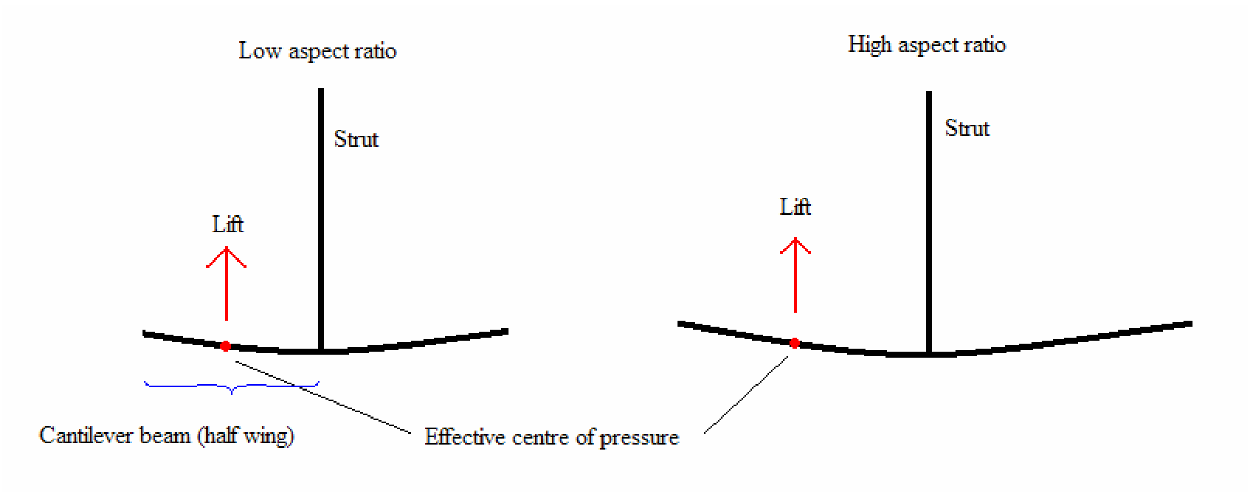


Figure 95 – Centre of pressure to aspect ratio relationship

The maximum bending moment in the wing occurs at the joint between each side of the wing and the strut and is expressed:

$$M_{\max} = -\frac{1}{2}WL$$ **Equation 58**

Where in this case, L (/m) is the half the length of the wing (distance from the strut attachment to wing tip) and W (/N) is the uniformly distributed load w (Nm^{-1}) multiplied by length L.

As well as increasing the bending moment in the wing, the increased aspect ratio causes the wing to become more slender (chord is proportional to thickness). The wing cross section becomes increasingly smaller, with less room to fit a load member capable of supporting the lift load. Figure 96 shows a model for the basic build structure of the prototype foils, ignoring the trailing edge flap.

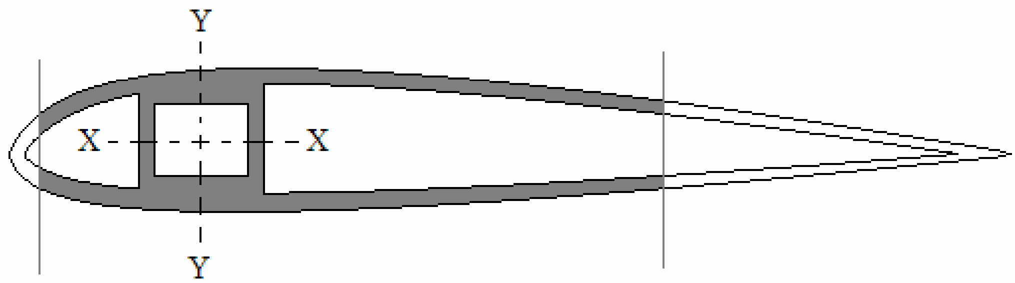


Figure 96 - Showing the I-beam approximation of the prototype foil design.

For the purposes of modelling, the profile is modelled as an I-beam, symmetric about XX and YY axes. The GRP skins of the wing model the flange, and the hollow box section load member represents the web. For ease of calculation, the width of the flange is taken as the chord, and the load member is assumed to be situated at the half chord position.

The material structure of the beam is split into the load member taken as a square beam equal to the thickness of the foil minus two layers of 3mm GRP skin, and the flange modelled as two flat plates of 3mm GRP. The two bond layers between the three parts are also considered in the spreadsheet.

The second moment of area (*I*) for the material elements is calculated, and with the maximum bending moment is used to calculate the worst-case stress imparted to each element. This worst case is assumed to take place at the outer most limit (y_{max}) of each material, and at the centre of the bond layer.

$$\sigma = \frac{My_{\max}}{I}$$ **Equation 59**

Where the notation is as standard.

By checking the maximum stresses in the elements of the beam against safety factored values for strengths of possible suitable materials, the maximum aspect ratio that each chosen material can support can be identified. Values for yield strength have been used for the load member and tensile strength for the GRP skins, as these are the likely to be the properties of the material responsible for supporting the load.

As can be seen from the spread sheet, it is failure of the bond layer that is likely to be responsible for the total failure of the foil, as even the highest quality epoxy adhesives cannot offer the resistance to shear loading required. In order to work round this problem, it was decided that the load member should be built into the GRP skin (upper surface) of the foil, with glass fabric passing over the load member, offering more than a just a shear resistant layer.

In order to account for the large gap in the required strength of the bond layer and that provided by the possible bonds, a further safety factor of ten is used to bring the complete structure well within safe working properties of the constituent material parts.

The final design outcome therefore places the dimensions of the three foils at:

Span = 1m **Chord = 0.18m**

The rear foil does not need to provide the same amount of lift as each of the front foils, and hence requires a smaller span. For ease of manufacture (one size of mould), the chord will be kept the same; and does not compromise the strength of the foil, as this will only bring it further within the safe material limits.

The spreadsheet also provides a good approximation of the likely finished mass of the lifting foils.

12.3.2 Design against strut failure

A similar method of failure assessment has been carried out for the struts, in order to ascertain a safe length for the design (dictating flying height). As mentioned in section 4.9 Design for Manufacture, the moulds for the lifting foil will double up as the moulds for the strut, predefining the chord and hence the thickness of the NACA 0018 profile.

Design optimisation spreadsheet 1 (Appendix 3) shows a comprehensive assessment of the strength of different length struts composed of varying GRP skin thickness and load member materials. Euler buckling is assumed as the first mode of failure of the struts and as the main body of the craft represents a solid heavy platform, the member is modelled as having one ‘free’ and one ‘fixed’ end. The results of the spreadsheet work are given in section 4.8 Foil Design output.

12.4 Foil Materials

The computer program ‘Cambridge Engineering Selector’ (CES) was used to choose the material for the foils. Initial research on the Internet and relevant literature did not provide a lot of information on current foil materials. As this was a new area for the group it was decided to use CES to provide a range of suggestions that would aid the material choice decision.

There are several advantages of using the computer program. The main advantage is that it is not reliant on a human to make many judgements to material or process suitability. The commonly used Ashby charts can be very cluttered and it can be hard for the eye to assess where lines originate from and the areas that they encompass. Using the charts gives limited variables that can be chosen, these usually relate to basic physical characteristics and cost considerations. The computer can easily identify materials that would be suitable for the parameters that have been entered. With the databases of the program being updated the computer can take into account new materials that Ashby charts may not have been produced for.

The major disadvantage with using the computer based selection tools is that the computer only looks at outcomes that can satisfy the parameters that are entered into it. A human using charts can see materials that may be right on the boundaries of selected areas, and therefore may be possible choices.

CES was used to find suitable materials for the foil skin, and the supporting internal beam.

Taking the designs supplied by the foil design team the relevant parameters were extracted and entered in to the computer.

Tensile strength for skin: 22.079Pa

Tensile strength for beam: 16.82Pa

Compressive strength for skin: -22.079Pa

Compressive strength for beam: -16.82 Pa

CES eliminates different materials in a series of stages. To ensure sensible results seven individual stages were used, each incorporating a different factor to be considered. The first factor was the compressive strength that the material would need to have. This value was obtained from the test spreadsheet supplied by the foil design team. The maximum value was entered to ensure the material chosen could withstand the forces, a value of 22.079e-006 MPa. This reduced the number of materials from the initial list. The next filter was the tension strength, again a value of 22.079e-006 MPa.

These two filters produced a list of materials that would be strong enough to be used for the design that had been chosen. The nest stages concentrated on the environmental conditions the foils would be exposed to. Firstly the operating temperatures were entered. The temperature of the water will not be colder than 275K (0^oC) and no warmer than 300K (25^oC). This further reduced the list of materials available for selection.

As the foils will be immersed in water it was important to ensure that the material chosen would be suitable for an aqueous environment. The filter asked for water resistance to be ‘very good’.

The weight of the foils was an important consideration. Therefore it was decided that a density as close to that of water was important. If the foils were too heavy they would hinder the performance of the lifting forces generated. At first a density of one tonne per m^3 was entered, but this reduced the list of available materials too much, instead a density of 1 ½ tonnes / m^3 was chosen. This produced a better list of suitable materials. Finally as we have a budget for the project a desired cost per Kg was entered. This was in the range £1 - £5 /Kg.

After all these filters were applied there were 95 suitable materials remaining. Working through the list and considering the suitability of the remaining materials with respect to our knowledge and expertise the polyester with 30% glass fibre was chosen. This also had benefits, as it was the same as the material used for the hull, so bulk buying and price discounts were available.

Below is a screenshot from CES showing the selected material.

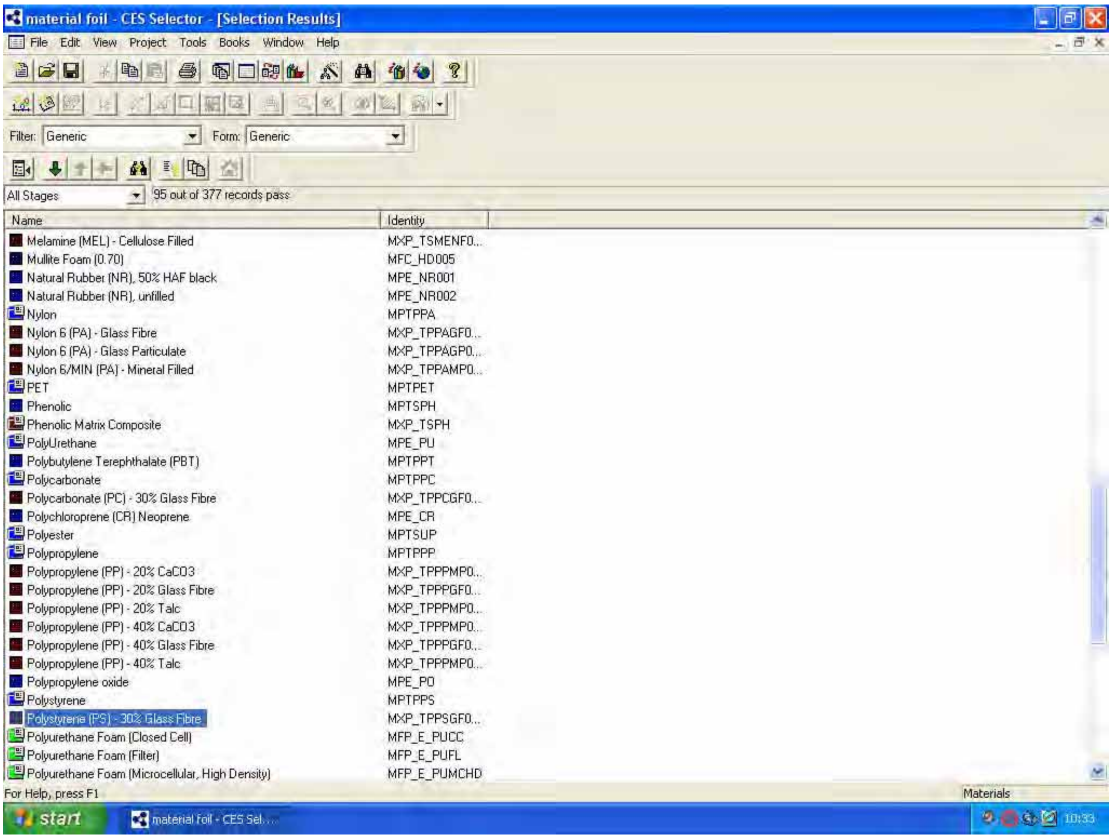


Figure 97 - CES Screenshot

13 CONTROL SYSTEM

13.1 Model for Aerated Flow Control System

In the control system section of the summary report (Chapter 5) two spreadsheet models were introduced. They can be found in Appendix 5 and Appendix 6. This section explains how the two spreadsheets work row by row.

The spreadsheet in Appendix 5 models the boat as it hydrofoils using the aerated flow control system from section 6.4.1Design Concept 1: Aerated Flow Control System

Rows 1 – 35 are inputs. Most will stay fixed but some are variables that can be changed to investigate different situations. Row 26 calculates the total weight of the boat including all the fixtures and the sailor by summing all their masses and multiplying by the acceleration due to gravity, 9.81 ms^{-1}.

The lift and drag coefficients are taken from visual foil and allow calculations for the lift and drag to be made.

Row 38

The apparent course, β, is the angle between the course of the boat and the apparent wind. It is necessary later in the spreadsheet to calculate the apparent wind speed. Here it is an input but can be only one of three possible angles: 25, 27.5 or 30. The apparent course is used in Row 40 and the reason for it being limited to these three values is given below.

Row 39

Here β is converted into radians because Excel calculates in radians.

Row 40 and 41

The driving and heeling coefficients were taken from the graph in Figure 98, which is from Marchaj [1991, page 25].

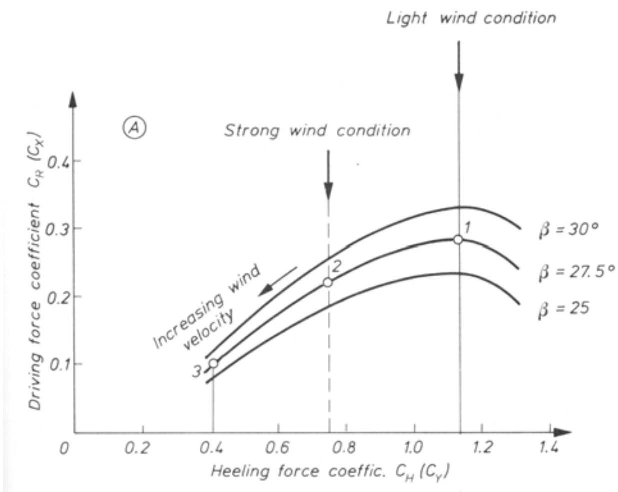


Figure 98 – Driving force coefficient vs. Heeling force coefficient for different apparent course angles.

Three values for the driving coefficient and one for the heeling coefficient were taken from the graph. The three lines on the graph are for three values of β. Therefore β can only be inputted as one of these values on Row 38. Row 40 puts the driving coefficient that corresponds to the value of β in Row 38 by using an 'If' statement.

=IF(B38=30,0.3,IF(B38=27.5,0.26,0.22))

In an attempt to find average values for the driving coefficient the values were taken from a line halfway between the strong and light wind condition lines already drawn on the graph.

The heeling force in **Row 41** is always 0.94.

Row 43

Wind speed is an input to the spreadsheet.

Row 44

Here the wind speed is converted from knots to metres per second. Sailors use knots as the preferred unit of speed. To make the calculations in the rest of the programme simpler it is converted using the identity:

$1ms^{-1} = 0.5144$ knots

Row 47

The boat speed is an input rather than an output because it determines the drag and the apparent wind speed. The model uses an iteration approach, using this boat speed to calculate the apparent wind speed, driving force and drag. If the driving force is not equal to the drag the boat speed must be adjusted until it is. This is explained more clearly by the flow chart in 6.4.2 Modelling of the Aerated Flow control system in the summary report.

Row 48

The boat speed is converted into metres per second using the same conversion as wind speed in Row 44.

Row 49

The apparent wind speed (V_{Ap}) is calculated using vector addition. The actual wind speed (V_{Ac}) and the angle of attack, β, are known and the boat speed (V_B) has been guessed.

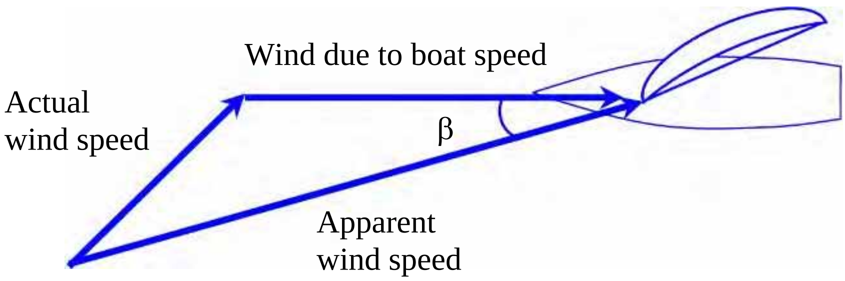


Figure 99 - Apparent Wind Speed Vector Diagram

Cosine rule is used to calculate the apparent wind speed:

$V_{Ac}^2 = V_{Ap}^2 + V_B^2 - (2 \times V_{Ap} \times V_B \times \cos\beta)$

Rearranging into the form $ax^2 + bx + c = 0$:

$V_{Ap}^2 - (2 \times V_B \times \cos\beta)\, V_{Ap} + (V_B^2 - V_{Ac}^2) = 0$

The apparent wind speed is now calculated by solving the quadratic equation:

$V_{Ap} = \{(2 \times V_B \times \cos\beta)+ \sqrt{[(2 \times V_B \times \cos\beta)^2-[4 \times (V_B^2-V_{Ac}^2)]]}\}/2$

Row 50

The force on the sail is found by using the driving coefficient in Row 40. This is multiplied by the density of the air, 1.177kgm^{-3}, the area of the sail, (Row 30), and the square of the apparent wind speed, (Row 49). All of this is divided by two to give the driving force on the sail.

$$\text{Driving Force} = \frac{\text{Density of Air} \times \text{Driving Coefficient} \times \text{Sail Area} \times \text{Apparent Wind}^2}{2}$$

Row 51

The lift from the total span of foils at the boat speed in Row 48 is calculated using a similar equation to the driving force equation:

$$\text{Lift} = \frac{\text{Density of water} \times \text{Lift Coefficient} \times \text{Chord} \times \text{Span} \times \text{Boat Speed}^2}{2}$$

Row 52

Row 51 calculates the lift from the total span of foil. However, this lift is excessive, as the foils only need to create enough lift to overcome the weight of the boat. Therefore Row 52 calculates the fraction of the lift that is needed by dividing the weight of the boat by the lift. Then this fraction is multiplied by the total span of foil to give the necessary total span.

Rows 53, 54 and 55

An identical equation to the lift calculation in Row 51 is used to calculate the drag on the foils and struts. The lift coefficient is substituted by the drag coefficient. The total span of foils will cause drag, regardless of the span that is creating lift. The total strut span is not in the water, so will not create hydrodynamic drag (aerodynamic drag is considered negligible). The effective strut span (span under water) from Row 16 is used instead. Row 55 sums the two drag components.

Row 56

On this row an ‘If’ statement is used to compare the driving force with the drag. If the drag is greater than the 101% of the driving force the display reads, “Reduce boat speed”. If the drag is less than 99% of the driving force the display reads, “Increase boat speed”. If neither of these inequalities is true the display reads, “OK”.

This is where the iteration starts; the operator of the spreadsheet must return to the boat speed and change it as instructed until the display in Row 56 reads, “OK”.

Row 57

This is a safety measure, built into the model to ensure that the necessary foil span in Row 52 does not exceed the available foil span, set in Row 7. It is an ‘If’ statement that displays "STOP, THE SPAN OF FOIL YOU NEED TO FLY IS BIGGER THAN THE ACTUAL FOIL" if Row 52 is greater than Row 7 or “OK” if it isn’t.

Row 59

To find the heeling moment of the wind on the sail, the heeling coefficient from Row 41 is substituted into the driving force equation of Row 50 in place of the driving coefficient. This gives the heeling force, which is modelled as a point load at the sails centre of effort (CE). The heeling force is multiplied by the height from the mast foot to the centre of effort of the sail:

$$\text{Moment} = \frac{1.177 \times \text{Heeling Coeff.} \times \text{Sail Area} \times \text{Apparent Wind}^2 \times \text{Height to CE}}{2}$$

Row 60

The moment from the sailor is the sailors weight multiplied by the distance that he sits from the mast. The sailor will sit on the very edge of the boat to give the maximum heeling moment, so the distance is half the width of the beam.

Moment from sailor = (Beam width × 0.5) × Mass of sailor × 9.81

Row 61

The net moment is the moment from the wind force minus the moment from the sailor.

Row 64.

The combined front foil lift is worked out by balancing moments about the rear foil. Figure 100 shows the forces acting on the boat that cause moments about the rear foil. The front foil is in line with the rear foil so the drag from it does not create a moment. The forces in Figure 100 are not labelled, instead they are colour coded against the moment balancing equation below.

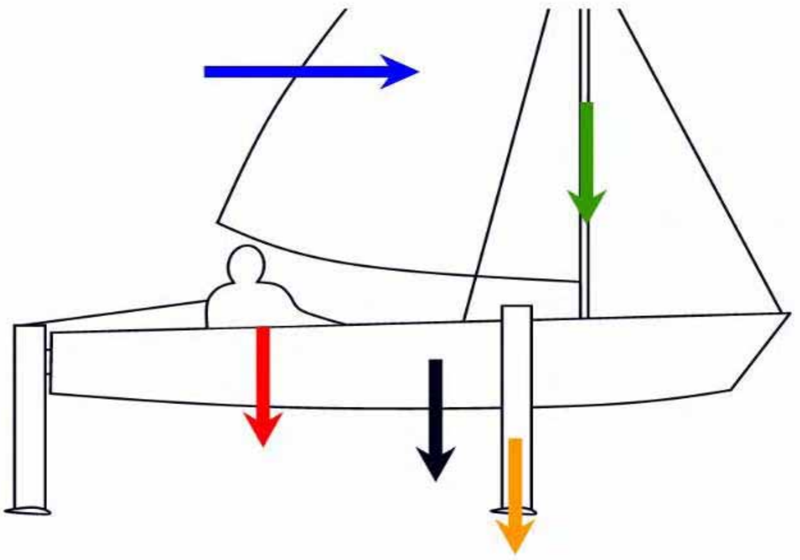


Figure 100 – Forces causing moments about the rear foil.

Lift from front foils = (((9.81 × ((Hull mass × (mast base to rear foil - mast base to centre of mass of boat)) + (sailor mass × (mast base to rear foil-mast base to sailor)) + (rig mass × mast base to rear foil) + (2 × front foil mass × (mast base to rear foil-mast base to line of front foils)))) + ((length of struts + height to centre of effort) × (force on sail))) / (mast base to rear foil - mast base to line of front foils))

Row 66.

The lift from the downwind front foil is found using the net heeling moment from Row 61 and the total combined front foil lift found on Row 64. First, to simplify the equations let the following abbreviations replace the terms:

L_{UW} = Upwind foil lift

L_{DW} = Downwind foil lift

L_T = Total front foil lift (Row 64)

X = Distance from mast to foil (Row 8)

M_N = Net moment (Row 61)

The sum of the two front foil lifts must equal the combined lift found in row 64:

$$\mathbf{L_{UW} + L_{DW} = L_T} \qquad \textbf{Equation 60}$$

The net moment must be equal and opposite to the net moment found in Row 61 so the boat does not capsize:

$$\mathbf{L_{DW}X - L_{UW}X = M} \qquad \textbf{Equation 61}$$

The downwind foil has most lift to counter the moment from the wind on the sail.

From Equation 60:

$L_{UW} = L_T - L_{DW}$

Substituting into Equation 61:

$L_{DW}X - (L_T - L_{DW})X = M$

$[L_{DW} - (L_T - L_{DW})]X = M$

$(2L_{DW} - L_T)X = M$

$L_{DW} =(M/X + L_T)/2$

Row 67

The total lift that is needed from all the foils is equal to the total weight of the boat and all its fixtures (including the sailor). Therefore the lift from the downwind foil is divided by the total weight from Row 26. This gives the fraction of the total lift that is provided by the downwind front foil.

Row 68

The combined span of foil that is necessary to lift the boat was found in Row 52. This is multiplied by the fraction of the lift from the downwind front foil, (Row 67), to give the length of that foil.

Rows 70 to 76

The upwind front foil and the rear foil spans are calculated in the same way as the downwind foil lift. The rear foil lift is found by taking moments about the front foils.

13.2 Trailing wand, trailing edge flap control system model

The spreadsheet in Appendix 6 models the trailing edge flap control system. This model is used to choose foil spans and predict at what wind speeds the boat will foil.

Rows 1 to 50

The first part of the spreadsheet is very similar to the aerated foils spreadsheet explained previously in section 13.1 Model for Aerated Flow Control System. The first 43 rows are the inputs to the programme. This programme allows different spans for the front and rear foils and the lift and drag coefficients for the foils are omitted because they are not constants in this model. Otherwise the inputs are the same.

Row 46 is the input for boat speed, which is the start of the iteration loop. The apparent wind speed, driving force on the sail and the drag on the struts are calculated in the same way as in rows 48 to 50 of the aerated foil model in Appendix 5 and explained in the previous section.

