# N12 wing design & build

Graham Camm, Tom Lee, Nigel White
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## 1 Introduction

This guide is for anyone thinking of experimenting with design and/or build or a winged rudder. I had previously made wings back in the early 2000s and had found the amateur construction of the very thin wing sections tricky to get right. In 2016 I spoke with Tom Lee about how he had made the wings for his home built DCB. Tom described a method using Plaster of Paris to fashion the mould and he had impressive results. I borrowed his moulds and made a set of wings from them and also had good results. Buoyed with the success of this second attempt and having been sailing the Dead Cat Bounce design for a few years and got used to sailing with the wings I decided to add designing and building a new wing shape to the winter project list. After Jo Richards successful season in the DCB I asked him what he would change and he replied that he’s make the wings even bigger! Food for thought…

Graham Camm

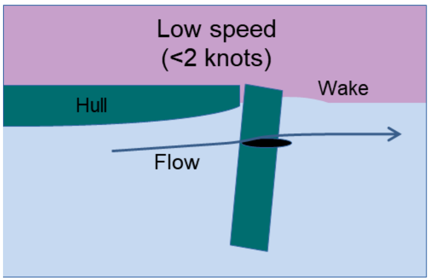
## 2 Designing the wings

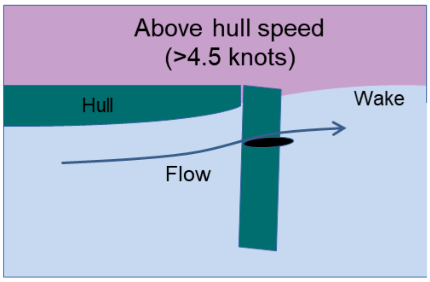
### 2.1 Design challenge

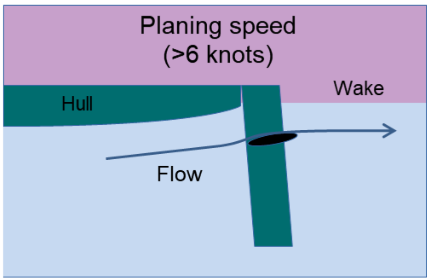
The wings on a 12 are a particularly interesting design challenge. Many hydrofoil craft are designed to operate at a specific speed, they will have a take-off speed and a cruising speed. For these craft the “flight parameters” are pretty constant at their cruising speed so it is relatively easy to optimise the hydrofoil design. On a 12 there isn’t a take-off or cruise speed so we’d like a wing that is optimal across a wide range of speeds. Ideally this means having a high lift co-efficient at low speeds and a low lift co-efficient at high speed (as the hull is doing quite a bit of lifting work when planning). Also we’d really like a wing that works well in reverse i.e. the mode where we are trying to keep the nose out of the water with the wing producing a downforce pulling the transom down. The ideal outcome is a pretty tall order and arguably impossible to achieve so the design needs to focus on a specific goal and then balance the trade-offs in performance outside the parameters of the goal.

The design challenge is added to by the fact that the wing position that appears to work on a 12 is where it is sitting in the stern wave, very close to the water surface. This means that the direction of water flow over the wing alters as the stern wave shape changes with speed. As the direction of flow changes so does the “angle of attack” that the water flow makes with the wings. At very low speeds the flow will be near horizontal. As the boat speed approaches the “hull speed” the flow will have a greater vertical component. According to Frank Bethwaite, at hull speed, the wave crest is exactly on the transom. The crest moves further aft as the speed increases with a massive increase in drag (what

Bethwaite calls the "forced mode") until the hull starts planning. In “forced mode” the boat is effectively sailing up-hill until it can get on the plane. It is in this range between hull speed and planning where the wake reaches its greatest with the stern wave resembling a rooster tail having a corresponding large upward component in the flow. Finally at planning speeds the flow will flatten out again. This change in water flow with speed is shown in the diagrams below. The series of pictures also show how the rudder tip is positioned forwards at low speeds making the wing horizontal and more in line with the flow. The rudder tip then moves further back as speed increases and amount of lift from the foil need tempering.