Rows 54 to 63

In these rows the heeling moments from the wind force and sailor and the lifts required from each foil are calculated in the same way as in the aerated foil model.

Row 66

Using the required lift for the downwind foil, Row 66 calculates the necessary lift coefficient by rearranging the formula:

Theoretical Lift = (water density / 2) × lift coeff × boat speed^2 × chord × span

However, the whole foil is not effective because of the tip vortices. The real lift is found by using:

Real lift = [Theoretical lift × (2 + aspect ratio)]/aspect ratio

Where the aspect ratio is the span over the chord of the foil.

Combining these two formulae and rearranging, the necessary lift coefficient can be found:

Lift Coeff. = {Real Lift × [(2 × chord) + span]}/ [(water density / 2) boat speed^2 × chord × span^2

Row 67

The data in Appendix 7 shows how the flap angle can be calculated using the necessary lift, the foil dimensions and the boat speed. The data was collected by putting each combination of speed and flap angle into Visual foil. The formula is:

Flap angle = 1.5014 x lift coeff^2 + 16.259 x lift coeff + 8.1065

Row 68

Using the flap angle in row 67 the drag coefficient is found:

Drag coeff = 9 x 10^{-6} x flap angle^2 + 0.0002 x flap angle + 0.0084

This formula also comes from the data in Appendix 7.

Row 69

The drag is calculated from the drag coefficient and the dimensions of the foil and the boat speed.

Row 70

This is an 'If' statement. It is programmed to display flap angle>9 if row 67 calculates a flap angle greater than 9 degrees. It shows flap angle<9 if this is true, and OK if the flap angle is within the safe range.

Rows 71 to 82 repeat the calculations in Rows 65 to 70 for the other two foils.

Row 84

The total drag is calculated by summing the drags from the three foils and the drag on the struts from Row 50.

Row 85 compares the drag to the driving force and instructs the spreadsheet operator to increase or decrease the boat speed as necessary.

13.3 Final Design

The final control system decision was to use a trailing wand that manipulates a trailing edge flap on the foil via a system of connecting rods. Here the critical dimensions of the mechanism are determined.

The flap is 30% of the foil chord, 54mm. It is limited to move nine degrees either up or down to ensure that the flow does not separate from the foil. The tip of the flap therefore has a vertical movement range of 17 mm.

The triangular motion translator will be an isosceles triangle so the horizontal rod will also have a movement range of 17 mm. It must connect to the trailing wand at exactly the right point so the large motion of the wand will be translated to a small range of movement for the horizontal rod.

The length of the strut is 1400 mm. The foils must not get too close to the surface of the water and neither must the hull of he boat. A 200 mm margin either way will be adequate. The hull is 400 mm deep at the deepest point. Therefore the trailing wand will have a vertical range of 600 mm. This range of motion must translate to 17 mm movement of the flaps. It will also act as a force multiplier.

At the highest-flying height the wand will be at 45 degrees to vertical and the bottom of the hull will be 800 mm from the surface of the water. So, from the attachment to the horizontal rod to the surface of the water (B), the rod must be

$$\frac{1200}{\cos 45} = 1697 \text{ mm}$$

The unknown dimensions are the length of the wand from the pivot to the horizontal rod, (B) and the angle through which the wand travels, (α). The angle depends on the unknown length so calculating these will be an iterative process.

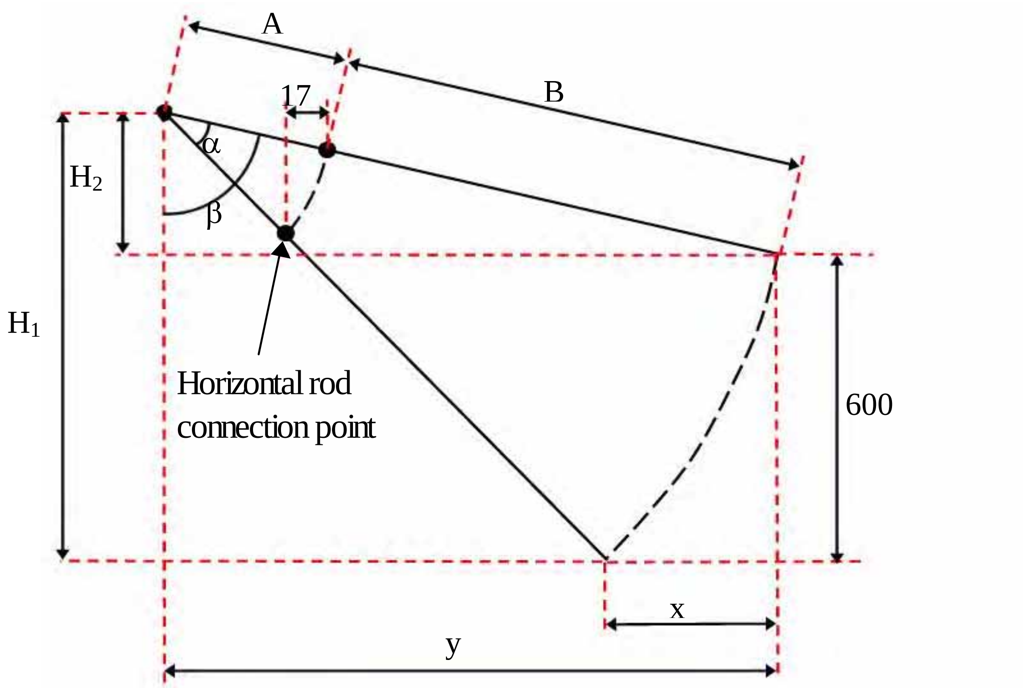


Figure 101 – Trailing Wand Diagram

Figure 101 represents the trailing wand in its two extreme positions. A spreadsheet was used to do the iteration. It takes an estimate for A, calculates the rest of the dimensions marked on the diagram and returns a calculated A. The operator must change the estimate until the two values match. The spreadsheet is shown below to show the order in which the dimensions are calculated.

input A	200	75	76
B	1697.056	1697.056	1697.056
L	1897.056	1772.056	1773.056
h1	1341.421	1253.033	1253.74
h2	741.4214	653.033	653.7401
beta (rads)	1.169266	1.193383	1.193178
	66.99401	68.37581	68.36404
alpha	21.99401	23.37581	23.36404
alpha (rads)	1260.164	1339.335	1338.661
x	1341.421	1253.033	1253.74
y	1746.172	1647.341	1648.136
y-x	404.7507	394.3077	394.3959
ratio	0.041754	0.04286	0.04285
A	79.20987	75.95021	75.97607

The L term is the sum of A and B. All the other dimensions are calculated using simple trigonometry.

The wand acts as a displacement multiplier. The input horizontal displacement comes from the float moving in an arc as it moves up and down relative to the hull. The output is the displacement of the horizontal rod. The ratio of the horizontal displacements is equal to the ratio of the lengths A and B. Therefore to find A the ratio is multiplied by B.

14 ELECTRONIC MEASUREMENT DESIGN AND BUILD

14.1 Sensors

14.1.1 Strain Gauges

The strain gauges to be used are 5mm metal foil strain gauges with a gauge factor of 2.00 and the standard low resistance of 120Ω to minimise noise effects. The strain gauge circuit takes the form of a bridge circuit input to a differential amplifier based on an op-amp. The circuit is shown below:

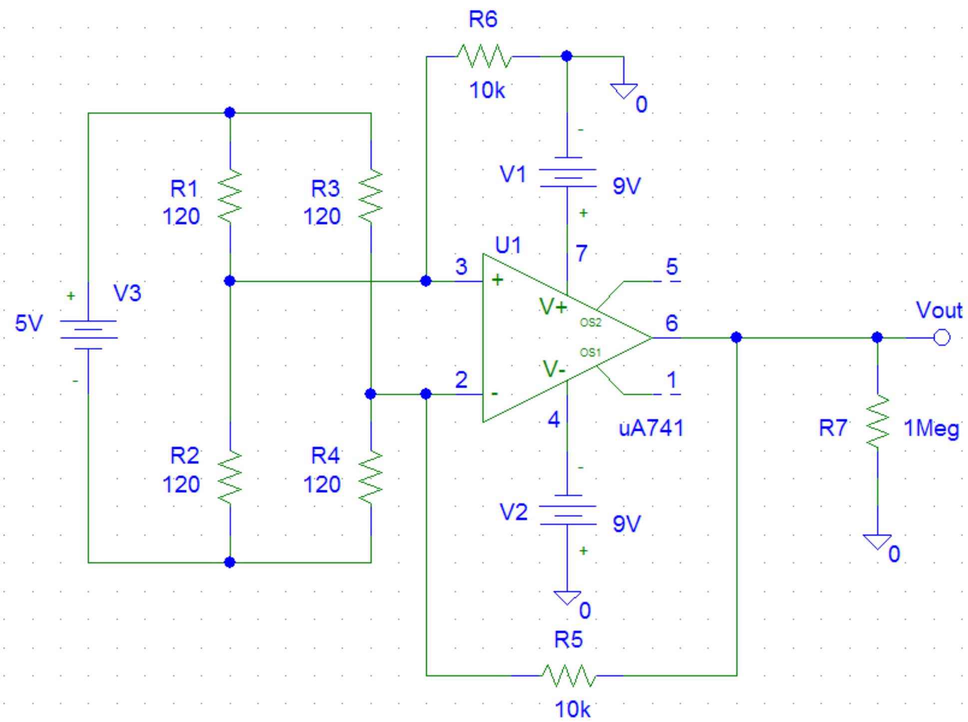


Figure 102 - Strain Gauge Circuit

The resistor R1 is the strain gauge and resistors R3 and R4 represent a potential divider, used to calibrate the circuit. R1-R4 form a bridge circuit required to provide the necessary sensitivity. The output of the bridge circuit is connected to an op-amp configured as a differential amplifier. The gain of this amplifier is governed by R5 and R6 and can be set as required. Noise rejection could be achieved by using an additional non active strain gauge in the place of R3 though an additional potentiometer would then be required for biasing. The circuit output is tested and an additional op-amp based variable gain stage is used to calibrate the circuit with a multimeter to give an output between 0-V_{ref} Maximum (ADC Voltage). Although this system is sufficient for measuring larger strains a strain of only a few millistrain is expected. The circuit does experience a high noise level, possibly due to the testing environment and possibly due to the reduced sensitivity of using only one strain gauge. A dedicated strain gauge amplifier may be able to reduce this effect. These are however specialist devices any are typically around £30-40.

14.1.2 Wind/Water Speed Sensors

The speed sensors consist of a rotation magnet and a pick up coil taken from a 9V relay. The rotating magnet induces a sinusoidal voltage in the pickup coil whose frequency varies with speed. This signal requires amplification and frequency to voltage conversion to produce an output voltage proportional to speed. Many frequency to voltage converters (tachometers) require many external components but the low cost LM2917 from National Semiconductors is designed for ease of use with a minimum number of components and an integrated op-amp. The configuration of the LM2917 for use as a tachometer is shown below:

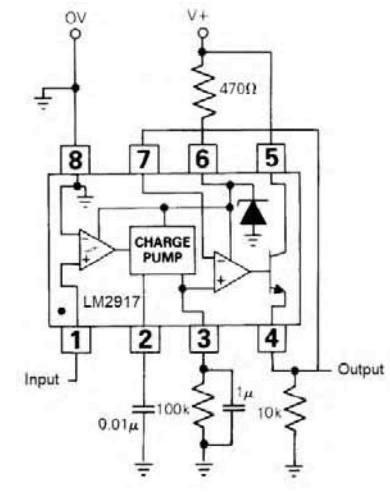


Figure 103 – Frequency to Voltage Converter Circuit

The output voltage is given by: $V_{OUT} = f_{IN} \times V_{CC} \times R_1 \times C_1$ The circuit above gives an output of 111Hz/V (V_{cc}=9V, R_1=100k, C_1=0.01μF) but this is easily calibrated by changing the values of R1 and C1. The sensor is not affected by the separation between the pickup and sensor as long as this is not too great. This is because the frequency remains constant. The signal is still detectable at a distance of over 100mm.

14.2 Development Board and Circuit

The development board was bought as a kit and soldered by hand. The circuit was used as the basis for the data logger. The circuit is shown overleaf:

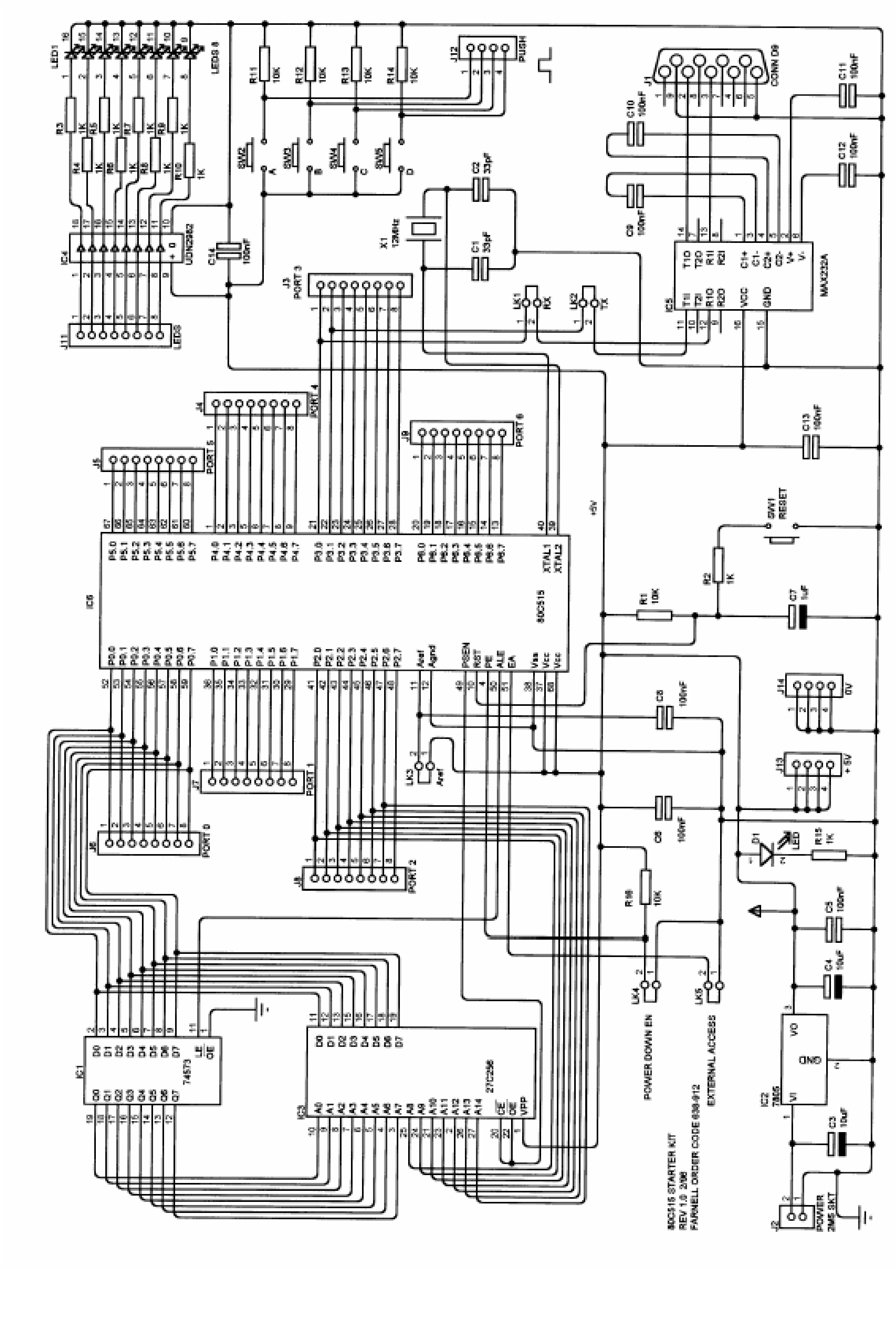


Figure 104 – Development Board Circuit

The sensors are each connected to one of the 12 ADC input lines on port 7 and 8. Port 1 is used for input switches and status LEDs. Line P1.0 is connected to a SPST switched used to start and stop data logging. Line P1.1 is connected to a PTM switch to trigger the collected data to be dumped to serial. Line P1.2 is connected to a yellow LED to signal data collection in progress and line P1.3 is connected to a red LED to signal data dump in progress. A green power LED is already included in the development board circuit. An extra data EEPROM is required on the address and data busses from ports 0 and 2 for the final design.

14.3 Program Development

14.3.1 ADC Test Program

This simple program, modified from a Kiel example, tests the on board analogue to digital converter and outputs the values from each of the 12 input lines (ports 7 and 8) sequentially to the serial port. Unfortunately Kiel, the software development environment used cannot handle to full 10-bit output of the on-chip ADC. Hence the output will be unsigned char (single byte) giving an output level from 0-255. This program is important to check the correct operation of the ADC and to evaluate the performance of the sensor inputs to allow the full range of sensitivity to be reached by calibration. The full program listing is displayed in Appendix 11.

The output can be viewed using the program LookRS232, which can be used to ‘watch’ a serial port without requiring handshaking.

The output will be as below:

```
ADC Channel 0 = 0
ADC Channel 1 = 255
ADC Channel 2 = 145
......
```

This program, together with LookRS232 can be used to calibrate the sensors before use without having to use the data logger. It therefore could be included as a calibration routine in the main program, triggered to test and calibrate the sensors onshore before the data logging commences.

14.3.2 Memory Test

This program tests writing to XRAM/External EEPROM and is designed for simulation only. The program simply creates a large array in XDATA memory and fills it with a test pattern. The program was simulated and the correct operation was observed. The full program listing is displayed in Appendix 11.

14.3.3 Final Program

This program writes the value of 4 input ports of the ADC to RAM (2k on-chip XRAM) storing 4x1 bytes every second. The use of on-chip ram allowed the program to be tested and developed without using a separate data EEPROM in addition to the EEPROM for program memory. The program therefore only currently allows approximately 4 minutes of recording time with a sampling time of 0.5s. With small modifications to address values this program can be altered to use external data memory as opposed to XRAM. This is supported in Keil.

When the enable switch (P1.0) is in the on position the timer triggers data collection at the rate specified as a constant. Each sensor is read by triggering a subroutine. The data pointer is incremented each time a value is stored. This continues until the data memory is full or the enable switch is placed in the off position. In the idle state the program waits for the enable switch (P1.0) or the data output button to be held down for a second. When this is detected a function is called that outputs the data in ASCII format to the serial port. This can be read and captured by LookRS232 and the results imported into a program such as MATLAB for processing. Status LEDs show whether the program is recording or outputting data. The program is close to completion but is currently not functional and requires further debugging. The fully commented program is displayed in Appendix 11.

14.4 Data processing and presentation

The raw data output is formatted as shown below (Test data pattern for 4 sensors):

```
0 0 0 0
1 1 1 1
8 16 32 64
64 32 16 8
255 255 255 255
```

This layout makes it simple to import into MATLAB for processing using the ‘load’ command to create a matrix of values. Constants are set at the start of the program.

These constants are determined through calibration. The data matrix is split into separate matrices for each sensor before further processing.

The height above water is not determined directly hence further calculation is required.

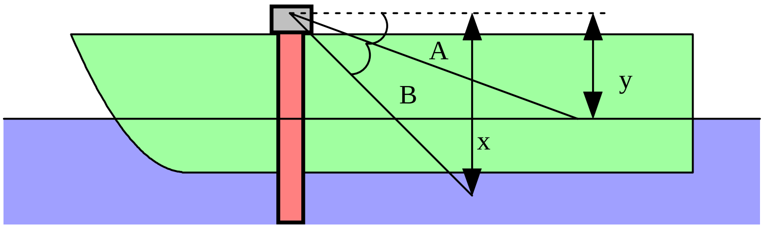


Figure 105 –Height Above Water Measurement

The data recorded for height above water measures the angle *(B)*. Assuming we can measure the length of the trailing wand, the angle of the trailing wand at minimum height *(A)*, and the angle at maximum height *(A+B)* the height above water can be calculated. Taking the cosine of the angle *(A+B)* and using the length of the trailing wand the vertical displacement between the ends of the trailing wand can be calculated. The reference point is taken as the position of the boat while not under way so the length *(y)* must be subtracted from this value giving the final value for the height above water.

All other readings are scaled by a set constant to give their real world value. The true wind speed can be calculated from the apparent wind speed and boat speed using the vector relationship shown below:

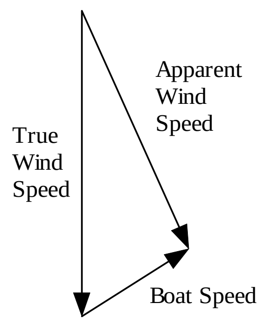


Figure 106 – Apparent Wind as Vector Components

Since the apparent wind speed, boat speed and the angle between the two are know its is simple to work out an estimate of the true wind speed using the cosine rule.

Once these values have been calculated it is possible to use the MATLAB program to import and scale the data and to calculate an estimate of the true wind speed and height above water. This is shown in Appendix 11.

14.5 TESTING

To aid testing a record of the wind speed at our test location, Draycote Water, has been created. This will allow us to obtain an idea of the wind conditions at the location prior to testing the boat. It was felt this was important to ensure that there would be suitable strength wind for testing the boat at our chosen location.

The wind speed at 12pm each day was recorded, and then charted on the chart below. The data was collected from Draycote Water's own weather station. A trendline has been plotted to smooth the data and remove the influence of any localised effects.

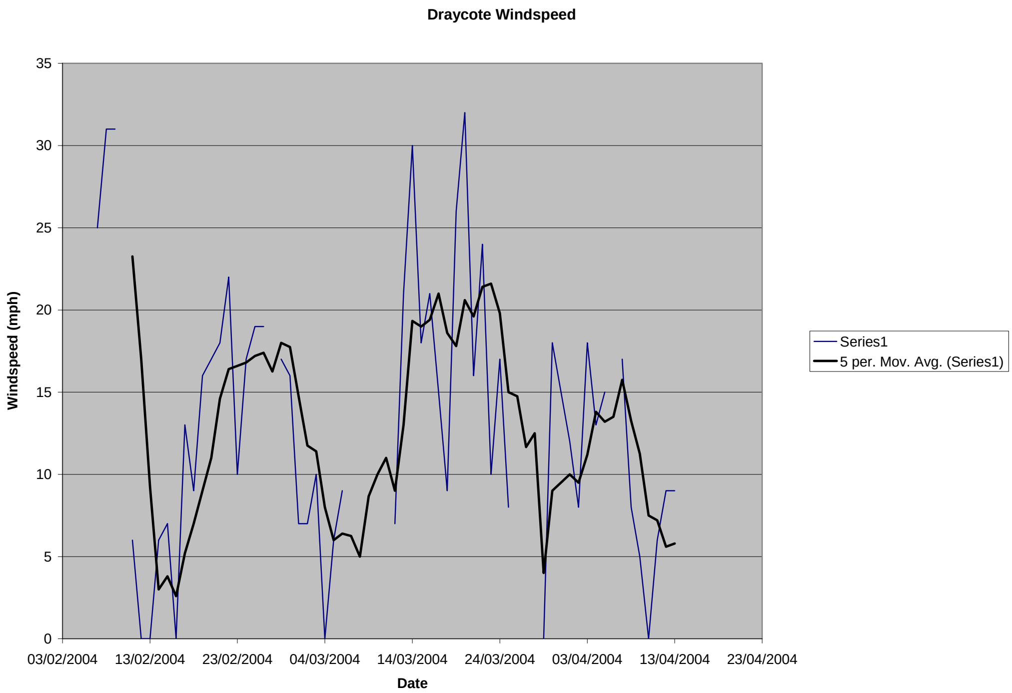


Figure 107 - Draycote Water Windspeed

The average windspeed for the data collection period was 13mph

Hydrofoil Sailing

Business, Financial and Management Report
(including References and Appendices)

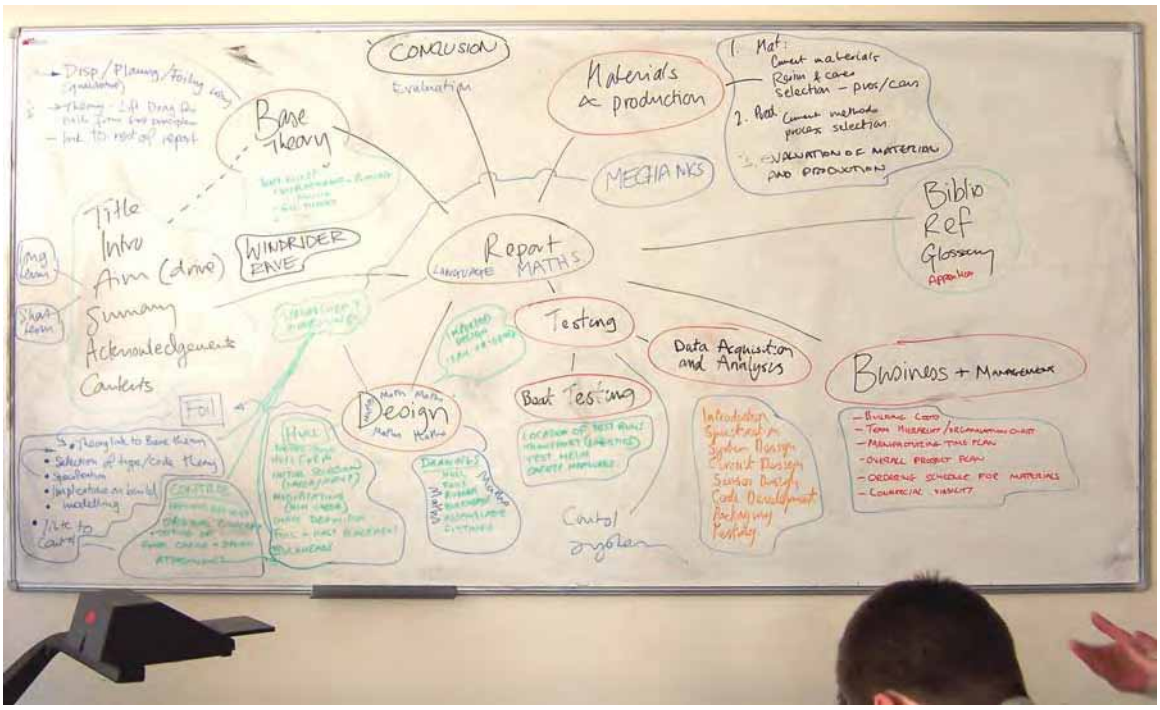
FUTURE FOILS

THE HIGH SPEED FUTURE OF SAILING

THE UNIVERSITY OF
WARWICK

MANAGEMENT AND FINANCE REPORT

15 PROJECT MANAGEMENT



15.1 Introduction

The management of the project has over the past six months been both one of its strongest and weakest points; both of which having been learning experiences for the team. The project has come to a satisfactory conclusion of the initial aim and will make a strong basis for a future phase of the project.

The stronger management points can be seen in the good relationships and mutual respect maintained within the team over the project period, as well as the production of a working prototype boat which satisfies the initial aim to a pleasing degree.

The management weaknesses over the period have mainly been concerned with difficulty in constructive use of the available time and budget. These factors should have received a much greater deal of time and planning during the initial stage of the project. However, as the project started almost completely from scratch this year, this is perhaps an expected area of difficulty.

This summary of the management of the project has been broken down here into six naturally observed areas of study:

- Human Resource Management
- Communication
- Budget
- Material resource
- Goodwill
- Time and progress

The dynamic enthusiasm of the team has helped to build a hard working group

15.2 Human Resource

Members of the team were not strictly chosen for the project, but have worked very well together, become good friends and as a result, a very effective team. The magnitude of the project and understanding that as a group we are pioneering this area of study at the University has added to the drive and enthusiasm within the team. We are working towards a significant, but achievable goal, building what is widely believed to be the largest student built prototype at the University.

Having a team made up of students from four streams of engineering (EDAT, Electronics, Manufacturing and Mechanical) has been a factor much appreciated by all members. This element of project is most noticeable when tackling problem solving as a group. The diversity of opinion and background knowledge makes it much easier to keep an open mind on a problem and cover many more possible solutions before an agreed idea is taken further.

The team has been working closely with two third year projects also initiated on the basis of the previous year’s project and working towards this project and its future next year and beyond. A mutually beneficial relationship has been built with these students with inclusions in our weekly team meeting. The knowledge base gained by these students also provides a strong foothold for the future of the project.

Keeping work has enhanced the spirit of the team and meetings enjoyable and open to discussion while remaining relevant to an agenda set out prior to each meeting. This appears to have been one of the strong points of the group, observing that similar groups have had a great deal of difficulty in the wake of small arguments. A number of social events outside of academic umbrella of the project (a total ban on its discussion for the evening!) have further helped the team to gel and build important friendships.

15.3 Communication

The project structure and timing have revolved around weekly meetings held on a Wednesday during the autumn term and Fridays during the spring term. An agenda has been produced for each meeting in order to utilize the hour together to summarise progress, discuss the immediate and long-term tasks, and delegate the work. Within each meeting we have made time to help brainstorm a particular problem from a member of the group (see minutes – Appendix 14).

Our secretary Paul Price has taken minutes at each of the weekly meetings, which are then typed up and circulated by e-mail, providing a useful resource for members as a reminder of delegated work and to give an overall picture of the project.

As well as the weekly meeting, a large number of informal, smaller problem based meetings have occurred within the week between members working on the same area of the project. These more informal meetings have generated the bulk of the project progress.

Our electronics and website team member Tom Kennaugh has put together a team resource site available on the University network. The site has provided an excellent way to pool photos, a back catalogue of all the meeting minutes, report material, and with a copy of the each team member's timetable, enables much easier organisation of meetings. This internal website can be accessed on the University of Warwick network at: http://futurefoils.kicks-ass.net/ and off campus by setting up a proxy server – a simple process for which instructions are available at http://www.warwick.ac.uk/it-services . For a screenshot of the intranet homepage, see Appendix 12.

Group communication has been largely dealt with by e-mail circulating weekly reminders, reports on individual's work and requests from members for project material to be brought to the weekly meeting.

15.4 Budget

A full break down of our budget use can be found in spreadsheet form in Appendix 10

At the outset of the project we were concerned that the allocated budget at £1050 would be insufficient to enable the complete build of a working prototype, and set about exploring the possibility of sponsorship. The possible methods of gaining the publicity required to acquire sponsorship were explored during the first term of the project.

The timing of a number of good publicity events such as the Southampton Boat Show, Concept Boat competition and Weymouth Speed Weeks unfortunately contradicted timing of the project. The London Boat Show and Birmingham NEC Outdoor and Boat

Show did however suit our timescale to a better extent. We applied to the London Boat Show, January 2004 and were offered a place for approx £2000.

After discussing the fee with the Engineering department, it was decided that the cost and potentially damaging time schedule that entrance would place on the project out-weighed the benefits of attending the show. Instead of acquiring a stand at the show, a group of four team members visited the show and used the event to chat to staff from a large portion of our hypothetical market competition.

A batch of ¼ A4 colour fliers were printed for the occasion, detailing our aim, commercial angle on the project and our website and contact details. The idea proved to be a great success and enabled us to make personal contacts in 23 relevant companies, all of whom were interested in the project, and offered valuable advice and offers of help.

On returning from the show, a sponsorship brochure was produced for the website, and the contacts were e-mailed with a link to the site and relevant page. The sponsorship brochure can be found in Appendix 13, and on the website at http://futurefoils.webhop.net/.

Although a positive response was received from a number of the contacts, many were put-off by very small window of time in which the parts / money was required. A database of the contacts will be passed on to the following years project group with advice to get in touch with these companies at the outset of the new period with requests for help and materials.

After initial brainstorming of the electronic system and desired features we required for the working prototype, we set aside £150 to include money for data logging equipment, sensors, and the possibility of a radio boat – shore link to retrieve real time data.

At the same time our manufacturing students worked at forecasting our expenses and looking at the sourcing of materials to see if the prototype could be made within the budget.

The budget of the project has been one of the more difficult areas to manage because of the unpredictable costs incurred. Although a budget for materials and components could be fairly easily forecast, a lot of the materials used have come from goodwill sources and informal mutually beneficial work. The most significant examples of this are the help received from the university's ATC (Advanced Technology Centre) in the form of a great deal of manufacturing advice and materials (see budget Appendix 10) and the provision of a loaned sail and rig from one of the team members (Ian Godfrey).

Without these goodwill inputs, it is unlikely that the budget would have stretched to cover the expenditure required for such a large project. This emphasises the need for our successor team to acquire sponsorship right at the beginning of the next phase. This will be significantly easier with the work covered this year and contacts made.

In the final build stages of the project, our supervisor, Dr Li, extended the budget by £200 enabling a successful completion of the prototype.

```
% The varibles true_wind, wind_dir, wind_speed, boat_speed and boat_height
% contain the measured and calculated data for graphing or further processing
```

15.5 Material Resource

Work with composite materials in hand lay-up methods of construction requires a deal of careful calculation and planning before materials are ordered and used. By using hand lay calculations from SP Systems composite materials specialists, consultation with our university composites specialists and surface area outputs from CAD work a good estimate was made for the required amounts of polyester resin, catalyst, glass fabric and core material (see manufacture section for details). This simultaneously gave us a good forecast for the final weight of the craft.

Despite careful planning and forecasts, we still encountered major problems during the build process as a result of material management. Although the predictions we generated turned out to be accurate in the long term, we started the build process using resin kindly donated by The ATC and made poor initial estimate of the quantity of resin in the Keg, running out resin before only days after the new resin had been ordered. The problem was complicated by the longer than predicted lead time for the new material to arrive, a factor that would be better taken into account by assuming something like double the time suggested by the supplier.

A similar problem was encountered with the glass fabric. Confusion over the length of glass fabric material donated as goodwill-based sponsorship from *Security Composites* meant that this first roll came to an end even before a new roll was ordered. Whilst the break from major glass fibre work gave the team an opportunity to catch up with the list of other unfinished jobs, a full week passed before the new material was sourced.

We are extremely grateful to *Carr Reinforcements* and *Security Composites* for their support and help with glass fibre fabric.

This problem common also to a great deal of professional industry can be avoided with basic forward planning and purchase, and well-scheduled design work. It is best to have the materials ready and waiting for use, and costs nothing to have them ready ‘ahead’ of schedule.

15.6 Goodwill

Although much appreciated and very gratefully received, one of the difficult areas of the project has been managing goodwill input. Sponsorship without a contract can be extremely beneficial, introducing low cost / free materials to the build with minimal paperwork hassle. However, goodwill on this level is very hard to manage, with delivery times, and amount and choice of material being understandably unpredictable.

15.7 Time and Progress

Whilst the time plan has changed and developed over the past nine months, the aim of the project has to a great extent been satisfied through the hard work and dedication of the team. As a completely new project, there was uncertainty as to what could be done in the time scale and whether a modestly sized team and budget could tackle such a large prototype device. Whilst accurate testing and results are still a little way off, a lot of work has been packed into the year.

During the main period of the prototype build, *Microsoft* ***Project*** was used extensively to manage the time available effectively, splitting the available days into half day blocks and delegating various team members to tasks relevant to their area of project where possible. Three Gant charts were produced identifying the three main areas of manufacture: i) Hull, ii) Foils and iii) Electronic equipment. Examples of these Gant charts can be found in the Appendix.

A key time management area of the project has been the suitable delegation of tasks and management of deadlines for these tasks over the project period. At the start of the period, this was perhaps an area of lost time that went un-noticed until late on in the first term. This is in part due to a lack of strong relationships between the previously unacquainted group at the start, and hence became a much more manageable factor as these relationships became stronger and more dependable.

Ingrained in this area of management is the delegation of the right tasks to the right people. Often a task would have been allocated to a particular member of the group, who would not admit to struggling with the element of work until the following weeks project meeting, at which point a whole weeks input from a member can have been jeopardised.

15.8 PRODUCTION MANAGEMENT

The production of the hull is a large and complex task. To ensure that the correct materials and people are available at the correct times is very important to ensure an efficient and effective production plan, which allows production to be completed by the required deadlines.

To do this the manufacturing team have drawn up several management charts and tables to allow the production to be carried out smoothly. This was done using Microsoft Project.

All time plans started from the receiving of the design information from the design teams, this was the 5/1/04 (Week 11). The time plan also took into account the available working hours that the team has, principally Tuesday and Wednesday.

The large production task of constructing the whole hull, from moulds to glassing was broken down in to three distinct areas; frame assembly, honeycomb fitting, and glassing the components.

These separate areas were further broken down in to their constituent tasks to add detail to the time plan. Each of these tasks was given a time duration that it was estimated the process would take. These were educated guesses based on work that had previously been completed in other projects using similar techniques and materials.

After the durations were entered in to the program the relationships between each task were entered. This allowed the computer to recognise the hierarchy of tasks and then schedule them accordingly, taking into account the time the operation would take. From this data the program can produce several different charts, most importantly for scheduling and time control is the Gant chart. This shows how the processes are connected to each other on a common time frame, as well as the order of execution.

The computer can also produce Network Diagrams; these show the relationships of tasks and identify the order the tasks are performed, as well as their dependences. It also highlights the critical path, the operations which must happen on time and take the correct duration to complete the project on time.

Both charts were produced; the Gant Chart allowed the allocation of resources to each stage. In the case of people management the resources were the individual members of the team. This allows people to see when they are needed and for how long. From this data a task list of who does what when can be produced, an example of this is attached. These sheets were distributed to each member of the team so they were aware of when and what they were needed for.

To ensure the production was progressing as planned Microsoft Project allows you to enter current progress in real time. The program then highlights tasks that have been completed and those yet to be done. It also indicates when you begin to fall behind schedule.

All of these techniques were used to ensure that the production was completed effectively and on time.

All of the relevant charts and diagrams can be viewed in Appendix 14.

15.9 COMMERCIAL VIABILITY

The long-term aim of the project is to produce a boat that is commercially viable and would be attractive to a mass market. The boat would need to be easy to sail and something that current sailors could identify with. This idea has been at the heart of the design phases of the project, and also when considering costs of materials.

After researching various sailing markets and disciplines we felt it was most suitable to aim our boat at the Laser market. The Laser is a small boat sailed by one person; this is reflected in our one-person design. It was felt that looking at the Laser market would be most applicable for our project.

The Laser is one of the most popular boats; estimates for the number of Lasers being sailed are around 180,000 worldwide in over 120 countries (Laser Sailing). Laser International.org states that the Laser sailors ‘continue to be attracted at a rate of nearly 4000 new boats a year’. This gives us a large, growing potential market segment to target.

The principle idea of a hydrofoil boat is to allow the vessel to reach higher speeds than were traditionally possible. Therefore it is likely to be of great interest to those people who already like sailing fast. Investigation of various Laser racing organisations has proved promising. The UK Laser Association website (www.laser.org.uk) had almost 75,000 hits in October 2003. There are many different Laser racing associations all demonstrating an active racing community, and potential purchasers of our design.

This popularity among the sailing world has led us to design our own boat hull, with Laser characteristics. It was felt the original Laser was too heavy and this would impede on the performance we needed to ensure our boat would fly. Therefore the decision was taken to build our own hull from lightweight materials that would allow the boat to fly at lower speeds.

As yet there is no design on how to retrofit our foils to an existing design. It was felt that this would be hard to do and problems would be incurred with finding a design that would accept the hydrofoils, and still be possible to sail. This added further need for us to design and manufacture our own hull. It is hoped that the evolution of the Laser design will help attract Laser sailors to our product.

To ensure that we would be able to attract existing sailors to our design, and get an idea of target costs a questionnaire was devised to extract the information we required. The questionnaire focuses on peoples existing sailing habits and preferences. This gives us a good idea of the people who are already sailing and how they are sailing, for example racing weekly, or sailing for fun occasionally. This helps us to target the design of our boat. The questionnaire also looks at peoples concepts of cost, how much they would pay for a boat, and if they would pay more for a boat with hydrofoils. By looking at this we can ensure we don't produce a boat that would be too expensive for people to buy.

15.10 ELECTRONICS

The budget for the electronics section of the project was set at £150. This was to include the purchase of a development board, microcontroller and the production of sensors. With the typical cost of development boards plus microcontroller at around £100-200 it can be seen that this is a very low budget for the development of such a system. A low cost development board kit was found at a cost of £40 with the microcontroller costing £31. The spending on electronics to date is shown in the table below:

Item	Price
Development Board	£ 40.00
Infineon 80C517a Microprocessor	£ 31.24
Wind Direction Sensor	£ 8.57
Height above water sensor	£ 8.57
strain gauges (2)	£ 7.18
Misc Components (approx)	£ 10.00
EEPROM (prog)	£ 11.44
EEPROM (data)	£ 11.44
Water/Wind speed sensor	£ 19.00
Frequency to Voltage Converter	£ 1.70
TOTAL	**£ 149.14**

Figure 108 – Electronics Spending

The current spending is just below the allocated budget, though this does not include goodwill in the form of donated low cost components. The system is however currently not complete. An additional water speed sensor is required in addition to connectors wiring and multiple extra low cost components. If a custom circuit board were to be produced to replace the bulky development board this would incur further cost in board production and additional components. This budget overrun would however be expected given the initial low limit, however the cost of building the entire system is unlikely to be much more than £200.

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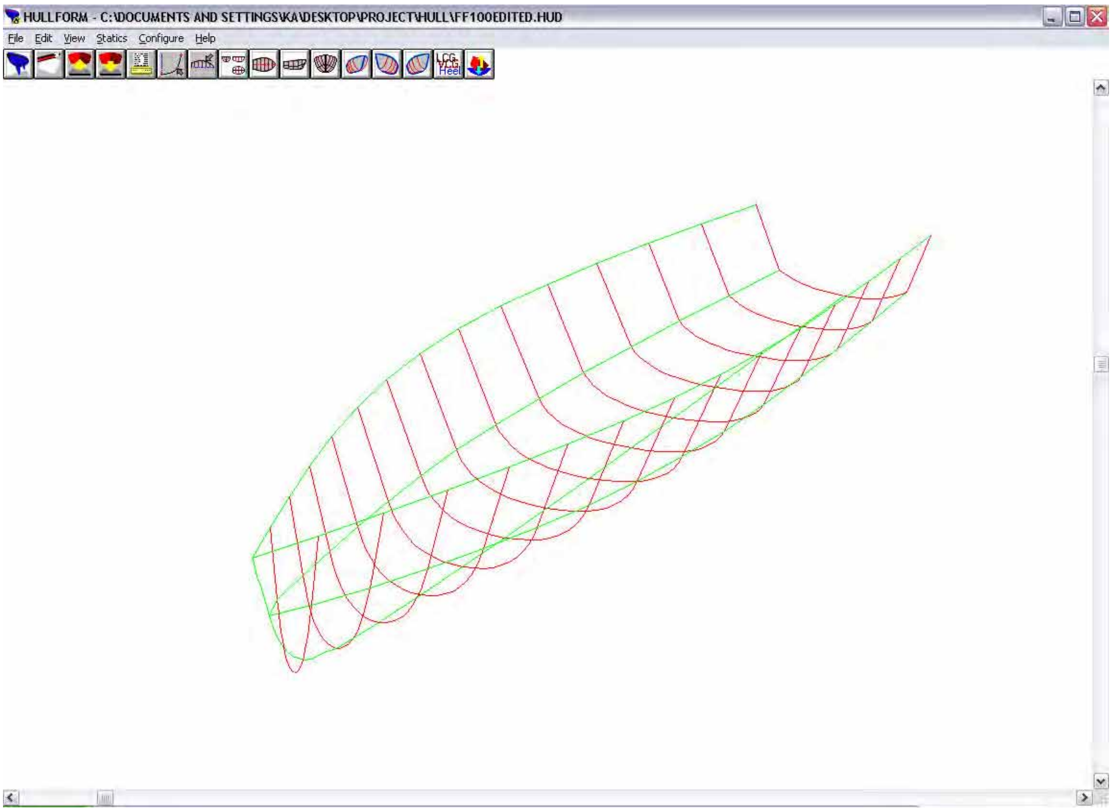
APPENDICES

15.14 Appendix 1 – Hull Design Decision Matrix

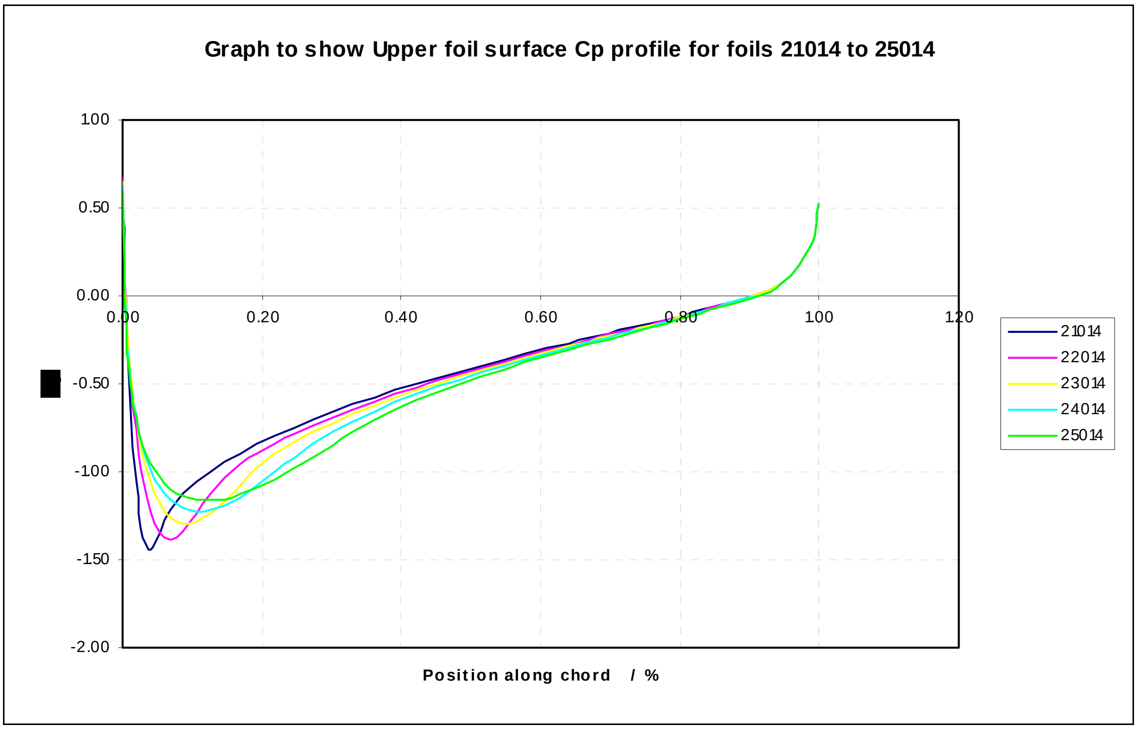
Max Beam Width (m)	1.42	1.28	1.14	1.00	0.85	0.72
SA/D	3.97	4.26	4.60	5.03	5.58	6.30
	0.630	*0.676*	*0.731*	*0.799*	*0.886*	*1.000*
D/L	842.24	758.02	669.12	581.42	494.92	412.43
	0.490	*0.544*	*0.616*	*0.709*	*0.833*	*1.000*
LWL/B	4.79	5.21	5.75	6.44	7.35	8.59
	0.557	*0.607*	*0.670*	*0.749*	*0.856*	*1.000*
TOTALS	1.677	1.827	2.017	2.258	2.575	3.000