The diagrams below are three CFD plots modelled at similar speeds to the three diagrams above. These are modelled on the DCB bull shape and show the water flow in detail.

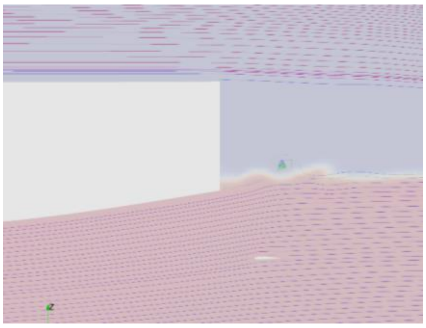


*Figure 3 Deep Foil at AoA 0 degrees (2 knots)*

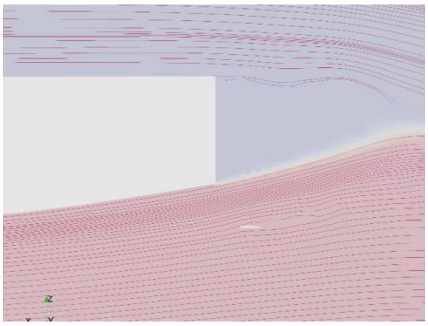


*Figure 2 Mid height Foil at AoA 2 degrees (4 knots)*

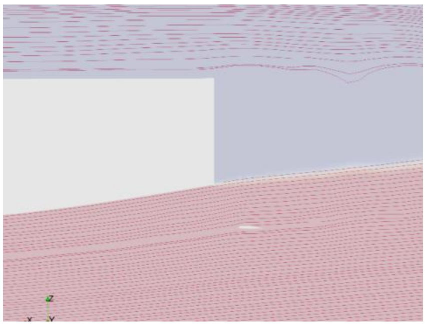


*Figure 1 Mid height Foil at AoA 2 degrees (8 knots)*

When mounting the wing onto the rudder blade, it is important to consider the angle of incident the wings make with the rudder. It is also important to consider how far below the water surface to position them.

When setting the angle, the aim is to ensure the correct angle of attack is achieved bearing in mind that the water flow behind the hull is not horizontal. At the same time the balance of the rudder needs to be right so the helm has the right amount of feel, not too light and not too heavy.

With the vertical position there appears to an advantage in getting the wings close to the surface as this has the greatest effect on the stern wave, but there is a trade-off as the closer to the surface they are then the less efficient the aero-foil will be and the more prone to cavitation/stalling it will be.

The series of CFD plots below show the effect the wing has on the stern wave at different depths and angles or attack.