15.15 Appendix 2 – Hullform printout of Final Hull Design

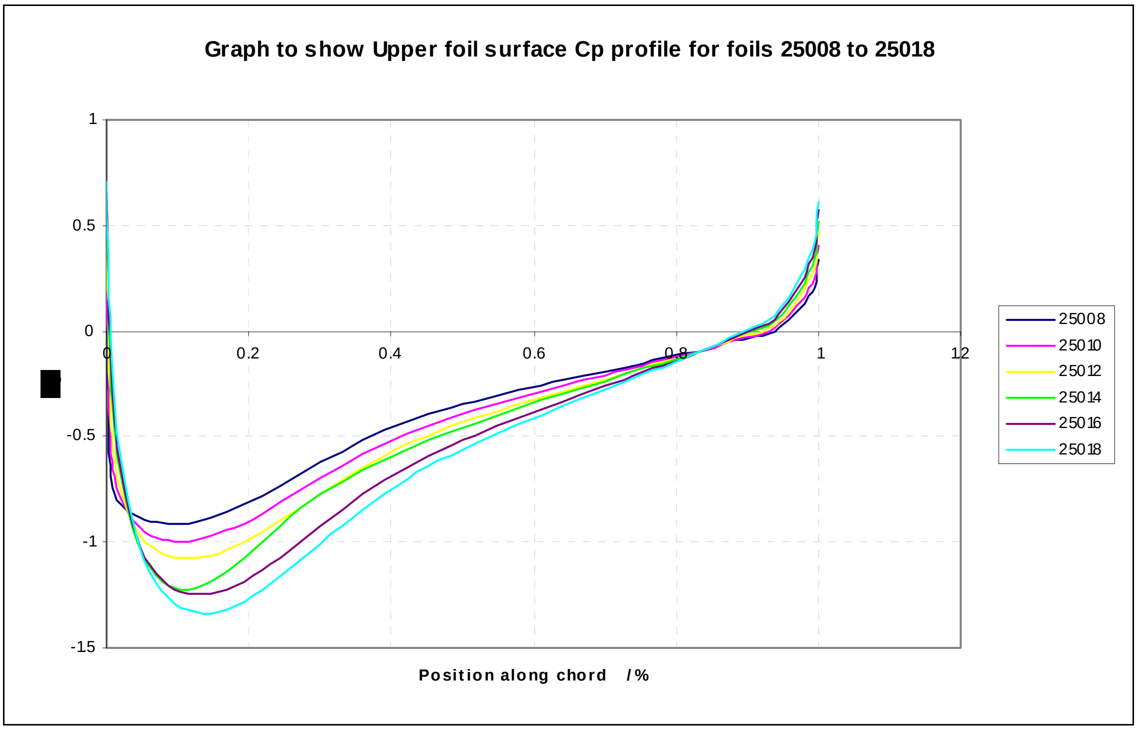


15.16 Appendix 3 - Foil Design Appendix: Graphs 1 - 7

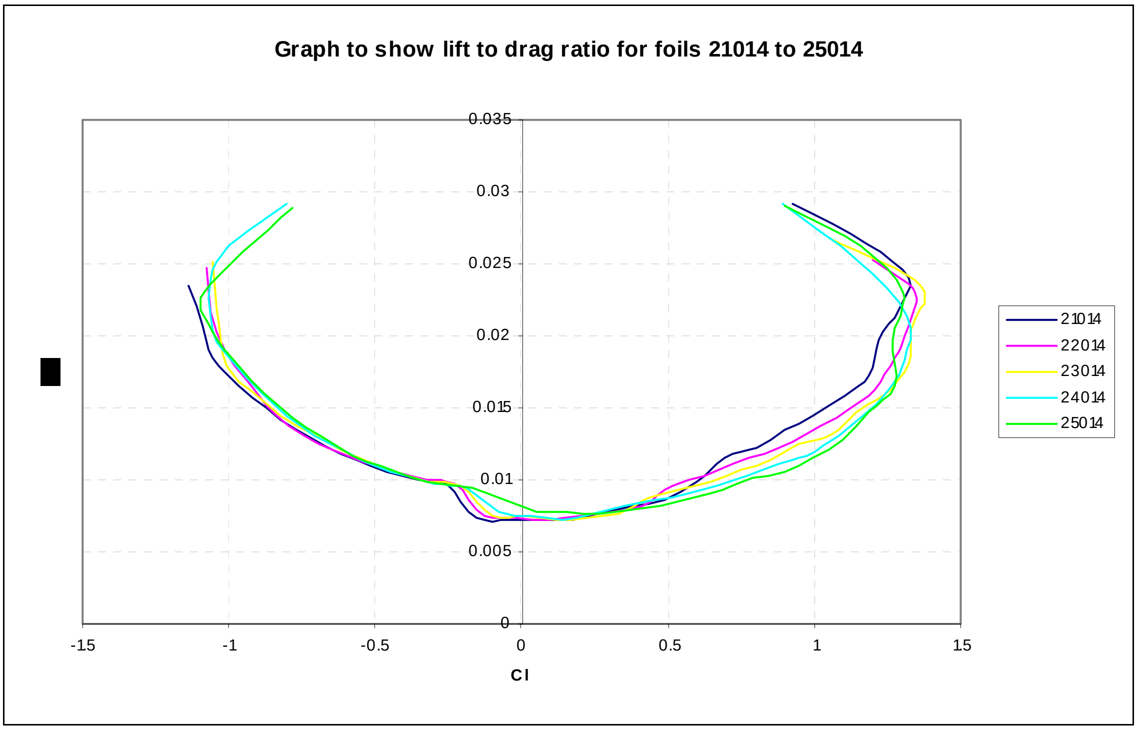
Graph 1



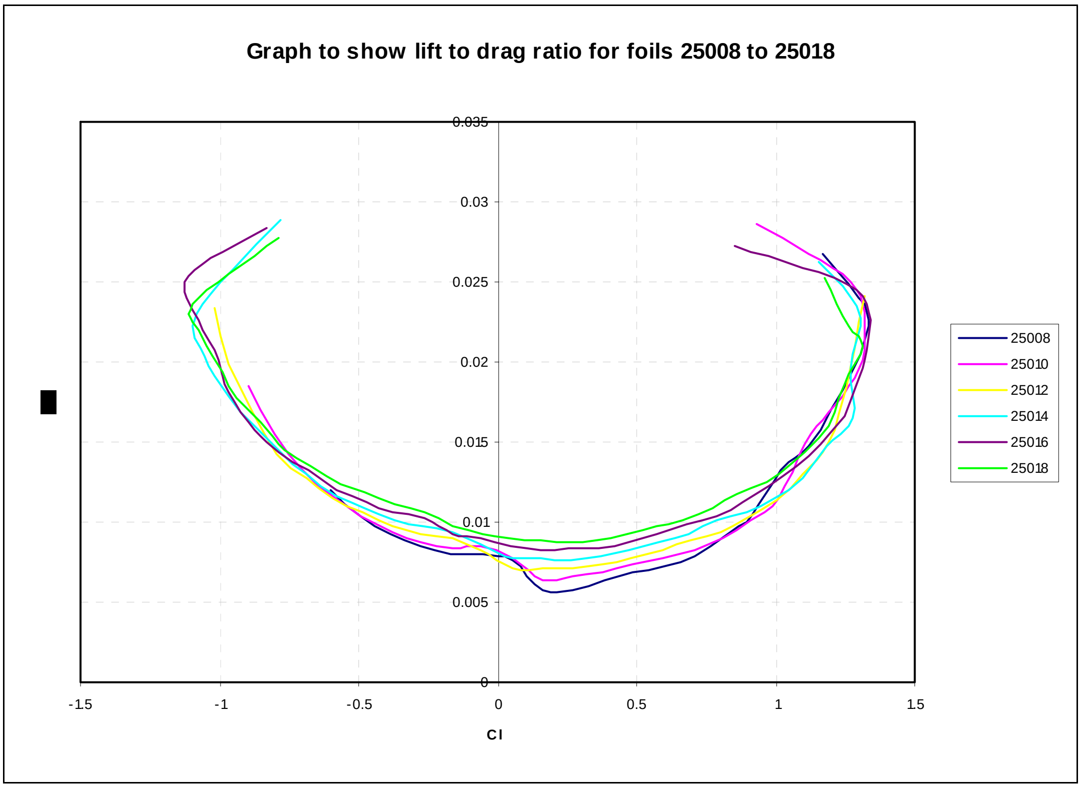
Graph 2



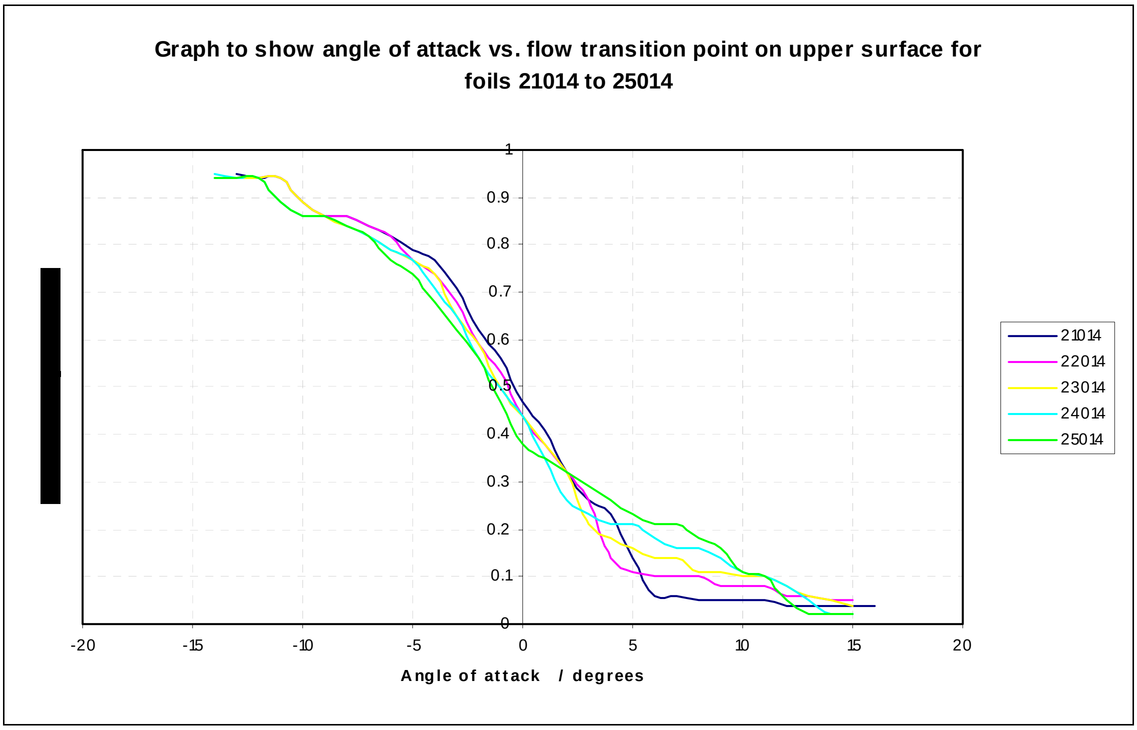
Graph 3



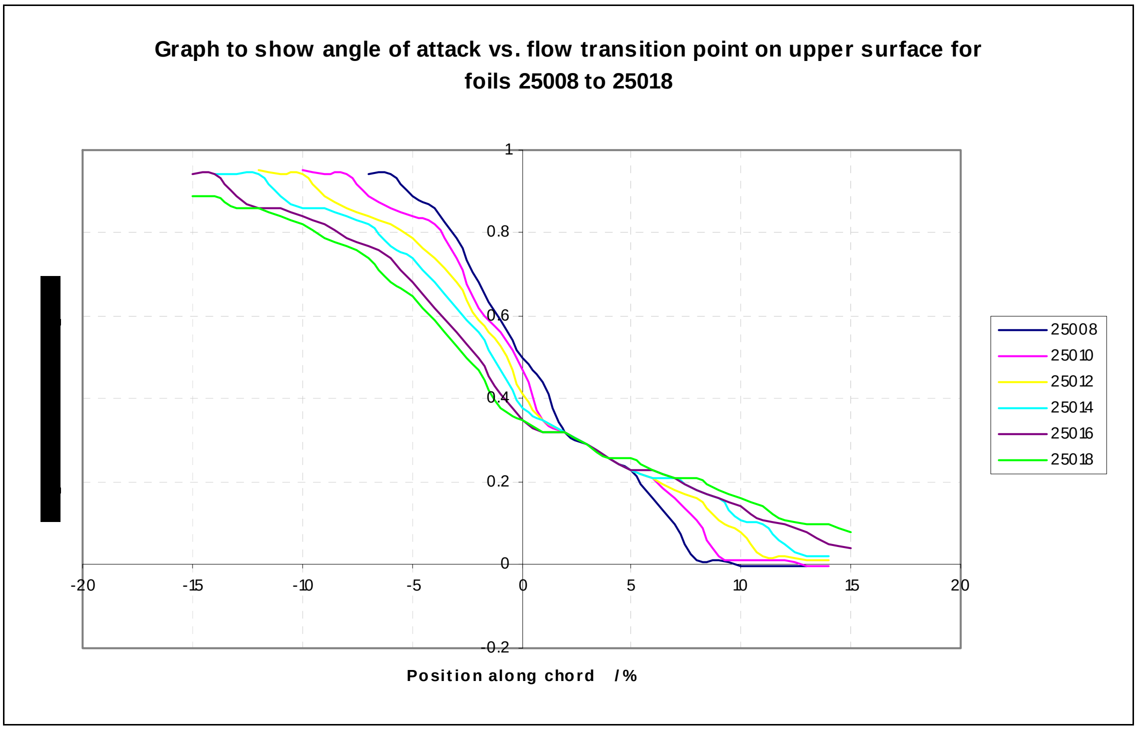
Graph 4



Graph 5



Graph 6


Graph to show angle of attack vs. flow transition point on upper surface for foils 25008 to 25018
[redacted]
Position along chord /%
25008
25010
25012
25014
25016
25018

Graph 7

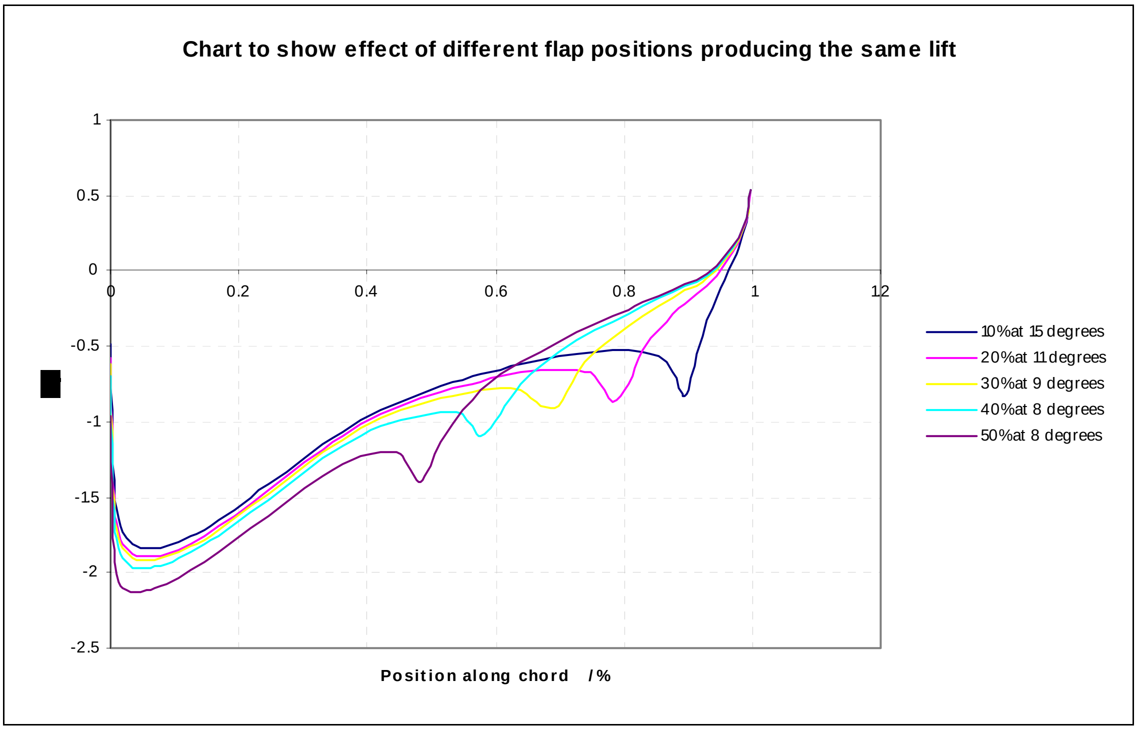


Chart to show effect of different flap positions producing the same lift
[redacted]
Position along chord /%
10% at 15 degrees
20% at 11 degrees
30% at 9 degrees
40% at 8 degrees
50% at 8 degrees

15.17 Appendix 4 – Mast Location Spreadsheet

length of boat	m	4.5		
mast to centre of effort		0.640638744		
%lead		13		
distance from bow to front foils	m	0	0.1	0.2
FOR FOILBOURNE BOAT				
centre of lateral resistance from bow	m	=((2*C7)+$C3)/3	1.566667	1.633333
centre of effort of sail position from bow	m	=C9-(($C5/100)*$C3)	0.981667	1.048333
position of mast from bow	m	=C10-$C4	0.341028	0.407695
FOR DISPLACEMENT SAILING				
centre of lateral resistance of hull	m	2.6	2.5	2.5
hull profile area below waterline	m^2	0.375	0.375	0.375
centre of lateral resistance of foil struts	m	=C9	1.566667	1.633333
foil strut profile area below waterline	m^2	0.54	0.54	0.54
total centre of lateral resistance	m	=((C14*C15)+(C16*C17))/(C15+C17)	1.94918	1.988525
centre of effort of sail position from bow	m	=C18-(($C5/100)*$C3)	1.36418	1.403525
position of mast	m	=C19-$C4	0.723542	0.762886
mast in same place for both?		=IF(C11<(C20-(C20/100)),"no",IF(C11>(C20+(C20/100)),"NO","yes"))	no	no

This is a sample of the spreadsheet used to find the mast position. It shows the formulae used in each cell and two example columns. The full version of the spreadsheet continues for the whole length of the boat.

15.18 Appendix 5 – Aerated Flow Control System Spreadsheet Model

FOIL DETAILS			
naca	2 40 14	2 40 14	2 40 14
angle of attack, deg	3.00	3.00	3.00
chord, m	0.15	0.15	0.15
span, m	2.40	2.40	2.40
distance from mast to side foil strut	2.00	2.00	2.00
Lift coefficient	0.458	0.458	0.458
Drag coefficient	0.009248	0.009248	0.009248
STRUT DETAILS			
Naca code	00 18	00 18	00 18
Chord	0.15	0.15	0.15
Length of struts	1.50	1.50	1.50
Effective Span (span under water)	0.5	0.5	0.5
Lift Coefficient	0.308	0.308	0.308
Drag Coefficient	0.008	0.008	0.008
MASSES			
Hull, kg	120	120	120
Rig, kg	10	10	10
Sailor, kg	80	80	80
Each front foil (including strut)	10	10	10
Rear foil	10	10	10
Total weight, N	**=(B21+B22+B23+(2*B24)+B25)*9.81**	**2354.40**	**2354.40**
DIMENSIONS			
height to centre of effort	2.76	2.76	2.76
Sail area,m^2	8.70	8.70	8.70
Width of beam	1.00	1.00	1.00
Mast base to centre of mass of whole boat	0.10	0.10	0.10
Mast base to sailor	1.00	1.00	1.00
Mast base to rear foil	3.00	3.00	3.00
Mast base to line of front foils	-0.20	-0.20	-0.20
ANGLES AND COEFFICIENTS			
Apparent course, β	25.00	25.00	25.00
β in rads	**=(B38*PI())/180**	**0.44**	**0.44**
Driving coeff	**=IF(B38=30,0.3,IF(B38=27.5,0.26,0.22))**	**0.22**	**0.22**
Heeling coeff	0.94	0.94	0.94
Windspeed (knots)	9.84	5.00	6.00
Windspeed (m/s)	**=B43*0.5144**	**2.572000**	**3.086400**
BOAT SPEED			

boat speed (guess)(knots)	15.55	7.90	9.50
boat speed (m/s)	=B47*0.5144	4.063760	4.886800
apparent windspeed (m/s)	=((2*B48*COS(B39))+(SQRT(((2*B48*COS(B39))^2)-(4*((B48^2)-(B44^2))))))/2	5.597607	6.722545
force on sail	=1.177*B$30*B$40*(B49^2)/2	35.29	50.90
lift from total length of foils	=(1000*(B48^2)*B$9*B$6*B$7)/2	1361.4	1968.7
Combined span of foil needed, m	=(B26/B51)*B7	4.15	2.87
drag from foils	=(1000*(B48^2)*B$10*B$6*B$7)/2	27.5	39.8
drag on struts, N	=(1000*(B48^2)*B18*B14*B16)/2	5.0	7.2
total drag	=B53+B54	32.44	46.92
	=IF(B55>(B50+(B50/100)),"reduce boat speed",IF(B55<(B50-(B50/100)),"increase boat speed","OK"))	increase boat speed	increase boat speed
	=IF(B52>B7,"STOP, THE SPAN OF FOIL YOU NEED TO FLY IS BIGGER THAN THE ACTUAL FOIL","OK")	STOP, THE SPAN OF FOIL YOU NEED TO FLY IS BIGGER THAN THE ACTUAL FOIL	STOP, THE SPAN OF FOIL YOU NEED TO FLY IS BIGGER THAN THE ACTUAL FOIL
HEELING MOMENTS			
From wind, Nm	=((B41*1.177*(B49^2)*B30)/2)*B29	416.21	600.30
From sailor, Nm	=(B31*0.5)*B23*9.81	392.40	392.40
Net	=B59-B60	23.81	207.90
FOIL LIFTS AND EFFECTIVE LENGTHS			
Combined front foil lift	=(((9.81*((B21*(B34-B32))+(B23*(B34-B33))+(B22*B34)+(2*B24*(B34-B35))))+((B15+B29)*B50))/(B34-B35))	1888.70	1907.96
Downwind foil			
Lift	=((B61/B8)+B64)/2	950.30	1005.96
Fraction of total lift	=B66/B26	0.40	0.43
Span	=B52*B67	1.68	1.23
Upwind foil			
Lift	=(B64-(B61/B8))/2	938.40	902.01
fraction of total lift	=B70/B26	0.40	0.38
Span	=B52*B71	1.65	1.10
Rear Foil			
Lift	=((9.81*((B22*(-B35))+(B21*(B32-B35))+(B23*(B33-B35))+(B25*(B34-B35))))-((B15+B29)*B50))/(B34-B35)	465.70	446.44
fraction of total lift	=B74/B26	0.20	0.19
Span	=B52*B75	0.82	0.54
total lift (check)	=B64+B74	2354.40	2354.40

15.19 Appendix 6 - Flap Angle Model

FOIL DETAILS			
naca	2 50 14	2 50 14	2 50 14
flap length	20%	20%	20%
chord, m	0.16	0.16	0.16
front foil span, m	1.00	1.00	1.00
rear foil span, m	0.80	0.80	0.80
distance from mast to side foil strut	1.20	1.20	1.20
STRUT DETAILS			
Naca code	00 18	00 18	00 18
Chord	0.16	0.16	0.16
Length of struts	1.50	1.50	1.50
Effective Span (length in water)	0.5	0.5	0.5
Lift Coefficient	0.308	0.308	0.308
Drag Coefficient	0.008	0.008	0.008
MASSES			
Hull, kg	100	100	100
Rig, kg	14	14	14
Sailor, kg	80	80	80
Each front foil (including strut)	6	6	6
Rear foil	6	6	6
Total weight, N	**=(B18+B19+B20+(2*B21)+B22)*9.81**	**2079.72**	**2079.72**
DIMENSIONS			
Height to centre of effort	2.76	2.76	2.76
Sail area,m^2	8.70	8.70	8.70
Width of beam	1.00	1.00	1.00
Mast base to centre of mass of whole boat	0.10	0.10	0.10
Mast base to sailor	1.50	1.50	1.50
Mast base to rear foil	3.30	3.30	3.30
Mast base to line of front foils	0.45	0.45	0.45
ANGLES AND COEFFICIENTS			
β	25.00	25.00	25.00
β in rads	**=(B36*PI())/180**	**0.44**	**0.44**
Driving coeff	**=IF(B36=30,0.3,IF(B36=27.5,0.26,0.22))**	**0.22**	**0.22**
Heeling coeff	0.94	0.94	0.94
Windspeed	2.00	4.00	4.00

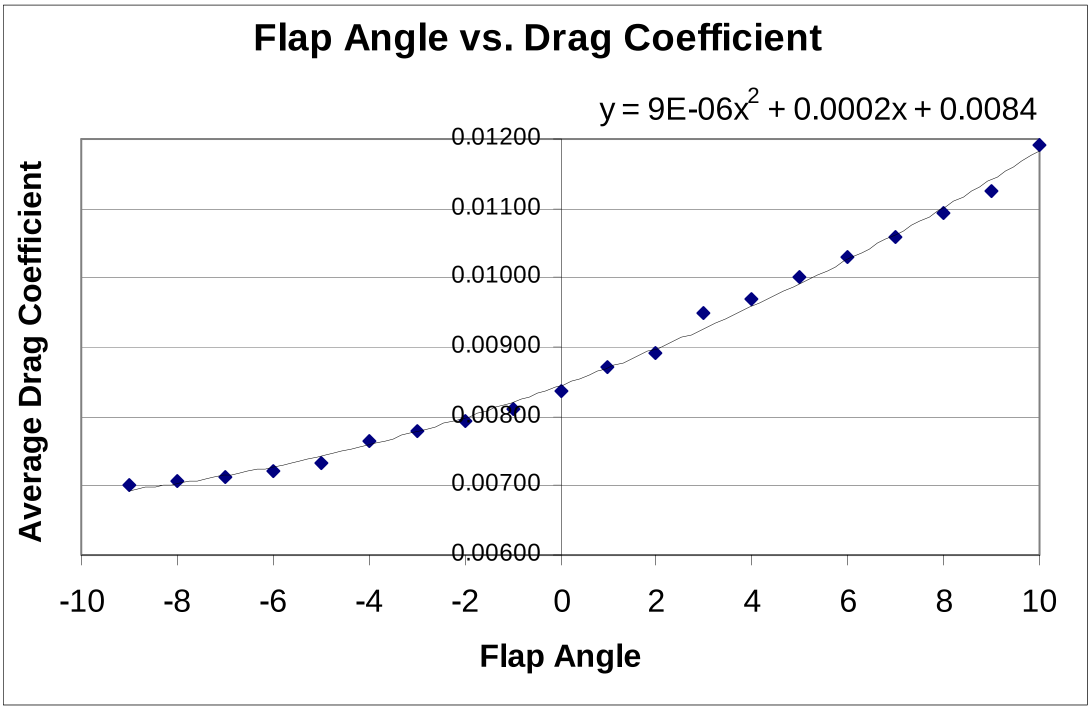
(knots)			
Windspeed (m/s)	**=B42*0.5144**	**2.06**	**2.06**
BOAT SPEED			
boat speed (guess)(knots)	1.00	8.30	7.70
boat speed (m/s)	**=B46*0.5144**	**4.27**	**3.96**
apparent windspeed (m/s)	**=((2*B47*COS(B37))+(SQRT(((2*B47*COS(B37))^2)-(4*((B47^2)-(B43^2))))))/2**	**4.86**	**4.79**
driving force on sail	**=1.177*B27*B38*(B48^2)/2**	**26.59**	**25.80**
drag on struts	**=3*500*(B$47^2)*B$15*B$11*B$13**	**17.5**	**15.1**
HEELING MOMENTS			
From wind, Nm	**=((B39*1.177*(B48^2)*B27)/2)*B26**	**313.54**	**304.30**
From sailor, Nm	**=(B28*0.5)*B20*9.81**	**392.40**	**392.40**
Net	**=B59-B60**	**-78.86**	**-88.10**
Foil Lifts and Flap Angles			
combined lift from front foils	**=(((9.81*((B20*(B33-B31))+(B22*(B33-B32))+(B21*B33)+(2*B23*(B33-B34))))+((B14+B28)*B49))/(B33-B34))**	**1913.62**	**1912.45**
lift needed from downwind foil	**=((B57/B9)+B60)/2**	**923.95**	**919.52**
lift needed from upwind foil	**=(B60-(B57/B9))/2**	**989.67**	**992.93**
lift from rear foil	**=((9.81*((B21*(-B34))+(B20*(B31-B34))+(B22*(B32-B34))+(B24*(B33-B34))))-((B14+B28)*B49))/(B33-B34))**	**166.10**	**167.27**
DOWNWIND FOIL			
lift coefficient needed	**=(B61*((2*B6)+B7))/(500*(B$47^2)*B$6*(B$7)^2)**	**0.84**	**0.97**
flap angle necessary for flight	**=(1.5014*(B66^2))+(16.259*B66)-8.1065**	**6.54**	**9.02**
drag coefficient	**=((9*10^(-6))*B67^2)+(0.0002*B67)+0.0084**	**0.01**	**0.01**
drag from foil	**=500*(B$47^2)*B68*B$6*B$7**	**14.7**	**13.7**
	=IF(B67>9,"flap angle>9",IF(B67<-9,"flap angle< -9","OK"))	**OK**	**flap angle>9**
UPWIND FOIL			
lift coefficient needed	**=(B62*((2*B6)+B7))/(500*(B$47^2)*B$6*(B$7^2))**	**0.90**	**1.04**
flap angle necessary for flight	**=(1.5014*(B72^2))+(16.259*B72)-8.1065**	**7.66**	**10.51**
drag coefficient	**=((9*10^(-6))*B73^2)+(0.0002*B73)+0.0084**	**0.01**	**0.01**
drag from foil	**=500*(B$47^2)*B74*B$6*B$7**	**15.3**	**14.4**

	=IF(B73>9,"flap angle>9",IF(B73<-9,"flap angle< -9","OK"))	OK	flap angle>9
REAR FOIL			
lift coefficient needed	=(B63*((2*B6)+B8))/(500*(B$47^2)*B$6*(B$8)^2)	0.20	0.23
flap angle necessary for flight	=(1.5014*(B78^2))+(16.259*B78)-8.1065	-4.81	-4.23
drag coefficient	=((9*10^(-6))*B79^2)+(0.0002*B79)+0.0084	0.01	0.01
drag from foil	=500*(B$47^2)*B80*B$6*B$8	8.9	7.7
	=IF(B79>9,"flap angle>9",IF(B79<-9,"flap angle<-9","OK"))	OK	OK
total drag	=(B50+B69+B75+B81)	56.40	50.96
	=IF(B84>(B49+(B49/100)),"reduce boat speed",IF(B84<(B49-(B49/100)),"increase boat speed","OK"))	reduce boat speed	reduce boat speed

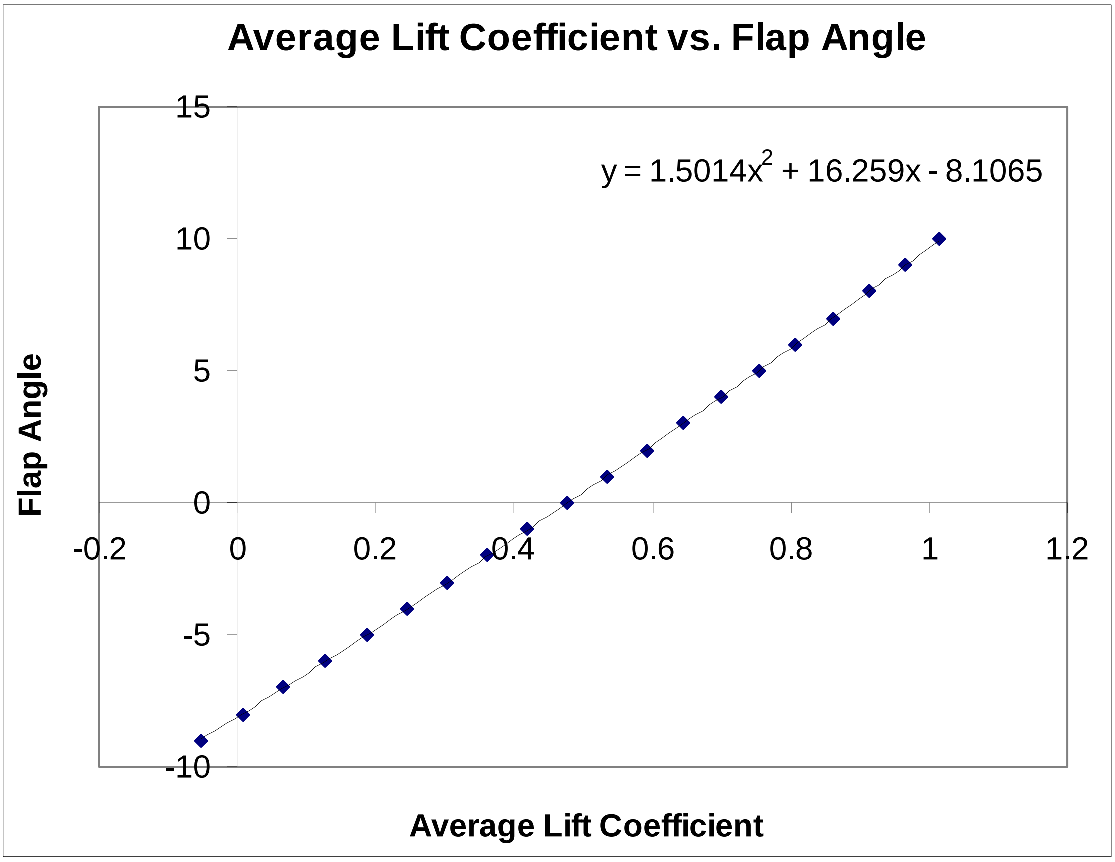
15.20 Appendix 7 - Foil Data

From 3 to 10 m/s (6 - 20 knots)   naca 25014   3 deg angle of attack
Chord of 160mm   Flap is 30% of chord

	Speed,m/s								
	3	4	5	6	7	8	9	10	Average
Angle of flap, deg	Drag coefficients								
-10									
-9	0.00868	0.00790	0.00737	0.00697	0.00666	0.00640	0.00619	0.00601	0.00702
-8	0.00878	0.00793	0.00741	0.00701	0.00670	0.00645	0.00624	0.00607	0.00707
-7	0.00884	0.00806	0.00744	0.00706	0.00676	0.00651	0.00631	0.00613	0.00714
-6	0.00891	0.00814	0.00759	0.00711	0.00682	0.00658	0.00637	0.00620	0.00721
-5	0.00899	0.00821	0.00769	0.00730	0.00698	0.00673	0.00644	0.00624	0.00732
-4	0.00935	0.00853	0.00800	0.00761	0.00729	0.00701	0.00680	0.00662	0.00765
-3	0.00949	0.00871	0.00812	0.00770	0.00739	0.00714	0.00693	0.00675	0.00778
-2	0.00965	0.00887	0.00829	0.00789	0.00753	0.00728	0.00706	0.00688	0.00793
-1	0.00985	0.00900	0.00846	0.00806	0.00773	0.00747	0.00720	0.00702	0.00810
0	0.01010	0.00930	0.00873	0.00832	0.00799	0.00772	0.00750	0.00730	0.00837
1	0.01051	0.00969	0.00912	0.00867	0.00834	0.00807	0.00784	0.00757	0.00873
2	0.01074	0.00991	0.00933	0.00889	0.00854	0.00818	0.00796	0.00776	0.00891
3	0.01138	0.01051	0.00992	0.00940	0.00905	0.00876	0.00852	0.00831	0.00948
4	0.01162	0.01070	0.01009	0.00964	0.00929	0.00900	0.00874	0.00853	0.00970
5	0.01193	0.01103	0.01046	0.00998	0.00960	0.00929	0.00905	0.00883	0.01002
6	0.01229	0.01135	0.01070	0.01026	0.00987	0.00955	0.00928	0.00905	0.01030
7	0.01257	0.01170	0.01102	0.01050	0.01016	0.00983	0.00955	0.00931	0.01058
8	0.01303	0.01202	0.01142	0.01089	0.01047	0.01012	0.00990	0.00965	0.01094
9	0.01344	0.01239	0.01167	0.01122	0.01079	0.01043	0.01013	0.00987	0.01124
10	0.01409	0.01318	0.01241	0.01183	0.01138	0.01112	0.01080	0.01053	0.01191



	Speed ,m/s								Average
	3	4	5	6	7	8	9	10	
Angle of flap, deg	Lift Coefficient								
-9	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053
-8	0.006	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.00775
-7	0.066	0.066	0.068	0.068	0.068	0.068	0.068	0.068	0.0675
-6	0.126	0.126	0.126	0.128	0.128	0.128	0.128	0.128	0.12725
-5	0.186	0.186	0.186	0.186	0.186	0.186	0.188	0.188	0.1865
-4	0.241	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.2445
-3	0.301	0.301	0.305	0.305	0.305	0.305	0.305	0.305	0.304
-2	0.36	0.36	0.36	0.36	0.365	0.365	0.365	0.365	0.3625
-1	0.413	0.419	0.419	0.419	0.419	0.419	0.425	0.425	0.41975
0	0.472	0.472	0.479	0.479	0.479	0.479	0.479	0.479	0.47725
1	0.531	0.531	0.531	0.538	0.538	0.538	0.538	0.538	0.535375
2	0.58	0.59	0.59	0.59	0.59	0.598	0.598	0.598	0.59175
3	0.638	0.638	0.648	0.648	0.648	0.648	0.648	0.648	0.6455
4	0.683	0.696	0.696	0.696	0.707	0.707	0.707	0.707	0.699875
5	0.741	0.741	0.755	0.755	0.755	0.755	0.766	0.766	0.75425
6	0.799	0.799	0.799	0.813	0.813	0.813	0.813	0.813	0.80775
7	0.839	0.857	0.857	0.857	0.872	0.872	0.872	0.872	0.86225
8	0.896	0.896	0.914	0.914	0.914	0.914	0.931	0.931	0.91375
9	0.953	0.953	0.953	0.973	0.973	0.973	0.973	0.973	0.9655
10	0.988	1.011	1.011	1.011	1.011	1.031	1.031	1.031	1.015625


Average Lift Coefficient vs. Flap Angle
y = 1.5014x2 + 16.259x - 8.1065
Flap Angle
Average Lift Coefficient
15
10
5
0
-5
-10
-0.2
0
0.2
0.4
0.6
0.8
1
1.2

15.21 Appendix 8 – Draycote Windspeed Data

Date	12pm MPH	Date	12pm MPH
07/02/2004	25	11/03/2004	website unavailable
08/02/2004	31	12/03/2004	7
09/02/2004	31	13/03/2004	21
10/02/2004	website unavailable	14/03/2004	30
11/02/2004	6	15/03/2004	18
12/02/2004	0	16/03/2004	21
13/02/2004	0	17/03/2004	15
14/02/2004	6	18/03/2004	9
15/02/2004	7	19/03/2004	26
16/02/2004	0	20/03/2004	32
17/02/2004	13	21/03/2004	16
18/02/2004	9	22/03/2004	24
19/02/2004	16	23/03/2004	10
20/02/2004	17	24/03/2004	17
21/02/2004	18	25/03/2004	8
22/02/2004	22	26/03/2004	website unavailable
23/02/2004	10	27/03/2004	website unavailable
24/02/2004	17	28/03/2004	website unavailable
25/02/2004	19	29/03/2004	0
26/02/2004	19	30/03/2004	18
27/02/2004	website unavailable	01/04/2004	12
28/02/2004	17	02/04/2004	8
29/02/2004	16	03/04/2004	18
01/03/2004	7	04/04/2004	13
02/03/2004	7	05/04/2004	15
03/03/2004	10	06/04/2004	website unavailable
04/03/2004	0	07/04/2004	17
05/03/2004	6	08/04/2004	8
06/03/2004	9	09/04/2004	5
07/03/2004	website unavailable	10/04/2004	0
08/03/2004	website unavailable	11/04/2004	6
09/03/2004	11	12/04/2004	9
10/03/2004	website unavailable	13/04/2004	9
		Average	12.46428571

15.22 Appendix 9 - Optimising Aspect Ratio - Foil Design

Foil Section design			
NACA	25014		
Thickness	14 percent		
Speed	10 knots		5.1444 m/s
Req lift range	0 to 2000 N		
Worst case lift	2000 N		
Level flying lift	660 N	approx	
Plan area	0.18 ms^2		
Cd	0.00743		
Cl	0.911		

Materials		**Strength**	**Safe Strength value**		**Failure mode used**
1	Mahoganny (figures from data book)	100	50	MPa	Yield
2	Aluminium (figures from data book)	200	100	MPa	Yield
3	Medium carbon steel (figures from data book)	400	200	MPa	Yield
4	Polyester glass composite	400	200	MPa	Tensile
5	Epoxy glass composite	700	350	MPa	Tensile
6	Pre-pregnated carbon fibre	1100	550	MPa	Tensile

NB - Loctitie adhesive data is taken from the company web based data sheets that can be found at

Chord	**Span**	**Aspect ratic**	**Thickness**	**Cl**	**Lift Calc**	**Real Lift**	**Vortex los**	**Lift loss**	**Ft**	**Fw**	**F density**	**F mass**	**F E**	**F Ix'x'**
m	**m**		**mm**		**N**	**N**	**N**	**%**	**m**	**m**	**kg/m^3**	**kg**	**GPa**	
0.02	9.00	450.00	2.80	0.911	2169.9	2160.25	10	0.4	0.003	0.02	1800	0.0829	22	4.560E-11
0.04	4.50	112.50	5.60	0.911	2169.9	2131.95	38	1.7	0.003	0.04	1800	0.0006	22	2.928E-10
0.06	3.00	50.00	8.40	0.911	2169.9	2086.40	83	3.8	0.003	0.06	1800	0.0156	22	1.447E-09
0.08	2.25	28.13	11.20	0.911	2169.9	2025.80	144	6.6	0.003	0.08	1800	0.0548	22	4.214E-09
0.10	1.80	18.00	14.00	0.911	2169.9	1952.87	217	10.0	0.003	0.10	1800	0.1037	22	9.300E-09
0.12	1.50	12.50	16.80	0.911	2169.9	1870.56	299	13.8	0.003	0.12	1800	0.1575	22	1.741E-08
0.14	1.29	9.18	19.60	0.911	2169.9	1781.81	388	17.9	0.003	0.14	1800	0.2140	22	2.925E-08
0.16	1.13	7.03	22.40	0.911	2169.9	1689.33	481	22.1	0.003	0.16	1800	0.2723	22	4.552E-08
0.18	1.00	5.56	25.20	0.911	2169.9	1595.48	574	26.5	0.003	0.18	1800	0.3318	22	6.694E-08
0.20	0.90	4.50	28.00	0.911	2169.9	1502.21	668	30.8	0.003	0.20	1800	0.3920	22	9.420E-08
0.22	0.82	3.72	30.80	0.911	2169.9	1411.03	759	35.0	0.003	0.22	1800	0.4529	22	1.280E-07
0.24	0.75	3.13	33.60	0.911	2169.9	1323.08	847	39.0	0.003	0.24	1800	0.5142	22	1.691E-07
0.26	0.69	2.66	36.40	0.911	2169.9	1239.13	931	42.9	0.003	0.26	1800	0.5758	22	2.181E-07
0.28	0.64	2.30	39.20	0.911	2169.9	1159.66	1010	46.6	0.003	0.28	1800	0.6377	22	2.758E-07
0.30	0.60	2.00	42.00	0.911	2169.9	1084.93	1085	50.0	0.003	0.30	1800	0.6998	22	3.429E-07
0.32	0.56	1.76	44.80	0.911	2169.9	1015.00	1155	53.2	0.003	0.32	1800	0.7621	22	4.201E-07
0.34	0.53	1.56	47.60	0.911	2169.9	949.84	1220	56.2	0.003	0.34	1800	0.8246	22	5.080E-07
0.36	0.50	1.39	50.40	0.911	2169.9	889.28	1281	59.0	0.003	0.36	1800	0.8871	22	6.074E-07
0.38	0.47	1.25	53.20	0.911	2169.9	833.13	1337	61.6	0.003	0.38	1800	0.9498	22	7.191E-07
0.40	0.45	1.13	56.00	0.911	2169.9	781.15	1389	64.0	0.003	0.40	1800	1.0125	22	8.436E-07
0.42	0.43	1.02	58.80	0.911	2169.9	733.06	1437	66.2	0.003	0.42	1800	1.0753	22	9.817E-07
0.44	0.41	0.93	61.60	0.911	2169.9	688.60	1481	68.3	0.003	0.44	1800	1.1382	22	1.134E-06
0.46	0.39	0.85	64.40	0.911	2169.9	647.50	1522	70.2	0.003	0.46	1800	1.2011	22	1.302E-06

Chord	**W wall t**	**Wa**	**W density**	**W mass**	**W E**	**W Ixx**	**Total Ixx**	**Mmax**	**Max Web Stre**	**1 2 3**	**Max Flange Stress**	**4 5 6**	**Stress in Bond layer**	**Loctite Adhesive product**	**GRP b**
m	**m**	**m**	**kg/m^3**	**kg**	**GPa**			**Nm**	**MPa**		**MPa**		**MPa**	**330 326 3430 3422 3425**	**4 5**
0.02	0.0015	-0.0032	7500	2.025	200	-1.144E-10	-2.320E-11	2250.00	155185.792		-135787.568		106690.232		
0.04	0.0015	-0.0004	7500	2.025	200	-1.113E-11	5.745E-10	1125.00	-391.668		5483.353		587.502		
0.06	0.0015	0.0024	7500	2.025	200	2.754E-12	2.897E-09	750.00	310.650		1087.274		440.087		
0.08	0.0015	0.0052	7500	2.025	200	5.898E-11	8.488E-09	562.50	172.307		371.122		205.442		
0.10	0.0015	0.0080	7500	2.025	200	2.893E-10	1.889E-08	450.00	95.292		166.762		107.204		
0.12	0.0015	0.0108	7500	2.025	200	8.253E-10	3.564E-08	375.00	56.811		88.373		62.071		
0.14	0.0015	0.0136	7500	2.025	200	1.799E-09	6.030E-08	321.43	36.250		52.242		38.915		
0.16	0.0015	0.0164	7500	2.025	200	3.341E-09	9.439E-08	281.25	24.434		33.373		25.924		
0.18	0.0015	0.0192	7500	2.025	200	5.585E-09	1.395E-07	250.00	17.209		22.587		18.105		
0.20	0.0015	0.0220	7500	2.025	200	8.661E-09	1.971E-07	225.00	12.560		15.985		13.130		
0.22	0.0015	0.0248	7500	2.025	200	1.270E-08	2.687E-07	204.55	9.438		11.722		9.819		
0.24	0.0015	0.0276	7500	2.025	200	1.784E-08	3.560E-07	187.50	7.268		8.848		7.531		
0.26	0.0015	0.0304	7500	2.025	200	2.420E-08	4.604E-07	173.08	5.714		6.841		5.902		
0.28	0.0015	0.0332	7500	2.025	200	3.193E-08	5.836E-07	160.71	4.572		5.398		4.709		
0.30	0.0015	0.0360	7500	2.025	200	4.114E-08	7.269E-07	150.00	3.714		4.333		3.817		
0.32	0.0015	0.0388	7500	2.025	200	5.198E-08	8.921E-07	140.63	3.058		3.531		3.137		
0.34	0.0015	0.0416	7500	2.025	200	6.457E-08	1.081E-06	132.35	2.548		2.915		2.609		
0.36	0.0015	0.0444	7500	2.025	200	7.905E-08	1.294E-06	125.00	2.145		2.434		2.193		
0.38	0.0015	0.0472	7500	2.025	200	9.555E-08	1.534E-06	118.42	1.822		2.054		1.861		
0.40	0.0015	0.0500	7500	2.025	200	1.142E-07	1.801E-06	112.50	1.561		1.749		1.593		
0.42	0.0015	0.0528	7500	2.025	200	1.351E-07	2.099E-06	107.14	1.348		1.501		1.373		
0.44	0.0015	0.0556	7500	2.025	200	1.585E-07	2.427E-06	102.27	1.172		1.298		1.193		
0.46	0.0015	0.0584	7500	2.025	200	1.843E-07	2.788E-06	97.83	1.025		1.130		1.042		

Buckling condition of main struts

Square section Mahogany:

NACA	Max load N	Strut Leng m	Chord m	Foil thickne m	Speed m/s	Strut drag	Wa m	W density kg/m^3	W mass kg	W Ixx	W E Pa	Fw m	Ft m	F density kg/m^3	F mass kg	F Ixx	F E Pa	Total Mass kg	Le m	Fe N
OO18	2000	1.00	0.18	0.032	5.144	17.35	0.026	545	0.38	4.048E-08	8.70E+09	0.18	0.003	1800	0.97	1.171E-07	1.00E+10	1.35	2.0	868.9474
OO18	2000	1.10	0.18	0.032	5.144	17.35	0.026	545	0.42	4.048E-08	8.70E+09	0.18	0.003	1800	1.07	1.171E-07	1.00E+10	1.49	2.2	718.1383
OO18	2000	1.20	0.18	0.032	5.144	17.35	0.026	545	0.46	4.048E-08	8.70E+09	0.18	0.003	1800	1.17	1.171E-07	1.00E+10	1.62	2.4	603.4357
OO18	2000	1.30	0.18	0.032	5.144	17.35	0.026	545	0.49	4.048E-08	8.70E+09	0.18	0.003	1800	1.26	1.171E-07	1.00E+10	1.76	2.6	514.17
OO18	2000	1.40	0.18	0.032	5.144	17.35	0.026	545	0.53	4.048E-08	8.70E+09	0.18	0.003	1800	1.36	1.171E-07	1.00E+10	1.89	2.8	443.3405
OO18	2000	1.50	0.18	0.032	5.144	17.35	0.026	545	0.57	4.048E-08	8.70E+09	0.18	0.003	1800	1.46	1.171E-07	1.00E+10	2.03	3.0	386.1988
OO18	2000	1.60	0.18	0.032	5.144	17.35	0.026	545	0.61	4.048E-08	8.70E+09	0.18	0.003	1800	1.56	1.171E-07	1.00E+10	2.16	3.2	339.4326
OO18	2000	1.70	0.18	0.032	5.144	17.35	0.026	545	0.65	4.048E-08	8.70E+09	0.18	0.003	1800	1.65	1.171E-07	1.00E+10	2.30	3.4	300.6738
OO18	2000	1.80	0.18	0.032	5.144	17.35	0.026	545	0.68	4.048E-08	8.70E+09	0.18	0.003	1800	1.75	1.171E-07	1.00E+10	2.43	3.6	268.1936
OO18	2000	1.90	0.18	0.032	5.144	17.35	0.026	545	0.72	4.048E-08	8.70E+09	0.18	0.003	1800	1.85	1.171E-07	1.00E+10	2.57	3.8	240.7056
OO18	2000	2.00	0.18	0.032	5.144	17.35	0.026	545	0.76	4.048E-08	8.70E+09	0.18	0.003	1800	1.94	1.171E-07	1.00E+10	2.70	4.0	217.2368
OO18	2000	1.00	0.16	0.029	5.144	17.35	0.023	545	0.28	2.252E-08	8.70E+09	0.16	0.003	1800	0.86	8.024E-08	1.00E+10	1.15	2.0	483.4117
OO18	2000	1.10	0.16	0.029	5.144	17.35	0.023	545	0.31	2.252E-08	8.70E+09	0.16	0.003	1800	0.95	8.024E-08	1.00E+10	1.26	2.2	399.5138
OO18	2000	1.20	0.16	0.029	5.144	17.35	0.023	545	0.34	2.252E-08	8.70E+09	0.16	0.003	1800	1.04	8.024E-08	1.00E+10	1.38	2.4	335.7026
OO18	2000	1.30	0.16	0.029	5.144	17.35	0.023	545	0.37	2.252E-08	8.70E+09	0.16	0.003	1800	1.12	8.024E-08	1.00E+10	1.49	2.6	286.0424
OO18	2000	1.40	0.16	0.029	5.144	17.35	0.023	545	0.40	2.252E-08	8.70E+09	0.16	0.003	1800	1.21	8.024E-08	1.00E+10	1.61	2.8	246.6386
OO18	2000	1.50	0.16	0.029	5.144	17.35	0.023	545	0.42	2.252E-08	8.70E+09	0.16	0.003	1800	1.30	8.024E-08	1.00E+10	1.72	3.0	214.8496
OO18	2000	1.60	0.16	0.029	5.144	17.35	0.023	545	0.45	2.252E-08	8.70E+09	0.16	0.003	1800	1.38	8.024E-08	1.00E+10	1.84	3.2	188.8327
OO18	2000	1.70	0.16	0.029	5.144	17.35	0.023	545	0.48	2.252E-08	8.70E+09	0.16	0.003	1800	1.47	8.024E-08	1.00E+10	1.95	3.4	167.2705
OO18	2000	1.80	0.16	0.029	5.144	17.35	0.023	545	0.51	2.252E-08	8.70E+09	0.16	0.003	1800	1.56	8.024E-08	1.00E+10	2.07	3.6	149.2011
OO18	2000	1.90	0.16	0.029	5.144	17.35	0.023	545	0.54	2.252E-08	8.70E+09	0.16	0.003	1800	1.64	8.024E-08	1.00E+10	2.18	3.8	133.9091
OO18	2000	2.00	0.16	0.029	5.144	17.35	0.023	545	0.57	2.252E-08	8.70E+09	0.16	0.003	1800	1.73	8.024E-08	1.00E+10	2.29	4.0	120.8529