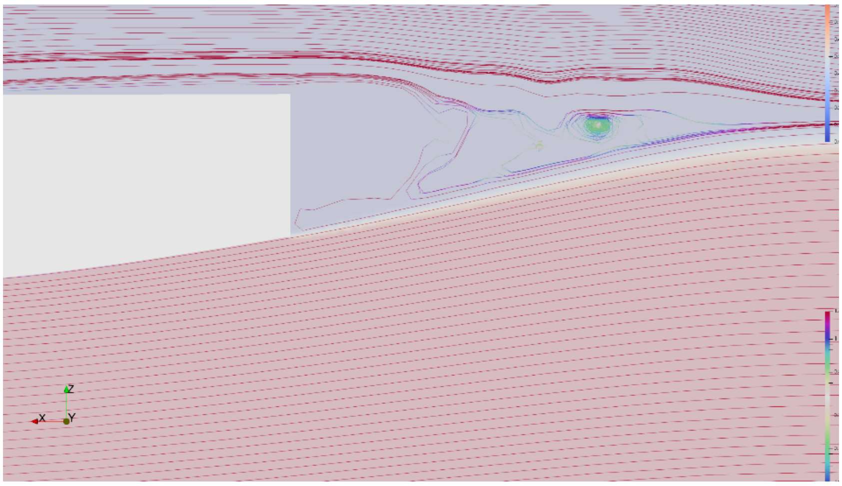



*Figure 4 - No wing*

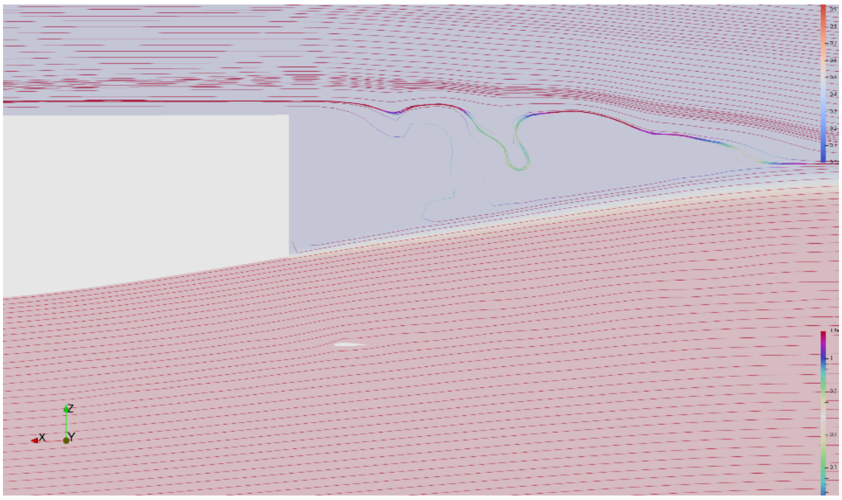



*Figure 5 - Deep wing (280mm from surface), Zero AoA*

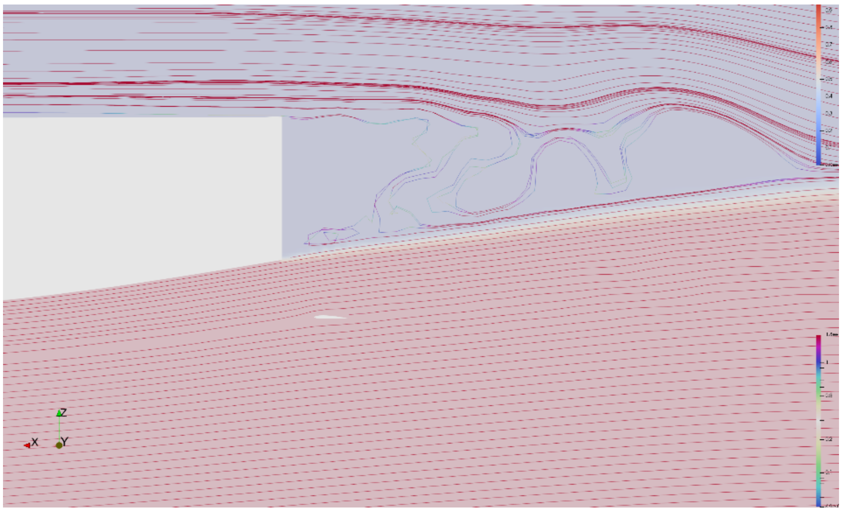



*Figure 6 - Mid height wing (180mm from surface), 2 degrees AoA*

The stern wave can be seen to flatten out be introducing the wings. The closer to the surface and the greater angle of attack of the wing then the flatter the stern wave.

**Hull speed definition (Wikipedia)**

Hull speed or displacement speed is the speed at which the wavelength of the boat's bow wave (in displacement mode) is equal to the boat length. As boat speed increases from rest, the wavelength of the bow wave increases, and usually its crest-to-trough dimension (height) increases as well. When hull speed is reached, a boat in pure displacement mode will appear trapped in a trough behind its very large bow wave.

From a technical perspective, at hull speed the bow and stern waves interfere constructively, creating relatively large waves, and thus a relatively large value of wave drag. Though the term "hull speed" seems to suggest that it is some sort of "speed limit" for a boat, in fact drag for a displacement hull increases smoothly and at an increasing rate with speed as hull speed is approached and exceeded, often with no noticeable inflection at hull speed.