3mm wall box section Aluminium

NACA	Max load N	Strut Leng m	Chord m	Thickness m	Speed m/s	Strut drag	Wa m	W density kg/m^3	W mass kg	W Ixx	W E Pa	Fw m	Ft m	F density kg/m^3	F mass kg	F Ixx	F E Pa	Total Mass kg	Le m	Fe N
OO18	2000	1.00	0.16	0.029	5.144	17.35	0.023	2700	1.40	1.588E-08	7.10E+10	0.16	0.003	2700	1.30	8.024E-08	1.00E+10	2.70	2.0	2782.153
OO18	2000	1.10	0.16	0.029	5.144	17.35	0.023	2700	1.54	1.588E-08	7.10E+10	0.16	0.003	2700	1.43	8.024E-08	1.00E+10	2.97	2.2	2299.3
OO18	2000	1.20	0.16	0.029	5.144	17.35	0.023	2700	1.68	1.588E-08	7.10E+10	0.16	0.003	2700	1.56	8.024E-08	1.00E+10	3.24	2.4	1932.051
OO18	2000	1.30	0.16	0.029	5.144	17.35	0.023	2700	1.82	1.588E-08	7.10E+10	0.16	0.003	2700	1.68	8.024E-08	1.00E+10	3.51	2.6	1646.244
OO18	2000	1.40	0.16	0.029	5.144	17.35	0.023	2700	1.96	1.588E-08	7.10E+10	0.16	0.003	2700	1.81	8.024E-08	1.00E+10	3.78	2.8	1419.466
OO18	2000	1.50	0.16	0.029	5.144	17.35	0.023	2700	2.11	1.588E-08	7.10E+10	0.16	0.003	2700	1.94	8.024E-08	1.00E+10	4.05	3.0	1236.512
OO18	2000	1.60	0.16	0.029	5.144	17.35	0.023	2700	2.25	1.588E-08	7.10E+10	0.16	0.003	2700	2.07	8.024E-08	1.00E+10	4.32	3.2	1086.778
OO18	2000	1.70	0.16	0.029	5.144	17.35	0.023	2700	2.39	1.588E-08	7.10E+10	0.16	0.003	2700	2.20	8.024E-08	1.00E+10	4.59	3.4	962.6826
OO18	2000	1.80	0.16	0.029	5.144	17.35	0.023	2700	2.53	1.588E-08	7.10E+10	0.16	0.003	2700	2.33	8.024E-08	1.00E+10	4.86	3.6	858.6891
OO18	2000	1.90	0.16	0.029	5.144	17.35	0.023	2700	2.67	1.588E-08	7.10E+10	0.16	0.003	2700	2.46	8.024E-08	1.00E+10	5.13	3.8	770.6794
OO18	2000	2.00	0.16	0.029	5.144	17.35	0.023	2700	2.81	1.588E-08	7.10E+10	0.16	0.003	2700	2.59	8.024E-08	1.00E+10	5.40	4.0	695.5382
OO18	2000	1.00	0.16	0.029	5.144	17.35	0.025	2700	1.66	2.111E-08	7.10E+10	0.16	0.002	2700	0.86	5.757E-08	1.00E+10	2.52	2.0	3698.667
OO18	2000	1.10	0.16	0.029	5.144	17.35	0.025	2700	1.83	2.111E-08	7.10E+10	0.16	0.002	2700	0.95	5.757E-08	1.00E+10	2.78	2.2	3056.75
OO18	2000	1.20	0.16	0.029	5.144	17.35	0.025	2700	1.99	2.111E-08	7.10E+10	0.16	0.002	2700	1.04	5.757E-08	1.00E+10	3.03	2.4	2568.519
OO18	2000	1.30	0.16	0.029	5.144	17.35	0.025	2700	2.16	2.111E-08	7.10E+10	0.16	0.002	2700	1.12	5.757E-08	1.00E+10	3.28	2.6	2188.56
OO18	2000	1.40	0.16	0.029	5.144	17.35	0.025	2700	2.32	2.111E-08	7.10E+10	0.16	0.002	2700	1.21	5.757E-08	1.00E+10	3.53	2.8	1887.075
OO18	2000	1.50	0.16	0.029	5.144	17.35	0.025	2700	2.49	2.111E-08	7.10E+10	0.16	0.002	2700	1.30	5.757E-08	1.00E+10	3.79	3.0	1643.852
OO18	2000	1.60	0.16	0.029	5.144	17.35	0.025	2700	2.66	2.111E-08	7.10E+10	0.16	0.002	2700	1.38	5.757E-08	1.00E+10	4.04	3.2	1444.792
OO18	2000	1.70	0.16	0.029	5.144	17.35	0.025	2700	2.82	2.111E-08	7.10E+10	0.16	0.002	2700	1.47	5.757E-08	1.00E+10	4.29	3.4	1279.816
OO18	2000	1.80	0.16	0.029	5.144	17.35	0.025	2700	2.99	2.111E-08	7.10E+10	0.16	0.002	2700	1.56	5.757E-08	1.00E+10	4.54	3.6	1141.564
OO18	2000	1.90	0.16	0.029	5.144	17.35	0.025	2700	3.16	2.111E-08	7.10E+10	0.16	0.002	2700	1.64	5.757E-08	1.00E+10	4.80	3.8	1024.562
OO18	2000	2.00	0.16	0.029	5.144	17.35	0.025	2700	3.32	2.111E-08	7.10E+10	0.16	0.002	2700	1.73	5.757E-08	1.00E+10	5.05	4.0	924.6668
OO18	2000	1.00	0.18	0.032	5.144	17.35	0.026	2700	1.88	2.605E-08	7.10E+10	0.18	0.003	2700	1.46	1.171E-07	1.00E+10	3.34	2.0	4563.058
OO18	2000	1.10	0.18	0.032	5.144	17.35	0.026	2700	2.07	2.605E-08	7.10E+10	0.18	0.003	2700	1.60	1.171E-07	1.00E+10	3.67	2.2	3771.122
OO18	2000	1.20	0.18	0.032	5.144	17.35	0.026	2700	2.26	2.605E-08	7.10E+10	0.18	0.003	2700	1.75	1.171E-07	1.00E+10	4.01	2.4	3168.79
OO18	2000	1.30	0.18	0.032	5.144	17.35	0.026	2700	2.45	2.605E-08	7.10E+10	0.18	0.003	2700	1.90	1.171E-07	1.00E+10	4.34	2.6	2700.034
OO18	2000	1.40	0.18	0.032	5.144	17.35	0.026	2700	2.63	2.605E-08	7.10E+10	0.18	0.003	2700	2.04	1.171E-07	1.00E+10	4.68	2.8	2328.091
OO18	2000	1.50	0.18	0.032	5.144	17.35	0.026	2700	2.82	2.605E-08	7.10E+10	0.18	0.003	2700	2.19	1.171E-07	1.00E+10	5.01	3.0	2028.026
OO18	2000	1.60	0.18	0.032	5.144	17.35	0.026	2700	3.01	2.605E-08	7.10E+10	0.18	0.003	2700	2.33	1.171E-07	1.00E+10	5.34	3.2	1782.444
OO18	2000	1.70	0.18	0.032	5.144	17.35	0.026	2700	3.20	2.605E-08	7.10E+10	0.18	0.003	2700	2.48	1.171E-07	1.00E+10	5.68	3.4	1578.913
OO18	2000	1.80	0.18	0.032	5.144	17.35	0.026	2700	3.39	2.605E-08	7.10E+10	0.18	0.003	2700	2.62	1.171E-07	1.00E+10	6.01	3.6	1408.351
OO18	2000	1.90	0.18	0.032	5.144	17.35	0.026	2700	3.58	2.605E-08	7.10E+10	0.18	0.003	2700	2.77	1.171E-07	1.00E+10	6.35	3.8	1264.005
OO18	2000	2.00	0.18	0.032	5.144	17.35	0.026	2700	3.76	2.605E-08	7.10E+10	0.18	0.003	2700	2.92	1.171E-07	1.00E+10	6.68	4.0	1140.764
OO18	2000	1.00	0.18	0.032	5.144	17.35	0.028	2700	2.18	3.323E-08	7.10E+10	0.18	0.002	2700	0.97	8.329E-08	1.00E+10	3.15	2.0	5821.646
OO18	2000	1.10	0.18	0.032	5.144	17.35	0.028	2700	2.40	3.323E-08	7.10E+10	0.18	0.002	2700	1.07	8.329E-08	1.00E+10	3.46	2.2	4811.278
OO18	2000	1.20	0.18	0.032	5.144	17.35	0.028	2700	2.61	3.323E-08	7.10E+10	0.18	0.002	2700	1.17	8.329E-08	1.00E+10	3.78	2.4	4042.81
OO18	2000	1.30	0.18	0.032	5.144	17.35	0.028	2700	2.83	3.323E-08	7.10E+10	0.18	0.002	2700	1.26	8.329E-08	1.00E+10	4.09	2.6	3444.761
OO18	2000	1.40	0.18	0.032	5.144	17.35	0.028	2700	3.05	3.323E-08	7.10E+10	0.18	0.002	2700	1.36	8.329E-08	1.00E+10	4.41	2.8	2970.228
OO18	2000	1.50	0.18	0.032	5.144	17.35	0.028	2700	3.27	3.323E-08	7.10E+10	0.18	0.002	2700	1.46	8.329E-08	1.00E+10	4.72	3.0	2587.398
OO18	2000	1.60	0.18	0.032	5.144	17.35	0.028	2700	3.48	3.323E-08	7.10E+10	0.18	0.002	2700	1.56	8.329E-08	1.00E+10	5.04	3.2	2274.081
OO18	2000	1.70	0.18	0.032	5.144	17.35	0.028	2700	3.70	3.323E-08	7.10E+10	0.18	0.002	2700	1.65	8.329E-08	1.00E+10	5.35	3.4	2014.41
OO18	2000	1.80	0.18	0.032	5.144	17.35	0.028	2700	3.92	3.323E-08	7.10E+10	0.18	0.002	2700	1.75	8.329E-08	1.00E+10	5.67	3.6	1796.804
OO18	2000	1.90	0.18	0.032	5.144	17.35	0.028	2700	4.14	3.323E-08	7.10E+10	0.18	0.002	2700	1.85	8.329E-08	1.00E+10	5.98	3.8	1612.644
OO18	2000	2.00	0.18	0.032	5.144	17.35	0.028	2700	4.36	3.323E-08	7.10E+10	0.18	0.002	2700	1.94	8.329E-08	1.00E+10	6.30	4.0	1455.412

3mm wall steel box section

NACA	Max load N	Strut Leng m	Chord m	Thickness m	Speed m/s	Strut drag	Wa m	W density kg/m^3	W mass kg	W Ixx	W E MPa	Fw m	Ft m	F density kg/m^3	F mass kg	F Ixx	F E Pa	Total Mass kg	Le m	Fe N
OO18	2000	1.00	0.16	0.029	5.144	17.35	0.023	7500	3.90	1.588E-08	2.1E+11	0.16	0.003	2700	1.30	8.024E-08	1.00E+10	5.19	2.0	8228.903
OO18	2000	1.10	0.16	0.029	5.144	17.35	0.023	7500	4.29	1.588E-08	2.1E+11	0.16	0.003	2700	1.43	8.024E-08	1.00E+10	5.71	2.2	6800.746
OO18	2000	1.20	0.16	0.029	5.144	17.35	0.023	7500	4.68	1.588E-08	2.1E+11	0.16	0.003	2700	1.56	8.024E-08	1.00E+10	6.23	2.4	5714.516
OO18	2000	1.30	0.16	0.029	5.144	17.35	0.023	7500	5.07	1.588E-08	2.1E+11	0.16	0.003	2700	1.68	8.024E-08	1.00E+10	6.75	2.6	4869.173
OO18	2000	1.40	0.16	0.029	5.144	17.35	0.023	7500	5.46	1.588E-08	2.1E+11	0.16	0.003	2700	1.81	8.024E-08	1.00E+10	7.27	2.8	4198.42
OO18	2000	1.50	0.16	0.029	5.144	17.35	0.023	7500	5.85	1.588E-08	2.1E+11	0.16	0.003	2700	1.94	8.024E-08	1.00E+10	7.79	3.0	3657.29
OO18	2000	1.60	0.16	0.029	5.144	17.35	0.023	7500	6.24	1.588E-08	2.1E+11	0.16	0.003	2700	2.07	8.024E-08	1.00E+10	8.31	3.2	3214.415
OO18	2000	1.70	0.16	0.029	5.144	17.35	0.023	7500	6.63	1.588E-08	2.1E+11	0.16	0.003	2700	2.20	8.024E-08	1.00E+10	8.83	3.4	2847.371
OO18	2000	1.80	0.16	0.029	5.144	17.35	0.023	7500	7.02	1.588E-08	2.1E+11	0.16	0.003	2700	2.33	8.024E-08	1.00E+10	9.35	3.6	2539.785
OO18	2000	1.90	0.16	0.029	5.144	17.35	0.023	7500	7.41	1.588E-08	2.1E+11	0.16	0.003	2700	2.46	8.024E-08	1.00E+10	9.87	3.8	2279.474
OO18	2000	2.00	0.16	0.029	5.144	17.35	0.023	7500	7.80	1.588E-08	2.1E+11	0.16	0.003	2700	2.59	8.024E-08	1.00E+10	10.39	4.0	2057.226
OO18	2000	1.00	0.16	0.029	5.144	17.35	0.025	7500	4.61	2.111E-08	2.1E+11	0.16	0.002	2700	0.86	5.757E-08	1.00E+10	5.48	2.0	10939.72
OO18	2000	1.10	0.16	0.029	5.144	17.35	0.025	7500	5.07	2.111E-08	2.1E+11	0.16	0.002	2700	0.95	5.757E-08	1.00E+10	6.02	2.2	9041.091
OO18	2000	1.20	0.16	0.029	5.144	17.35	0.025	7500	5.54	2.111E-08	2.1E+11	0.16	0.002	2700	1.04	5.757E-08	1.00E+10	6.57	2.4	7597.028
OO18	2000	1.30	0.16	0.029	5.144	17.35	0.025	7500	6.00	2.111E-08	2.1E+11	0.16	0.002	2700	1.12	5.757E-08	1.00E+10	7.12	2.6	6473.207
OO18	2000	1.40	0.16	0.029	5.144	17.35	0.025	7500	6.46	2.111E-08	2.1E+11	0.16	0.002	2700	1.21	5.757E-08	1.00E+10	7.67	2.8	5581.49
OO18	2000	1.50	0.16	0.029	5.144	17.35	0.025	7500	6.92	2.111E-08	2.1E+11	0.16	0.002	2700	1.30	5.757E-08	1.00E+10	8.22	3.0	4862.098
OO18	2000	1.60	0.16	0.029	5.144	17.35	0.025	7500	7.38	2.111E-08	2.1E+11	0.16	0.002	2700	1.38	5.757E-08	1.00E+10	8.76	3.2	4273.328
OO18	2000	1.70	0.16	0.029	5.144	17.35	0.025	7500	7.84	2.111E-08	2.1E+11	0.16	0.002	2700	1.47	5.757E-08	1.00E+10	9.31	3.4	3785.37
OO18	2000	1.80	0.16	0.029	5.144	17.35	0.025	7500	8.30	2.111E-08	2.1E+11	0.16	0.002	2700	1.56	5.757E-08	1.00E+10	9.86	3.6	3376.457
OO18	2000	1.90	0.16	0.029	5.144	17.35	0.025	7500	8.76	2.111E-08	2.1E+11	0.16	0.002	2700	1.64	5.757E-08	1.00E+10	10.41	3.8	3030.393
OO18	2000	2.00	0.16	0.029	5.144	17.35	0.025	7500	9.23	2.111E-08	2.1E+11	0.16	0.002	2700	1.73	5.757E-08	1.00E+10	10.95	4.0	2734.93
OO18	2000	1.00	0.18	0.032	5.144	17.35	0.026	7500	5.23	2.605E-08	2.1E+11	0.18	0.003	2700	1.46	1.171E-07	1.00E+10	6.69	2.0	13496.37
OO18	2000	1.10	0.18	0.032	5.144	17.35	0.026	7500	5.75	2.605E-08	2.1E+11	0.18	0.003	2700	1.60	1.171E-07	1.00E+10	7.35	2.2	11154.02
OO18	2000	1.20	0.18	0.032	5.144	17.35	0.026	7500	6.27	2.605E-08	2.1E+11	0.18	0.003	2700	1.75	1.171E-07	1.00E+10	8.02	2.4	9372.477
OO18	2000	1.30	0.18	0.032	5.144	17.35	0.026	7500	6.80	2.605E-08	2.1E+11	0.18	0.003	2700	1.90	1.171E-07	1.00E+10	8.69	2.6	7986.016
OO18	2000	1.40	0.18	0.032	5.144	17.35	0.026	7500	7.32	2.605E-08	2.1E+11	0.18	0.003	2700	2.04	1.171E-07	1.00E+10	9.36	2.8	6885.902
OO18	2000	1.50	0.18	0.032	5.144	17.35	0.026	7500	7.84	2.605E-08	2.1E+11	0.18	0.003	2700	2.19	1.171E-07	1.00E+10	10.03	3.0	5998.386
OO18	2000	1.60	0.18	0.032	5.144	17.35	0.026	7500	8.36	2.605E-08	2.1E+11	0.18	0.003	2700	2.33	1.171E-07	1.00E+10	10.70	3.2	5272.019
OO18	2000	1.70	0.18	0.032	5.144	17.35	0.026	7500	8.89	2.605E-08	2.1E+11	0.18	0.003	2700	2.48	1.171E-07	1.00E+10	11.36	3.4	4670.023
OO18	2000	1.80	0.18	0.032	5.144	17.35	0.026	7500	9.41	2.605E-08	2.1E+11	0.18	0.003	2700	2.62	1.171E-07	1.00E+10	12.03	3.6	4165.545
OO18	2000	1.90	0.18	0.032	5.144	17.35	0.026	7500	9.93	2.605E-08	2.1E+11	0.18	0.003	2700	2.77	1.171E-07	1.00E+10	12.70	3.8	3738.606
OO18	2000	2.00	0.18	0.032	5.144	17.35	0.026	7500	10.45	2.605E-08	2.1E+11	0.18	0.003	2700	2.92	1.171E-07	1.00E+10	13.37	4.0	3374.092
OO18	2000	1.00	0.18	0.032	5.144	17.35	0.028	7500	6.05	3.323E-08	2.1E+11	0.18	0.002	2700	0.97	8.329E-08	1.00E+10	7.02	2.0	17218.95
OO18	2000	1.10	0.18	0.032	5.144	17.35	0.028	7500	6.65	3.323E-08	2.1E+11	0.18	0.002	2700	1.07	8.329E-08	1.00E+10	7.72	2.2	14230.54
OO18	2000	1.20	0.18	0.032	5.144	17.35	0.028	7500	7.26	3.323E-08	2.1E+11	0.18	0.002	2700	1.17	8.329E-08	1.00E+10	8.43	2.4	11957.61
OO18	2000	1.30	0.18	0.032	5.144	17.35	0.028	7500	7.86	3.323E-08	2.1E+11	0.18	0.002	2700	1.26	8.329E-08	1.00E+10	9.13	2.6	10188.73
OO18	2000	1.40	0.18	0.032	5.144	17.35	0.028	7500	8.47	3.323E-08	2.1E+11	0.18	0.002	2700	1.36	8.329E-08	1.00E+10	9.83	2.8	8785.18
OO18	2000	1.50	0.18	0.032	5.144	17.35	0.028	7500	9.07	3.323E-08	2.1E+11	0.18	0.002	2700	1.46	8.329E-08	1.00E+10	10.53	3.0	7652.868
OO18	2000	1.60	0.18	0.032	5.144	17.35	0.028	7500	9.68	3.323E-08	2.1E+11	0.18	0.002	2700	1.56	8.329E-08	1.00E+10	11.23	3.2	6726.154
OO18	2000	1.70	0.18	0.032	5.144	17.35	0.028	7500	10.28	3.323E-08	2.1E+11	0.18	0.002	2700	1.65	8.329E-08	1.00E+10	11.94	3.4	5958.115
OO18	2000	1.80	0.18	0.032	5.144	17.35	0.028	7500	10.89	3.323E-08	2.1E+11	0.18	0.002	2700	1.75	8.329E-08	1.00E+10	12.64	3.6	5314.492
OO18	2000	1.90	0.18	0.032	5.144	17.35	0.028	7500	11.49	3.323E-08	2.1E+11	0.18	0.002	2700	1.85	8.329E-08	1.00E+10	13.34	3.8	4769.793
OO18	2000	2.00	0.18	0.032	5.144	17.35	0.028	7500	12.10	3.323E-08	2.1E+11	0.18	0.002	2700	1.94	8.329E-08	1.00E+10	14.04	4.0	4304.738

15.23 Appendix 10 – Budget

DATE	COST ELEMENT NAME	PURCHASE ORDER TEXT	PURCHASE DOCUMENT	QUANTITY	VALUE	TOTAL
				#	£	£
28/11/2003	Photocopying	Poster 6x3				50.00
15/12/2003	Cons Lab & W/S	18mm Far Eastern Ply	4500228256	3 sheets		90.61
	IntDpt ReApp Stores	Stringers				25.00
05/01/2004	Sainsbury's	Petrol for Moth viewing	Kiran Card			20.00
	IntDpt ReApp Stores	Carpenters time for cutting uprights				20.00
25/02/2004	Homebase	Right angled brackets for uprights	Tom C. Card	14		
25/02/2004	Homebase	Roller	Tom C. Card	2		
25/02/2004	Homebase	PVA Glue	Tom C. Card	1l		
						30.00
	IntDpt ReApp Stores	1" wood screws				20.00
03/03/2004	Homebase	Wooden brushes	Ian G. Card	2	4.59	9.18
03/03/2004	Homebase	Mini roller	Ian G. Card	2	3.99	7.98
03/03/2004	Homebase	10 pack mini rollers	Ian G. Card	1	4.99	4.99
03/03/2004	Homebase	7 litre bucket	Ian G. Card	1	2.99	2.99
14/03/2004	Moto (Exeter)	Petrol - Mould collection	Ian G. Card	1	19.16	19.16
17/03/2004	Car user	P38 Car body filler	Paul W. Card	2	15.00	30.00
18/03/2004	Homebase	Varnish Matt (250ml)	Ian G. Card	1	4.99	4.99
18/03/2004	Homebase	Finesse Brush (1")	Ian G. Card	1	3.99	3.99
20/03/2004	Scott Bader	Crystic Resin (25 Kg)	Ian	1	52.75	
20/03/2004	Scott Bader	Catalyst (500ml)	Ian	1	7.21	
20/03/2004	Scott Bader	Amberseal release agent (400g)	Ian	1	10.7	
					70.66	
				Vat @ 17.5	12.37	
				Carriage	15.00	
				Total		98.03
		Glass				120.00
		Honeycomb				230.00
24/03/2004	Homebase	Wooden brushes	Ian G. Card	2	4.59	9.18
24/03/2004	Homebase	Finesse Brush (1")	Ian G. Card	1	3.99	3.99
24/03/2004	Homebase	Varnish Matt (750ml)	Ian G. Card	1	10.99	10.99
24/03/2004	Homebase	Briwax	Kiran Cash	1	5.99	5.99
	International paints	Paint				50.00
		Electronics budget	Tom K.			150.00
					Total	1,017.07

15.24 Appendix 11 - Electronics

15.24.1 ADC Test Program

```
#include <stdio.h> // Implements IO functions including printf()

//cpu specific special function registers
sfr   ADCON0 = 0xD8;
sfr   ADCON1 = 0xDC;
sfr   ADDATH = 0xD9;
sfr   ADDATL = 0xDA;

sfr   S0CON  = 0x98;
sfr   TMOD   = 0x89;
sfr   TH1    = 0x8D;
sbit  TR1    = 0x8E;
sbit  TI0    = 0x99;

/* Read_ADC: reads an analog signal from the given chanel */
unsigned Read_ADC( unsigned char channel )
{

   ADCON1 &= ~0x0F;                  //Clears Channel for selection
   ADCON1 |= 0x0F & channel;         //Selects received Channel

   ADDATL |= ~ADDATL;                //Write to ADDATL starts execution of ADC

   while( ADCON0 & 0x10);            //Wait until A to D is complete

   return( (  ( (unsigned) ADDATH << 8) | ADDATL ) >> 6 );
}

/* main() : Outputs the digital conversion of channels 0 - 11. */
void main( void )
{
   unsigned char i;

    S0CON  = 0x50;              /* SCON: mode 1, 8-bit UART, enable rcvr        */
    TMOD |= 0x20;               /* TMOD: timer 1, mode 2, 8-bit reload          */
    TH1   = 232;                /* TH1:  reload value for 1200 baud @ 11.0592MHz*/
    TR1   = 1;                  /* TR1:  timer 1 run                            */
    TI0    = 1;                 /* TI:   set TI to send first char of UART      */

   while( 1 )
   {
      for( i = 0; i < 12; i++ )
      {
         printf("ADC Channel %u = %4u\n", (unsigned) i, Read_ADC( i ) );
      }
   }
}
```

15.24.2 Memory Test

```
/*--------------------------------------------------------------------------------
memorytest.c
Fills an array in xdata memory with a test pattern
--------------------------------------------------------------------------------*/

#include <reg517a.h> // Chip special function registers

static unsigned char xdata store[2000]; // 2000 byte global data array in xdata memory
static unsigned long dptr = 0; // data pointer for store array

// This function runs first
void main( void )
{
   while(1) {  // main program loop
      while (dptr < 2000) {
         store[dptr++] = 0xff;
         store[dptr++] = 0x22;
       }
```

```
   }
}
```

15.24.3 Final Program

```
/*---------------------------------------------------------------------------------
datalogger.c
Main datalogger program for Future Foils

Tom Kennaugh 2004
-------------------------------------------------------------------------------*/

#include <reg517a.h> // Chip special function registers
#include <stdio.h> //provides printf function

#define NO_OF_SENSORS 4 // Number of sensors
#define SAMPLE_RATE 50 // Sampling rate expressed in 1/100th sec

static unsigned char xdata store[2000]; // 2000 byte global data array in xdata memory
static unsigned long dptr = 0; // data pointer for store array
static unsigned long sensor = 0; // current sensor (allows resume)

sbit PT0  = 0xB9; // Timer priority sfr
sbit EA   = 0xAF; // Interupt enable sfr

sbit P1_0 = P1^0;     /* SFR for P1.0 */
sbit P1_1 = P1^1;     /* SFR for P1.1 */
sbit P1_2 = P1^2;     /* SFR for P1.2 */
sbit P1_3 = P1^3;     /* SFR for P1.3 */

//Fuction Prototypes
unsigned Read_ADC(unsigned char channel);
void dump_data(void);
void timer0_initialize (void);
void timer0_delay (unsigned count);

// This function runs first
void main( void )
{
   unsigned char i;

    //   Setup serial port
    S0CON  = 0x50;            /* SCON: mode 1, 8-bit UART, enable rcvr       */
    TMOD |= 0x20;       /* TMOD: timer 1, mode 2, 8-bit reload         */
    TH1   = 232;        /* TH1:  reload value for 1200 baud @ 11.0592MHz    */
    TR1   = 1;          /* TR1:  timer 1 run                           */
    TI0    = 1;         /* TI:   set TI to send first char of UART     */

   P1_0 = 1; //set as input
   P1_1 = 1; //set as input

   timer0_initialize(); // Initialize timer for data recording

   while(1) {  // main program loop
         P1_2 = 0; //turn recording led off
      P1_3 = 0; //turn data output led off
      if (sensor != 0) { //fix dptr for resume
         dptr = dptr + (NO_OF_SENSORS-sensor); //advance dptr for remaining sensors
         sensor = 0; //reset sensors counter
      }
      //while enable switch is on and memory is remaining record data
      while (P1_0 == 1 && dptr < 2000) {
         P1_2 = 1; // Turn recording LED on
         timer0_delay(SAMPLE_RATE); // Wait for set delay
         for( i = 0; i < NO_OF_SENSORS; i++ ) {
            sensor = i; // Store current sensor
            store[dptr++] = Read_ADC(i); //Read sensor
         }
      }
      //If data output switch is held down for 1 second output data
      if (P1_0 == 1) {
         timer0_delay(100); // user must hold down button fo over 1 second
         if (P1_0 == 1) dump_data();  // call function to output data
      }
   }
}
```

```
/* Read_ADC: reads an analog signal from the given channel */
unsigned Read_ADC( unsigned char channel )
{

   ADCON1 &= ~0x0F;                  //Clears Channel for selection
   ADCON1 |= 0x0F & channel;         //Selects received Channel

   ADDATL |= ~ADDATL;                //Write to ADDATL starts execution of ADC

   while( ADCON0 & 0x10);            //Wait until A to D is complete

   return( (  ( (unsigned) ADDATH << 8) | ADDATL ) >> 6 );
}

//Dumps formatted data to serial upto dptr
void dump_data(void) {
   unsigned long i = 0;
   unsigned char j;

   P1_3 = 1; // Turn data output LED on
   if (dptr == 0) dptr = 2000; // allow retreval of data after powerdown (EEPROM only)
   while (i < dptr) {
      for (j = 0; j<NO_OF_SENSORS-1; j++) {
         printf("%u ", store[i++] ); //Print all but last sensor with spaces
      }
      printf("%u/n", store[i++] ); // Print last sensor with CR
   }
   printf("\nDone\n"); // shows program completed sucessfuly
   dptr = 0; //Reset dptr
}


/*------------------------------------------------------------------------------
Timer functions. timer0_initialize() should be called during program
initilisation for these functions to operate
------------------------------------------------------------------------------*/

#define TIMER0_COUNT 0xDC11 /* 10000h - ((11,059,200 Hz / (12 * FREQ)) - 17) */

static unsigned timer0_tick; /* timer tick variable */

/*------------------------------------------------
interrupt service routine for TIMER 0
------------------------------------------------*/
static void timer0_isr (void) interrupt 1 using 1
  {
      unsigned i;
/*------------------------------------------------
Stop Timer 0, adjust the timer 0 counter so that
we get another interrupt in 10ms, and restart the
timer.
------------------------------------------------*/
TR0 = 0; /* stop timer 0 */
i = TIMER0_COUNT + TL0 + (TH0<<8);
TL0 = i;
TH0 = i >> 8;
TR0 = 1; /* start timer 0 */

/*------------------------------------------------
Increment the timer tick. This interrupt should
occur approximately every 10ms. So, the resolution
of the timer will be 100Hz not including interrupt
latency.
------------------------------------------------*/
timer0_tick++;
}

/*-----------------------------------------------------------------------------
This function enables TIMER 0. TIMER 0 generates a synchronous interrupt
once every 100Hz.
------------------------------------------------------------------------------*/
void timer0_initialize (void)
{
EA = 0; /* disable interrupts */
timer0_tick = 0;
TR0 = 0; /* stop timer 0 */
```

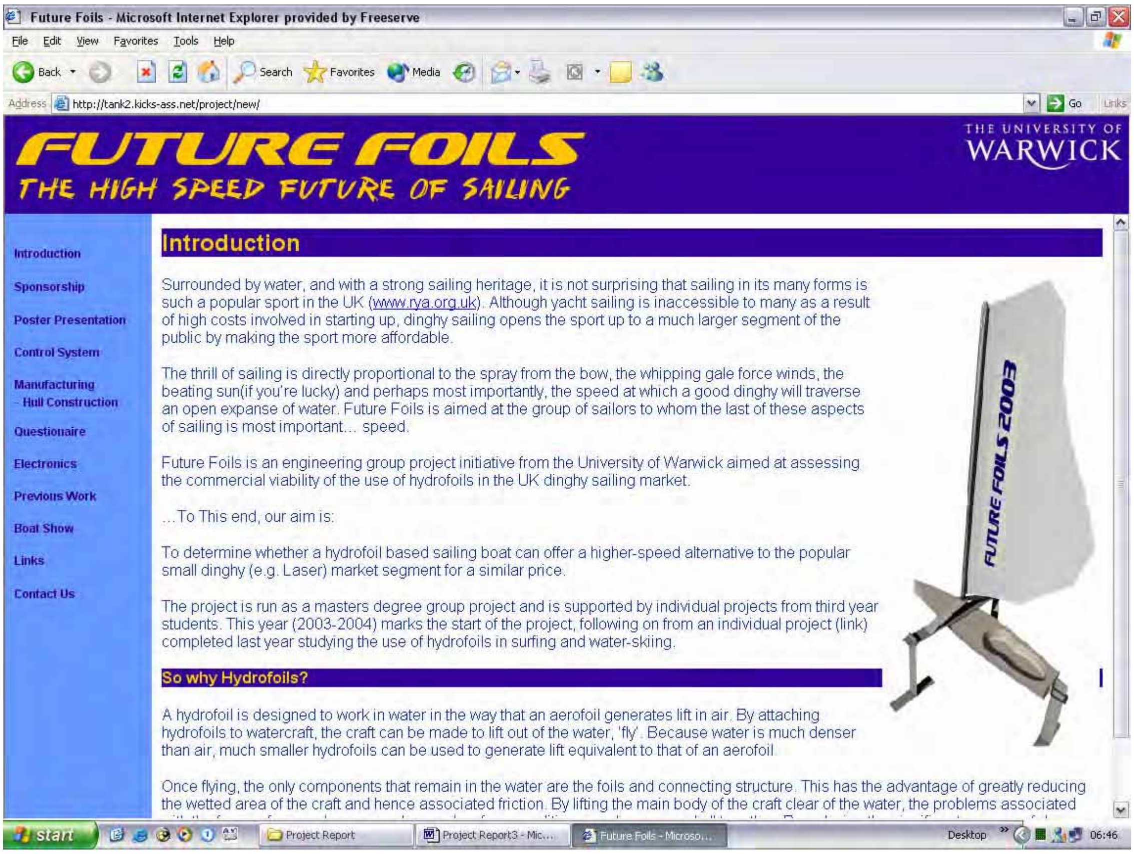
```
TMOD &= ~0x0F; /* clear timer 0 mode bits */
TMOD |= 0x01; /* put timer 0 into 16-bit no prescale */
TL0 = (TIMER0_COUNT & 0x00FF);
TH0 = (TIMER0_COUNT >> 8);
PT0 = 0; /* set low priority for timer 0 */
ET0 = 1; /* enable timer 0 interrupt */
TR0 = 1; /* start timer 0 */
EA = 1; /* enable interrupts */
}

/*------------------------------------------------------------------------------
This function returns the current timer0 tick count.
------------------------------------------------------------------------------*/
unsigned timer0_count (void)
{
unsigned t;
EA = 0;
t = timer0_tick;
EA = 1;
return (t);
}

/*------------------------------------------------------------------------------
This function waits for 'count' timer ticks (count*1/100th sec) to pass.
a value of 100 gives approximately a 1s delay.
------------------------------------------------------------------------------*/
void timer0_delay (
unsigned count)
{
unsigned start_count;
start_count = timer0_count (); /* get the starting count */
while ((timer0_count () - start_count) <= count) /* wait for count “ticks” */
{;}
}
```

15.24.4 Matlab Code

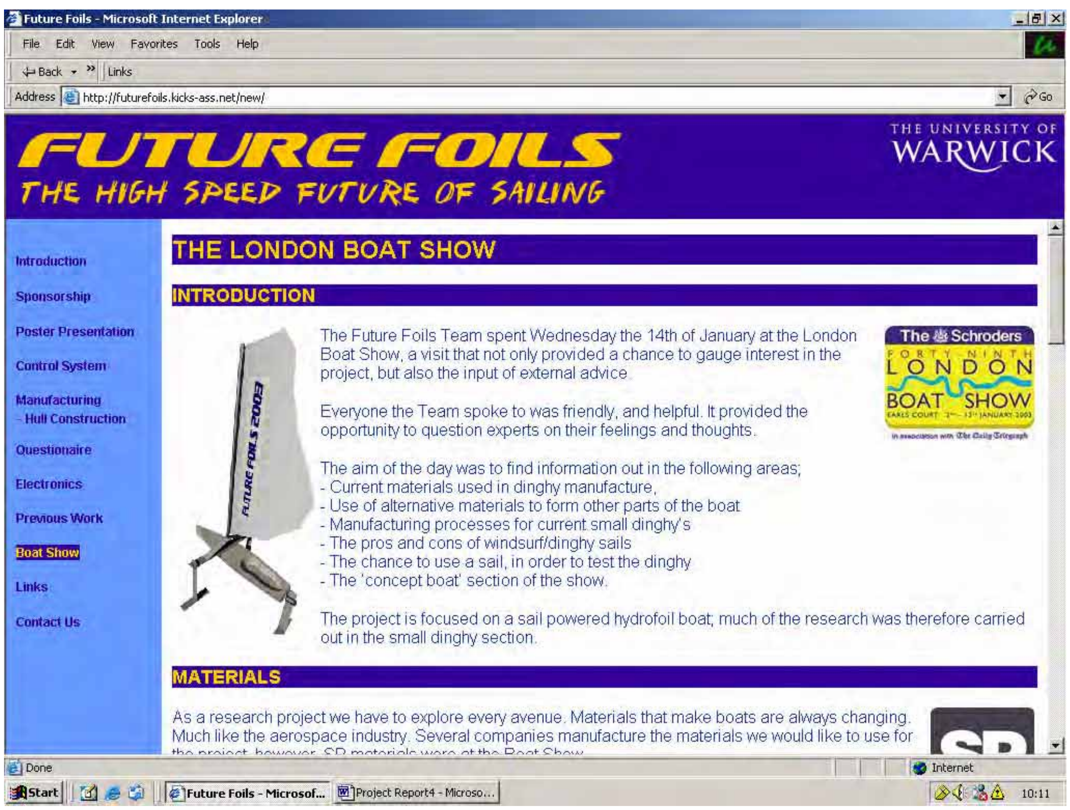
15.24.5 Procdata.m

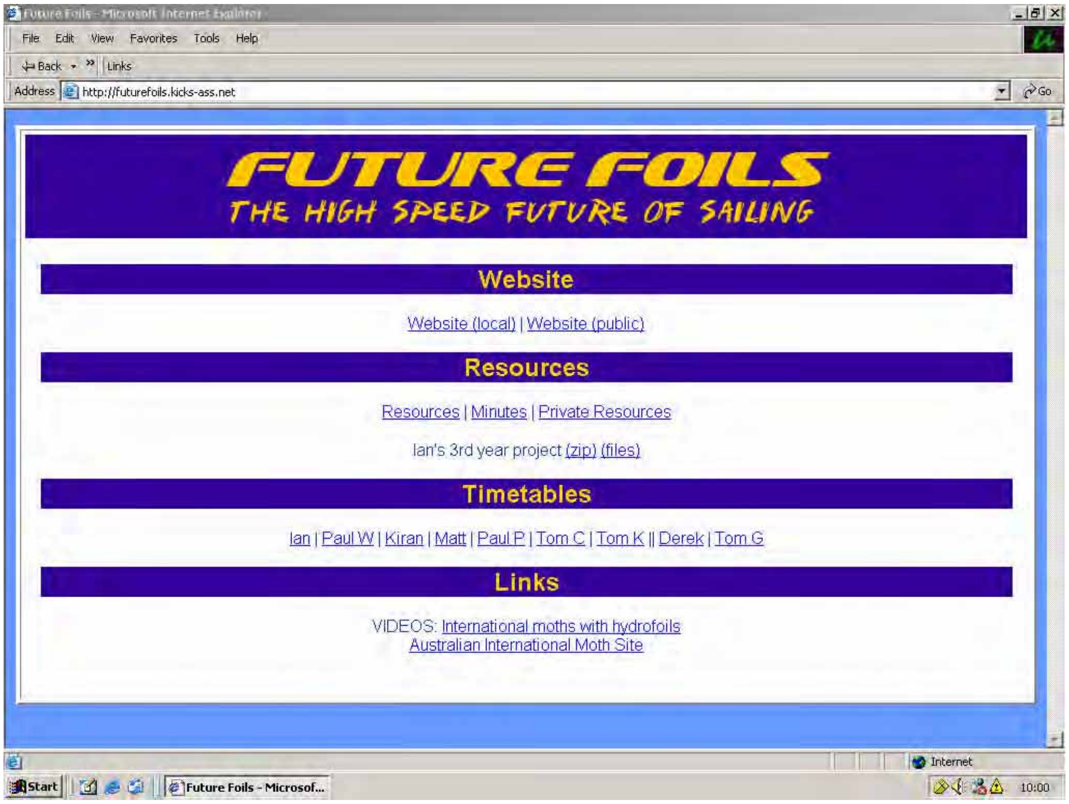
```
% procdata.m - Loads raw data from the datalogger and splits it into
% separate matricies and biases and scales as required

% Constants (Determined during calibration)
WIND_DIR_SCALE = 360; % Gives aparent wind angle in degrees
WIND_SPEED_SCALE = 40; % Maximum Readable Windspeed (knots)
BOAT_SPEED_SCALE = 30; % Maximum Readable Boat Speed (knots)
WAND_LENGTH = 1.4; % Trailing Wand Length (Meters)
MAX_ANGLE = 20; % Wand angle at 255 (degrees)
MIN_ANGLE = 50; % Wand angle at 0 (degrees)
ANGLE_OFFSET = 0; % Offset for angle data if required
PIVOT_HEIGHT = 0.0; % Height of trailing wand pivot above water at rest (meters)


load data.txt  % Loads the data file to the matrix 'data'
% Separates each sensors data
wind_dir = data(:,1);
wind_speed = data(:,2);
boat_speed = data(:,3);
wand_angle = data(:,4);

% Scales each value as required assuming bias is corrected by
% physical or electronic calibration
wind_dir = wind_dir./255.*WIND_DIR_SCALE
wind_speed = wind_speed./255.*WIND_SPEED_SCALE
boat_speed = boat_speed./255.*BOAT_SPEED_SCALE

% Calculate actual wand angle from input data and calibrated values
wand_angle = MIN_ANGLE-wand_angle./255.*(MIN_ANGLE-MAX_ANGLE);
% Calculate boat height from wand angle and length
boat_height                 =                WAND_LENGTH.*tan(wand_angle./360.*(2*pi))-
WAND_LENGTH*(MAX_ANGLE/360*(2*pi))

% Calculates an estimate of true wind speed using cosine rule
true_wind                    =                   sqrt((boat_speed.^2).*(wind_speed.^2)-
2.*boat_speed.*wind_speed.*cos(wind_dir./360.*(2*pi)))
```

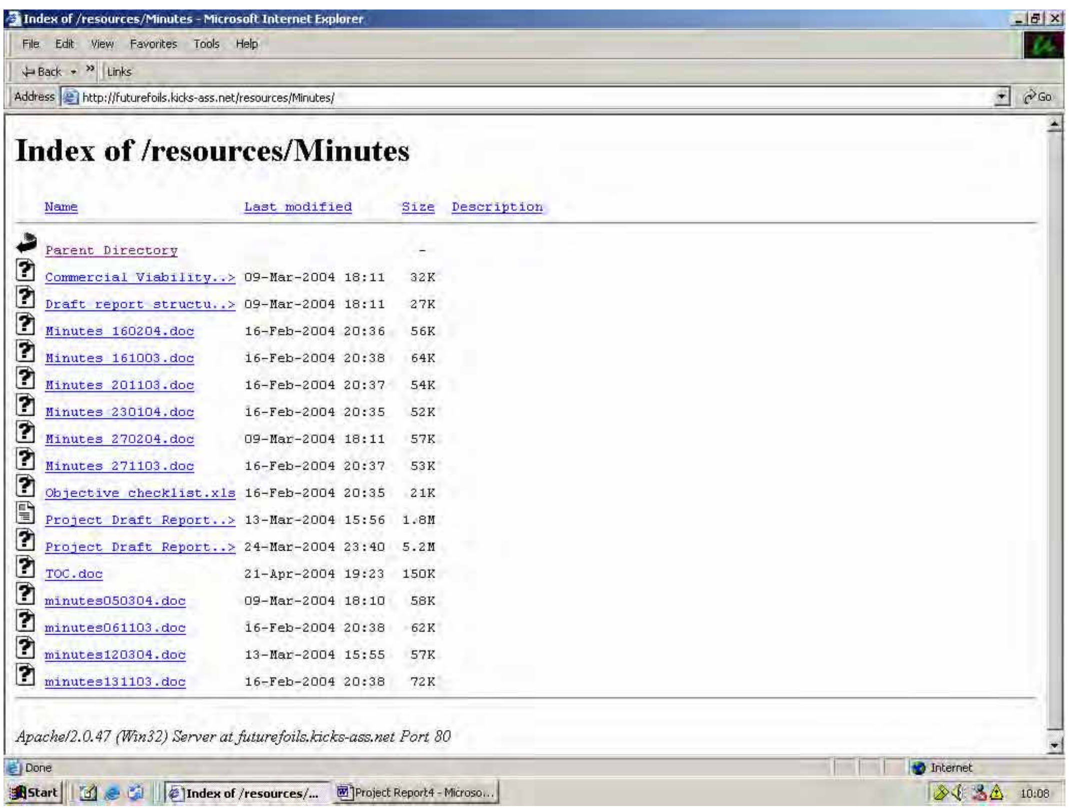
15.25 Appendix 12 - Screenshot of Future Foils Website




Future Foils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Links
Address http://futurefoils.kicks-ass.net/new/
FUTURE FOILS
THE HIGH SPEED FUTURE OF SAILING
THE UNIVERSITY OF WARWICK
Introduction
Sponsorship
Poster Presentation
Control System
Manufacturing - Hull Construction
Questionaire
Electronics
Previous Work
Boat Show
Links
Contact Us
Future Foils
The High Speed Future of Sailing
The Project…
Future Foils is a masters-degree engineering group-project initiative from the University of Warwick aimed at assessing the commercial viability of the use of hydrofoils in the UK dinghy sailing market.
The University of Warwick is an established centre of academic excellence. The Engineering department is no exception, there is a constant drive to improve and excel in all faculties of study. The Future Foils project follows the same ethos. This academic year, 2003/4, marks the start of the project, following on from an individual project completed last year studying the use of smaller scale hydrofoils in surfing and water-skiing (see 'previous work' – homepage).
8.26 x 11.69 in
1 of 4
Done
Internet
Start
Future Foils - Microsof...
Project Report4 - Microso...
10:09


Future Foils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Links
Address http://futurefoils.kicks-ass.net/new/
FUTURE FOILS
THE HIGH SPEED FUTURE OF SAILING
THE UNIVERSITY OF WARWICK
Introduction
Sponsorship
Poster Presentation
Control System
Manufacturing - Hull Construction
Questionaire
Electronics
Previous Work
Boat Show
Links
Contact Us
THE LONDON BOAT SHOW
INTRODUCTION
FUTURE FOILS 2003
The Future Foils Team spent Wednesday the 14th of January at the London Boat Show, a visit that not only provided a chance to gauge interest in the project, but also the input of external advice.
Everyone the Team spoke to was friendly, and helpful. It provided the opportunity to question experts on their feelings and thoughts.
The aim of the day was to find information out in the following areas;
- Current materials used in dinghy manufacture,
- Use of alternative materials to form other parts of the boat
- Manufacturing processes for current small dinghy's
- The pros and cons of windsurf/dinghy sails
- The chance to use a sail, in order to test the dinghy
- The 'concept boat' section of the show.
The Schroders FORTY NINTH LONDON BOAT SHOW
The project is focused on a sail powered hydrofoil boat; much of the research was therefore carried out in the small dinghy section.
MATERIALS
As a research project we have to explore every avenue. Materials that make boats are always changing. Much like the aerospace industry. Several companies manufacture the materials we would like to use for
Done
Internet
Start
Future Foils - Microsof...
Project Report4 - Microso...
10:11


Future Foils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Links
Address http://futurefoils.kicks-ass.net
Go
FUTURE FOILS
THE HIGH SPEED FUTURE OF SAILING
Website
Website (local) | Website (public)
Resources
Resources | Minutes | Private Resources
Ian's 3rd year project (zip) (files)
Timetables
Ian | Paul W | Kiran | Matt | Paul P | Tom C | Tom K || Derek | Tom G
Links
VIDEOS: International moths with hydrofoils
Australian International Moth Site
Internet
Start
Future Foils - Microsof...
10:00


Index of /resources/Minutes - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Links
Address http://futurefoils.kicks-ass.net/resources/Minutes/
Go
Index of /resources/Minutes
Name Last modified Size Description
Parent Directory -
Commercial Viability..> 09-Mar-2004 18:11 32K
Draft report structu..> 09-Mar-2004 18:11 27K
Minutes 160204.doc 16-Feb-2004 20:36 56K
Minutes 161003.doc 16-Feb-2004 20:38 64K
Minutes 201103.doc 16-Feb-2004 20:37 54K
Minutes 230104.doc 16-Feb-2004 20:35 52K
Minutes 270204.doc 09-Mar-2004 18:11 57K
Minutes 271103.doc 16-Feb-2004 20:37 53K
Objective checklist.xls 16-Feb-2004 20:35 21K
Project Draft Report..> 13-Mar-2004 15:56 1.8M
Project Draft Report..> 24-Mar-2004 23:40 5.2M
TOC.doc 21-Apr-2004 19:23 150K
minutes050304.doc 09-Mar-2004 18:10 58K
minutes061103.doc 16-Feb-2004 20:38 62K
minutes120304.doc 13-Mar-2004 15:55 57K
minutes131103.doc 16-Feb-2004 20:38 72K
Apache/2.0.47 (Win32) Server at futurefoils.kicks-ass.net Port 80
Done
Internet
Start
Index of /resources/...
Project Report4 - Microso...
10:08

15.26 Appendix 13 - Sponsorship Proposal

F u t u r e F o i l s

The High Speed Future of Sailing

The Project…

Future Foils is a masters-degree engineering group-project initiative from the University of Warwick aimed at assessing the commercial viability of the use of hydrofoils in the UK dinghy sailing market.