## 2.2 Design goal

Having understood the environment that the wings are operating in it is now time to decide your design goal. Here are some potential goals to consider, you may think of others.

1. Create the same lift as current wings but with lower drag across the full range of speeds
2. Create the same lift as current wings across all speeds with lower drag at high speeds
3. Create the same lift as current wings across all speeds with for lower drag at “hull speed”
4. Create more lift than current wings for the same drag at “hull speed” whilst having a small increase in drag at very high speeds

I chose design goal 4 on the basis that most of the time the 12 is sailing at around hull speed. I also figured that very high speeds (>12 knots) are infrequently experienced and wing drag is probably the least of your problems in those conditions as the survival instinct kicks in.

Having decided the design goal there are number of parameters that can be varied during design and build. But note that only the Angle of Attack can be (easily) adjusted post build. When sailing the Angle of Attack can be used to increase or decrease lift noting that the drag will change with adjustments in AoA. During the design phase it is worth considering how close the Angle of Attack operating point is to the stall angle (the point at which the angle of attack is so great that the flow detaches from the wing and lift is lost), I’d recommend ensuring the operating point is a few degrees away from the stall angle to allow for 1) natural variations in flow direction that occur when sailing in waves and 2) to give you some flexibility should you decide you want some more lift – if you are already operating close to the stall angle then you have nowhere to go.

The design parameters include:

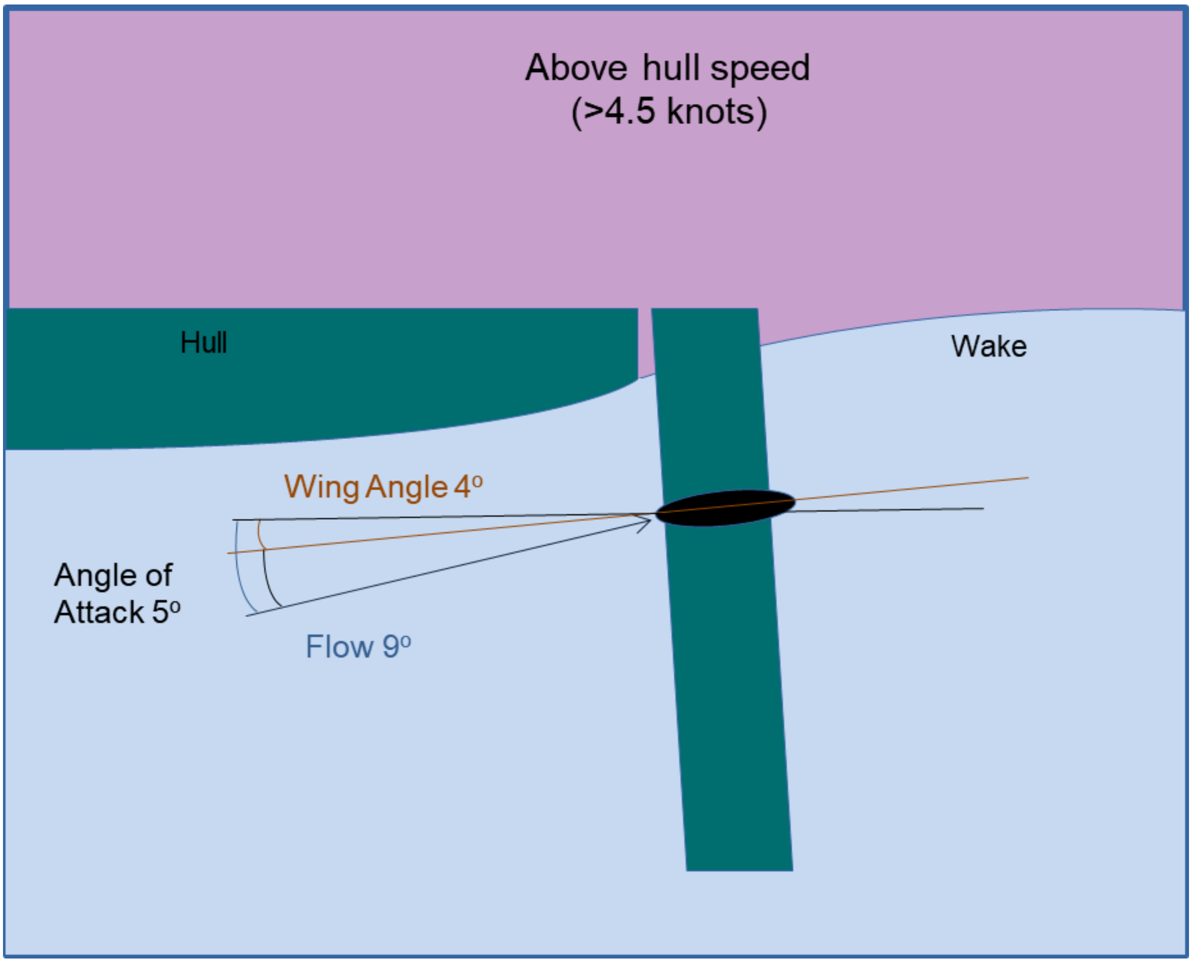
| Parameter | Impact |
|---|---|
| **Aero-foil section** | Some sections are optimised for specific speeds (Reynolds number) and will provide a high lift to drag ratio at that speed (i.e. high lift for low drag) whilst other sections will be low drag at high speed or low drag at low speed.<br><br>Some sections are tolerant to a wide range of speeds whilst others are tolerant to a wide range of angles of attack. |
| **Dimensions**<br><br>• Chord length (distance from leading edge to trailing edge)<br><br>• Wing length | The aspect ratio is measured by the wing length divided by the chord length and impacts the efficiency of the wing (drag). Gliders tend to have long thin wings which are good from a drag efficiency perspective but on a rudder has a trade-off against boat handling.<br><br>The area (Wing length x Chord length) affects total lift. |
| **Angle of attack** | Angle of attack combined with the wing area and foil section affects the total lift and stall angle |
| **Wing stiffness** | Stiffer wings will create more lift across the speed range but will be less forgiving and require more adjustment, whereas more flexible wings will automatically reduce lift as the boat accelerates. |

The wings can make the rudder feel heavy to the helm as it increases the drag on one side of the rudder as the wings are turned. The helm can be made to feel lighter by moving the centre of effort of the rudder forwards and closer to the rudder pivot point. The centre of effort can be moved in one of two ways:

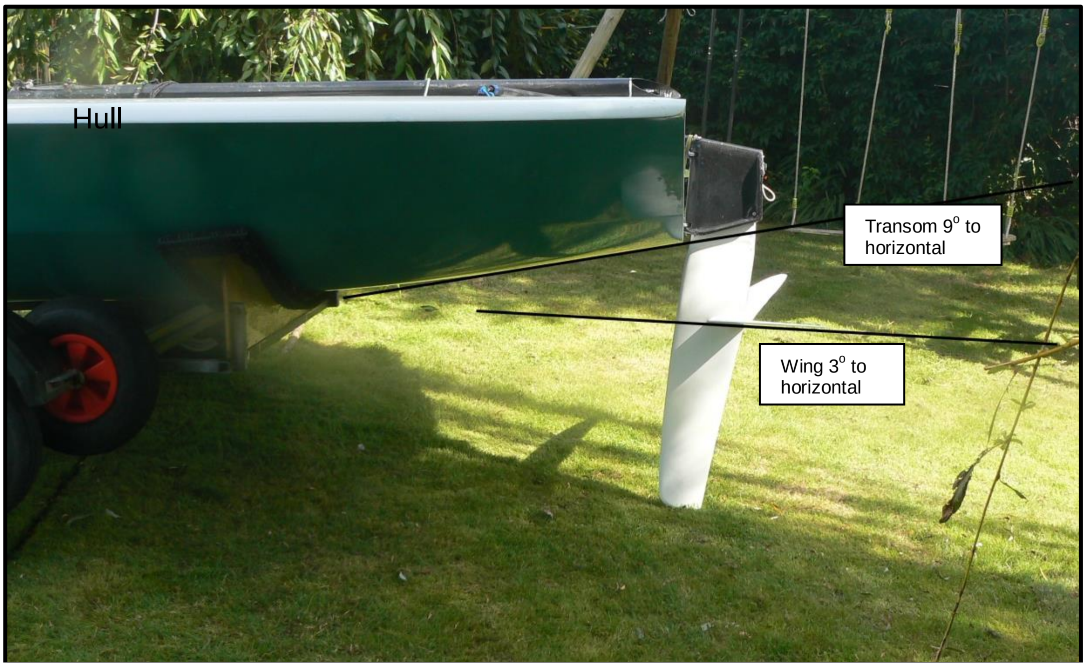
- Angle the rudder tip forwards to move the centre of effort forwards and closer to the rudder pivot point. Note angling the rudder forwards will change the AoA creating more lift.
- Shift the whole rudder blade forwards in the stock. This also moves the centre of effort forwards and closer to the rudder pivot point but without changing the AoA

The keen eyed may spot that the wings on 12 rudders are not mounted horizontal, instead they tend to be angled down slightly. This is to align them better with the stern wave flow which has an upward component at all but the very lowest speeds. If the wings were mounted horizontally, then the rudder would have to be angled back more, which would increase the heaviness of the helm.

Here's some tips on getting the alignment right. You should find the Angle of attack for the optimal lift:drag ratio (Cl/Cd) then estimate the water flow angle at you're the operating point you want to optimise and position your wing to that. As an example, say the optimum Cl/Cd is at an angle of attack of 5 degrees and say you want to optimise the wing for just above hull speed. You estimate the flow angle at this speed as 9 degrees. You position the wing to be at positive 5 degrees to the flow which means it should be 4 degrees from the horizontal. The example is shown in the diagram below




The photo below shows the actual angle when the rudder is in the maximum "on" position. At very low speeds the rudder is likely to be set to a horizontal position as this will create the least drag. As the boat picks up speed, at just a few knots, the wing can be pulled fully on and may be slightly above horizontal as shown in the picture below.



## 2.3 Selecting the aerofoil profile

There are many free sources of aerofoil sections and you could just chose one from the list or alternatively copy an existing wing section in use. If you want to try to design or optimise your wing then a software package such as the free, open source XFLR5 software would be a good place to start. This package allows you to analyse various aerofoil sections for lift and drag at different operating points i.e. combinations of different Reynolds numbers (influence by speed and chord length) and different angles of attack. See the references section for libraries of aerofoils and also the XFLR5 user guide.

It's all about Reynolds numbers. When modelling different aerofoils sections it is important to know the Reynolds number (Re). Re is a function of speed and wing chord. The foil modelling tools need to know the Reynolds number in order to predict the performance of the foil (lift / drag) at various angles of attack and for various aerofoil sections.

**Reynolds Number definition from Wikipedia**

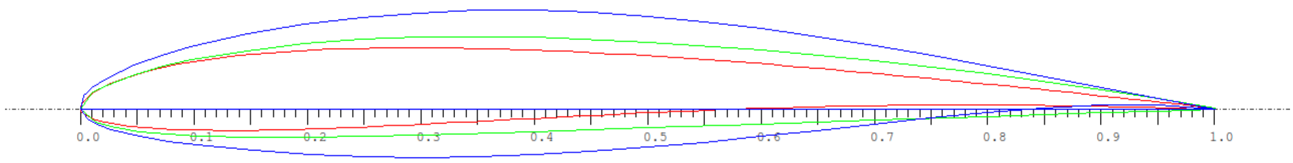
The Reynolds number (Re) is an important dimensionless quantity in fluid mechanics used to help predict flow patterns in different fluid flow situations. At low Reynolds numbers flow tends to be dominated by laminar (sheet-like) flow, but at high Reynolds numbers turbulence results from differences in the fluid's speed and direction, which may sometimes intersect or even move counter to the overall direction of the flow (eddy currents). These eddy currents begin to churn the flow, using up energy in the process, and for liquids increasing the chances of cavitation.