The University of Warwick is an established centre of academic excellence. The Engineering department is no exception, there is a constant drive to improve and excel in all faculties of study. The Future Foils project follows the same ethos. This academic year, 2003/4, marks the start of the project, following on from an individual project completed last year studying the use of smaller scale hydrofoils in surfing and water-skiing (see 'previous work' – homepage).

The aim of the project is to design a hydrofoil-based sailing boat that offers an exciting alternative to the conventional small dinghies. We aim to encapsulate innovation, design, manufacture and marketing within the project to produce a high quality prototype dinghy that makes a realistic step towards the exciting presence of hydrofoil technology in the common dinghy sailing market.

While previous attempts at designing hydro-foiling dinghies have been successful they have generally been one-off prototypes built by enthusiasts. An important component of the Future Foils project is the commercial viability of the finished product

The project is initially set to run for 3 years, based on the awareness of significant scope for continued development and engineering study.

This is the first year of the project and we hope to establish a foundation from which future years can build. The project is run as a mock small scale business venture as well as an academic exercise.

Future Foils is a diverse and exciting project, encompassing innovation and design, underpinned by prominent technical content

How you can benefit…

Advertising and media coverage

Web presence - As a contributor to the project, we aim to offer you publicity on our website, the address of which has been widely distributed to sailing groups over the past year and will soon have a link on the extensively used university homepage. Links to the sponsor's site will also be hosted if requested.

Logo display on our prototype will also be available, enabling sponsor publicity during test sessions at *Draycote Water* sailing club and in October at the country's premier speed sailing innovation event *Speed Weeks*. Further events such as those listed below will be considered in the coming years.

- Southampton boat show October 2004
- Speed weeks October 2004
- London Boat show January 2005
- NEC boat and outdoor show February 2005

Test results and a copy of the final portfolio report will also be available to contributors, although it must be made clear that intellectual property remains the right of the University of Warwick. The onboard data-logging unit will supply details of flying height, speed, direction (both for the wind conditions and boat) and stress / strain data from strain gauges in the foils, hull and hard points.

Recruitment opportunities

The Engineering department is renowned for producing high calibre students, and any association your company can have within the faculty will provide new potential recruitment avenues with students who may not have considered a future with your company.

All the members of the Future Foils Team will be actively seeking employment at the end of the project as they are all in their fourth and final year at the University of Warwick. Many are keen to find jobs in the marine sector, but others have their sights set on management, finance, or consultancy. The project setup hopes to encourage the development of many desirable soft skills including leadership, organisation, communication, and teamwork.

Involvement with an outstanding University

Warwick University has a world-renowned reputation, and is considered one of the top 5 universities in the country.

We hope that you can benefit from the association with our University, as well as being able to take pride in the fact that you have contributed directly to the success of Future Foils. The project offers the chance to not only develop a fantastic new innovation, but also see your product tested in greater engineering depth.

What We Need…

Sailing Equipment

The project focuses on the design of the hydrofoils, their control system and the method of attaching them to the hull. Design and manufacture of the rigging and sail is beyond the scope of the project for this year and we therefore intend to use an existing design that we can attach to our boat.

This is currently one of the most critical components of the project so far and although we are have access to a few second hand rigs. Ideally we would like to try a number of different setups over the future of the project. New, end-of-line products, last years stock, and even second hand components that you might be able to provide would be very gratefully received.

Materials

The construction of the hull, foils and nearly all components will be done by the team members in the University's Advanced Technology Centre (www.eng.warwick.ac.uk/atc/). With the many hours of lab work behind us, and experience of the ATC'S technicians on hand we will continue to work innovatively with composite materials. Our innovative GRP + Polypropylene honeycomb core hull construction is light and low-cost and most importantly, entirely new to the market!

We hope to build the foil structures and hard points for the craft from pre-pregnated carbon fibre using a rapid and accurate drawing to mould production method developed by the team.

Team Kit

When attending events and during testing we feel that a professional and serious image would greatly enhance the reception of our work. This could be anything from simple logo printed T-shirts upwards. We hop that these kits will:

• Help to raise the profile of the project
• Give the team a more professional image

• Identify the members of the team when appearing in public

Replies to our questionnaire

Our market research includes a questionnaire, which can be found here on the website. As the project is seriously interested in the market prospects for our project, we are trying to build a database of basic information from people involved in the market, from the sailing general public up to the professional sailing, manufacture and design level.

Responses would be very gratefully received, so perhaps as a final thought, you might be so kind as to e-mail the link round to members of staff in your organisation, friends, sailors etc.

We very much hope that you have enjoyed reading this brochure and are willing to give some help to the Future Foils team. If you feel that your company can help the team in any way, large or small, financially or otherwise, or if you're just interested, please contact us.

Contact us…

Matthew Caldwell (Sponsorship and Mechanics) – **Tel: 07855 211 416**

Website: http://futurefoils.webhop.net/

E-mail: future_foils@hotmail.com

15.27 Appendix 14 – Project Management Charts

15.28 Appendix 15 – Minutes of Group Meetings

Date:	Thursday 16th October 2003
Time:	15:00 – 16:00
Present:	I.D.Godfrey, S.Li, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.Gleadall, J.T.Looi, T.A.Carey, P.M.Wilde
Location:	A206A

Agenda

Finding a boat

- No luck online – too expensive
- Now focusing on directories and classifieds
- ‘Moth’ possibility – second hand ≈ £300 – also faster boats but more difficult to sail
- Topper not considered powerful enough
- Laser is only effective in high winds (>4 - 5 knots)

Proposed deadline – 30/10/03 (2 weeks) to:

1. Find a boat using contacts, directories and classifieds
2. Find transportation for boat – (laser trailer from sailing club, Tom K.)

Boat storage and workspace

- Potential space in main engineering building – none secured
- IMC not so helpful for space
- Roger Bull (helped last year with Ian’s project) is keen to help
- Support also found from IMC and ATC in manufacture

Aim

To claim a space in the main engineering building using posters, pictures photo’s etc.

Risk Assessment

- Contacted Clive Werrett - waiting for a response
- Risk assessment needs to be reviewed during project to highlight any changes

Aim
Review and use risk assessment from Ian’s third year project and Warwick University
Review risk assessment 17/10/03 (tomorrow), Kiran and Paul W.

Sponsorship

- Kiran’s Dad will circulate our project to the relevant people
- Tom G. has made some brilliant conceptual drawings of hydrofoils which will be used for presenting

Aim
Need some ideas and proposals documented with drawings to present to potential sponsors

Testing

- Not sailing club
- Draycote water looks promising
- Tom K. knows first year who sails moths and could help

Aim
Secure location to test the boat and find someone who will sail it (if required)

Boat

- Possible to build up own boat using windsurfing rig –
    - Tom C. has old windsurfing equipment which could be used
    - Ian has friends with old sailing equipment

Aim
Follow up these potential suppliers and monitor sponsorship possibilities

Manufacturing

- Most appropriate materials - composites: fibre glass and epoxy resins
- Manufactured using CNC machines
- Discussed Derek’s third year project aims
    - Look at sailing materials and manufacturing in general
    - Assume Ian’s design on one hydrofoil is being considered
    - Narrow processes down using CES and other resources

Time plan

- By 17/10/03 (tomorrow) send aims and objectives to Dr Chappell
- Poster deadline - end of term – possible to postpone and use London boat show instead for presentation venue
    - Waiting for a reply from boat show
- The project is handed in during Term 3
- Matt and Ian issued a time plan to all present
    - Due to time constraints the project will be split into four main areas of investigation

Title	**'Safe' Boat**	**Model Analysis**	**Manufacture**	**Testing**
Objectives	The manufacture of a 'safe' full-size working boat with hydrofoils to prove theory	The development of scale models to test variables and generate optimal design to obtain sponsorship	Manufacturing team to support both objectives ultimately developing a production plan for the optimal design	Electronic testing equipment to capture speed, ride height etc. and send it to land for analysis
Key Players	Ian Matt Kiran Tom G.		Tom C. Paul P. Derek	Tom K.

Aim

- Send email to Chappell detailing objectives and minutes
- Use technicians early (by week 5) when they are free
- Develop time plan with the use of Microsoft Project
- Optimistic getting entry to London boat show but will still pursue this and other events
    - Kiran has a contact with the IMechE

Tom G's project

- Look at how wind force transfers to forces on boat
- Hydrofoil force analysis – stability and speed
- Develop mathematical model on computer to optimise design

Testing

- Electronic testing on Boat
    1. Strain gauge
    2. Boat speed
    3. Weight of boat

4. Hydrofoil angles
5. Ride height / angle
6. Ride height variation

- Electronic testing on Land
    1. Wind speed
    2. Wind direction
- Testing tank could be used
    - 2 in Southampton, 1 in Newcastle and others exist

Aim
- Find possible testing tank
- Start research on electronic testing methods

Next meeting:

- “Hydrofoil theory” presentation by Tom G. and Ian.
- Review of progress on aims above

Date:	Thursday 23rd October 2003
Time:	15:00 – 16:00
Present:	I.D.Godfrey, M.Caldwell, T.J.Kennaugh, T.Gleadall, J.T.Looi, T.A.Carey, P.M.Wilde
Location:	ATC

The meeting described in the minutes below was an impromptu continuation of our Thursday meeting from this week. The opportunity arose to chat to Neil Reynolds and Mark Pharoah; two researchers from the university's ATC department that provided significant input to last years project. Mark and Neil sat down with us to discuss the material we have covered so far, and then took us into the composites lab to explain some of the material and manufacturing options that they can offer us

For those that missed this meeting, don't worry, Mark and Neil are keen to arrange a demonstration of hands on use of composite materials for the middle/end of next week. As not all were present, we delayed the discussion / presentation of basic fluid theory surrounding the project for next week.

Agenda

Project management

- Both Mark and Neil made the point that comprehensive management will help to maintain the project and to help all the team members to gain a good mark irrespective of whether completion of the boat design+build and testing is made or not.

Is our boat selection fast enough?

- Mark voiced further concern over the lack of speed available from a laser or boat of lower performance.
- It was ascertained that building a boat was not out of the question, especially if we worked from a basic design downloaded from the web (such as a Moth, see: www.moth.asn.au).
- Software – 'Hull Form' available to downloads for free from the web.
- With our own constructed craft, we could design for the foil attachment rather than risk extensive work modifying a bought craft.
- The craft could also be made cheaply.
- Neil suggested that we summarise the two design options; retro-fit / self build to enable reasoning behind a decision over the two options to be taken in two weeks time.

Aim

1. To assess the pros and cons behind a self-build in comparison to a retro fit approach to the project, in order to make a reasoned decision rather than one based on ‘word of mouth’.
2. Evaluate hull designs that ca be downloaded from the web.

Providing material to back the aim of our project theoretically.

- It was discussed that at this stage of the year in terms of the project time scale, we should be looking at some of the theoretical arguments for the use of hydrofoils on boats.
- Further discussion of how this work might feed into the design of our craft.

Aim

1. To begin work concurrent to the rest of the project begin researching and writing up topic.

Boat storage and workspace.

- Both Mark and Neil agreed that space in which to work and if necessary store parts of our project, would not be a problem, and that space can be made in the ATC if necessary.

Workshop tour and further discussion.

- Material types and processes that are available for use in the ATC.
- Referral to last years Formula Student based project to develop a ‘nose-cone’ for the car from polypropylene honeycomb core and GRP skin.
- Discussion of similarity between method of nose-cone production and possible hull form manufacture.
- Discussion of Marks model sailing boats, and the composite technology incorporated in the various designs.
- Basic information on the use of composite panels made from a core material and fibre+matrix skin.
- Basic hands on analysis of a few composite material examples to get a feel for weight and strength.

Aim

1. In conjunction with summary of commercial methods of foil production, begin evaluation of ATC offered methods of manufacture.

Date:	Thursday 6th November 2003
Time:	15:00 – 16:00
Present:	I.D.Godfrey, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.Gleadall, J.T.Looi, T.A.Carey, P.M.Wilde
Location:	A206A

Agenda

- Ian handed new minutes book to the secretary who was very pleased.

Manufacturing progress

- Flow chart outlining hull manufacturing process was produced
- Marketing information required

Aim

3. To produce flowchart for hydrofoil manufacture
4. Establish capabilities of CNC machine- will it accommodate the hydrofoil?
5. Establish complete material list and estimated cost (considering how much Mark and the ATC will contribute)
6. Construct a survey (using questionnaires and consultation) investigating the market/ competition and generate a commercial plan

3rd year progress

- Derek's making good progress
- Tom G. and Paul W. are going to work together on the dynamics of the hull and other mechanical issues

Electronic

- Focusing now on radio telemetry (system sending information from boat to shore)

Aim

1. Produce estimated price list for electrical components for next week
2. Strain gauge selection is now needed to be included in the design of the boat

Sponsorship

- London boat show (January) need something to show there, however, it could be very expensive
- Worst case scenario – no boat show - still keep to the suggested time plan

Aim

1. Ascertain how expensive the boat show will be to enter
2. Get Warwick to support our team there
3. Look for other boat shows that might be cheaper to enter – sailing magazines

Ian

- Produced a Gantt chart outlining the whole project. Each area of the project now needs to add their relevant details
- A variety of different logos have been produced which look promising – selection is needed for poster presentation etc.

Aim

1. Complete Gantt chart with each departments details
2. Select a logo and a team name
3. 500 words from each department detailing there work so far and future aims
    - This can then be used for the poster presentation, web site, report etc.
4. Photos of 3rd year project board assembly

Matt

Aim

1. Conducting an air travel experiment focusing on control mechanisms (this week)
2. Need to secure some tank time to test the variables associated with the hydrofoil. (end of week 9) – Birmingham University?

Poster Presentation

Aim

1. Look at other poster presentations in the ATC and around the workshops
2. Need to monitor progress and keep on documenting every action of the project to fill website, report, etc.

Date:	Thursday 13th November 2003
Time:	15:00 – 16:00
Present:	I.D.Godfrey, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.A.Carey, P.M.Wilde, S. Li
Location:	A206A

Agenda

Manufacturing progress

- Commercial / marketing information was produced from research
- Questionnaire produced for further marketing information

Action

7. Need to work with experienced sailor to ask the relevant questions
8. Display questionnaire on team website as well as other sailing areas / discussion / group pages – also ask certain companies, institutes to forward the questionnaires

3rd year progress

- Both tom G. and J.T.Looi were not present

Boat show (January 8th)

- Still considering the pro's and cons, Ian and Matt had meeting with Dr Chappell – He's going to have a meeting with Dr Price and Dr Rakels about the university of Warwick funding the event for our team
- Worried about the glamour and high expectations of the event – need to have a beautiful looking boat with all the commercial trimmings
- Will be an excellent vehicle for our project

Action

4. Possible funding from the a UK sports fund which promotes innovative ideas in sport (need to contact)
5. Waiting for a response from the NEC boat show (26th Feb), Tom K. has been previously – says very good, except the caravans.
6. Matt has visualisation of what the boat show set-up will be like
7. S Li suggested that an air flow model of the working hydrofoil will be much easier to display – we all agreed

Name and Logo

- Voted on 'Future Foils' as the group name
- Ian is working on different logo's

Model Testing

- Looked at rivers (1m deep) all around the Midlands
- Hopefully found one in Kingsbury (30 minutes away, North)
- Looking to complete by Wk 9
- Built an apparatus for testing the foil

Action

3. Continue developing the testing model

Website

- Control mechanism and Manufacturing information has been sent to Tom K. who has put it on the website
- Introduction is ready

Action

1. Put all other information up on the web by next week

Poster Presentation – 25th November

- Got enough information just need to collate it

Action

1. Look at other poster presentations in the ATC and around the workshops
2. Print on A1 printer in CADLAB and then laminate – will mean printing will be in-house
3. Put together all the different bits of information on one publishing package

Sailing and hydrofoil presentation

- Joddy Chapman will be giving a talk on some sailing and hydrofoil issues on the 8th or 9th of December

Action

1. Find a location for the presentation

Date:	Thursday 13th November 2003
Time:	15:00 – 16:00
Present:	I.D.Godfrey, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.A.Carey, P.M.Wilde, S. Li
Location:	A206A

Agenda

Manufacturing progress

- Commercial / marketing information was produced from research
- Questionnaire produced for further marketing information

Action

9. Need to work with experienced sailor to ask the relevant questions
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Date:	Thursday 27th November 2003
Time:	15:00 – 16:15
Present:	I.D.Godfrey, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.A.Carey, P.M.Wilde
Location:	A206A

Another discussion of things we have discussed before and really little progress was actually made as can be seen by the length of the minutes.

As an aside, I think having a meeting on Monday would be beneficial to plan the week ahead and a shorter meeting on Friday could be used as a review meeting of the week. Let me know what you think.

Agenda

Design and FEA

- Primary: Getting into boat, planning etc.
- Secondary: Foils
- Tertiary: Tacking, Jibing – capsizing
- Reverse proof of sail and hull design

Manufacture

- Hull form tool completed
- Foil design needed to ascertain material requirements
- Feasibility of using a CNC to manufacture hydrofoils
- Feasibility of using clay to manufacture hydrofoils – inaccurate?

Foils

- Pre-preg from formula student a possibility for foil material – heat resistant wood needed

Sail

- Wind surf sail could get from moth man
- Ian has a mast

Electronics

- Good progress has been made with the electronic systems

Date:	Thursday 27th November 2003
Time:	15:00 – 16:15
Present:	I.D.Godfrey, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.A.Carey, P.M.Wilde
Location:	A206A

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Electronics

- Good progress has been made with the electronic systems

Progress

Please refer to the attached objective checklist.

To my knowledge, not many objectives have been completed in the timeframe that we agreed on before Christmas. This is slightly worrying as Easter is fast approaching and other assignments and responsibilities are increasing. Please will everyone have a look at the objectives on the checklist and start to clarify and add any priorities that need addressing immediately.

Please also send any half completed or finished written material for the report as Tom and I will start compiling it now.

Date:	Friday 30th January 2004
Time:	12:00 – 13:00
Present:	K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, J.T.Looi, T.A.Carey, P.M.Wilde
Location:	A206A

Agenda

Production

- 75% of the honeycomb has been laid on the cavity tool
- Material will be used and then the total amount paid for – 3 sheets approx
- Windsurf pin needs machining
- Future foil colours for boat if coloured resin used

Action
Glassing boat Friday (06/02/04)
Cost sheet for materials for Mark
Front nose manufacture next week
CES selector for materials for report

Foil Manufacture

- Ian making clay moulds for foil this weekend

Action
Strain gauge placement needs to be considered

Sail

- Mothman possibility for sail but no mast

Action
Kiran and Paul W. going to see sail Saturday (31/01/04)

Design

- Design of foil now complete
- Trailing wand control system agreed on

Action
Mast location and bulkhead placement designed for Tuesday (03/02/04)
Need to agree on foil attachment

Need design of control system by next week

Web site

- More added looking good now

Action

Need to add more info to the website, send photos and info to Tom K. using **\\10.1.7.153\temp$**

Put foil doctor on as a resource

Date:	Friday 3rd February 2004
Time:	12:00 – 13:00
Present:	K.Asthana, P.J.Price, T.J.Kennaugh, T.A.Carey, I.D. Godfrey and Girlfriend
Location:	A206A

Agenda – Peer Assessment Wk 16

Material

- Hull weighs 38.9 Kg (Calculated)

Action
Need to ascertain who orders the materials and liaise with Mark

Foil Manufacture

- Mould evaluation this weekend
- Need 20% flap on the end of foil to support control system
- Manufacture whole and then cut in half attach with rubber hinge

Action
Strain gauge placement needs to be considered

Moth hull and extras

- Boat purchase completed
  - Plywood International Moth – Good condition
  - Good sail
  - Aluminium sail and mast
  - Carbon tiller
  - £550 with trailer

Action
Still get sail off Mark (for next year at least)
Need to find transport with tow hitch to Windsor

Design

- Good model on spreadsheets completed by Paul W.
- Trailing wand control system agreed on

Action
Find centre of effort of sail
Wind sensor placement

Bulkhead designs needed
Tiller design needed
Control system analysis – Kiran
Tom K. look at MATLAB for models
Strain gauge placement

Web site

- More added looking good now

Action
Need to add more info to the website, send photos and info to Tom K. using **\\10.1.7.153\temp$**
Need timeline of photos

Electronics

- Memory issues – need to flash the board
- Progress with sensors

Action
Need strain gauge placement

Report

- Week 8 deadline for draft report need 15,000 words

Action
1000 words each this week for

Kiran – Hull design
Tom K. – Electronics
Tom C. – Materials
Paul P. – Production
Paul W. – Modelling
Matt – Fluids section – planning vs. displacement
Ian – Project management

The report is marked by Dr Li need his input next meeting

Financials

- Over budget now - £1038 approx

Action
Talk to Dr Li concerning extra funding

Date:	Monday 16th February 2004
Time:	09:00 – 10:00
Present:	K.Asthana, P.J.Price, T.J.Kennaugh, T.A.Carey, I.D. Godfrey, P. Wilde, S. Li
Location:	F308

Agenda

Material

- Ian has justification for materials
- Honeycomb, glass and resin has arrived

Action

- Need to use CES to find material areas

Moth hull and extras

- Boat and bits now in the garage next to the ATC

Production

- Do bulkheads by eye

Action

- Refit last honeycomb panel
- Insert last honeycomb panel with pipe cleaners

Design

- Bulkhead can not be modelled on CAD
- Paul W. has the mast positions

Action

- Check mast placement with Paul W.
- Plan view with sail attachments and deck locations
- Need foam for buoyancy
- Drawing for rudder for Kiran’s dad

Electronics

- Joddy might have some information on sensors

Report

- Need a balance of short text passages and pictures, formulas

- Executive summary will not require the identity of the author on each page
- Technical report needs theory which is watertight and in our own words
- Put some language in (Paul W. Spanish?)
- Acknowledgements with helpers, suppliers, ATC etc.
- Need a good cover with a good picture
- Include number of hits on web page
- Need to include future work
- The financial section will not need too much detail
- Paul P. and Tom C. are the editors of the report and will compile all the different sections

Action

- Work out number of pages per chapter
- Proof read each others work

Financials

- Ian is buying boat so the budget is now back in the positive numbers

Date:	Friday 27th February 2004
Time:	12:00 – 13:00
Present:	K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.A.Carey, P.M.Wilde
Location:	A206A

Happy birthday to Ian for last Thursday – sorry its so late, hope you're feeling better now!

Please fill in the table saying when you will be at university in Easter on the second page.

Agenda

Design

- Designs for hull needed
    - Hull attachments
    - Control system

Manufacture

- Glassed both sides on schedule
    - Warped bulkhead needs attention (see Ian's email (29/02/04)
- Find out from Mark when it is appropriate to Glass inside of boat – concerns about vapour and smell affecting Corus staff
- Design mast mounting (hexagon)

Foils

- Production over Easter

Report

- Report structure is ok
- Organisational chart needed with relevant job roles allcated
- Questionnaires need to be distributed
- Send any documents you have written and any pictures you have to Tom C. and Paul P.
- **By Thursday 4th March**

Electronics

- List of deck fittings needed

Finance

- Send any payments / receipts to Tom C. and Paul P.

Date:	Friday 5th March 2004
Time:	12:00 – 13:00
Present:	I.D.Godfrey, K.Asthana, M.Caldwell, P.J.Price, T.J.Kennaugh, T.A.Carey, P.M.Wilde
Location:	CADLAB

Agenda

Manufacturing progress

- Awaiting delivery of resin
- Car filler will be used to fill the gaps between the bulkheads and the hull inside
- Investigate spray on latex
- Closed cell needed in hull cavity
- Tuesday afternoon – Paul W, Matt C, Ian G, Tom K, Kiran A

Electronic

- Speed sensor – Joddy or use impeller with reed switch

Report

- Ian will proof read the report
- Tom C. and Paul P. will compile the report over the weekend

Draft report section progress:

Ian G – No
Kiran A - Yes
Matt C – No
Paul P - Yes
Tom K - No
Tom C - Yes
Paul W - Yes

The Easter calendar will be distributed when I have all the dates from everyone

Date:	Friday 12th March 2004
Time:	12:00 – 13:00
Present:	I.D.Godfrey, P.J.Price, T.A.Carey, P.M.Wilde
Location:	A206A

Agenda

Manufacturing progress

- Foil moulds have been completed but are very heavy. Need collecting.
- Need sealant for these moulds (Spray-on latex?)

- Glassing of boat looking good
- Need to attach bulkheads with car body filler and then glass them in

- Need to order materials for attachments and nose
  - Stainless steel
  - Foam for nose
  - Glue for attaching deck (resin binder)

Draft Report

- Handed in report yesterday
- Have distributed a pdf version of the report

Financials

- Gloves - £5
- Other - £25

Hope everyone has a good Easter – stay in touch.