$$R_e = \frac{\rho V L}{\mu}$$

Where:
ρ is the density of the fluid e.g 1025 kg/m3
V is the velocity of the fluid, m/s
μ is the viscosity of fluid e.g. 1 $e^{-6}$ $m^2/s$
L is the length or diameter of the fluid. Profile chord e.g. 120mm

In the Twelve with foils of around 120mm chord the Reynolds number will vary between around 150,000 at low speeds to 700,000 at high speeds. The Reynolds number range doesn't get into a critical flow range so for the purpose of choosing an aerofoil section a mean Re can be chosen which is adequate to help to comparison and selection of a candidate aerofoil section.

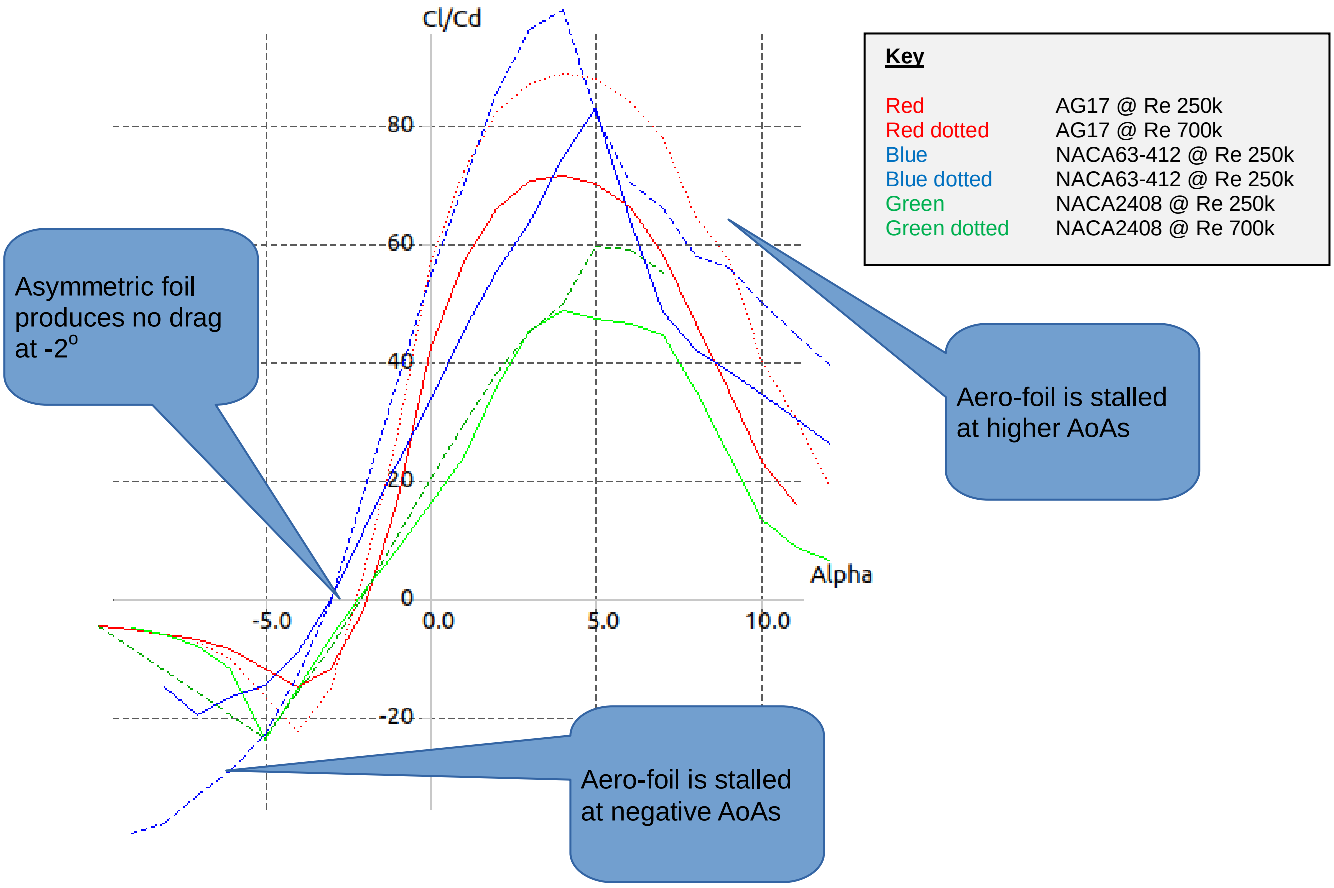
You can compare the physical foil sections as shown in the screen shot below. This shows the NACA 63-412 section (blue) which was common on Moths. This is a much fatter section than the NACA2408 (green) which is similar to that used on most National 12 DCBs. The AG17 foil (red) is the section I finally chose. Have fun going through the various sections available to make your own conclusion.




XFLR5 has a mode that allows you to load and compare the performance characteristics of different aerofoil sections, this is called “Xfoil Direct Analysis mode”. The graphs below show the XFLR5 analysis of the AG17 compared to the NACA2408 and NACA63-412. The graphs show the lift to drag ratio at different angles of attack (Alpha on the scale). Ideally you’d like to be operating at the highest lift:drag ratio at all speeds (REs). A foil that provides a large drag bucket will be tolerant and more likely to provide good lift:drag ratio across a wide range of speeds. A foil that keeps the coefficient of drag low across a wide range or REs will also be desirable.

Tips:

- Thin foils typically have a narrower drag bucket whereas thicker foils tend to have a wider drag bucket.
- A foil that is very asymmetric can produce a very efficient lift at moderate speeds but will likely create very high drag at high speeds where the angle of attack is zero or negative in order to reduce the lift.




What to look for in the graphs

1. A good ratio of lift to drag (Cl/Cd). The greater the coefficient of lift compared to the coefficient of drag the better.

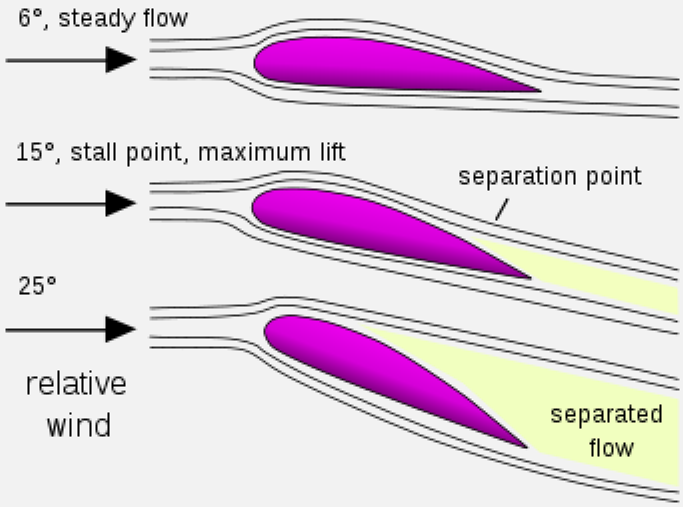
2. A wide drag bucket. The shape of the drag bucket is important to consider because a profile with a wide bucket is able to generate a good coefficient of lift across a wide range of operating points whilst keeping the coefficient of drag minimised. A profile with a narrow drag bucket will only operate with a low coefficient of drag over a much smaller coefficient of lift range.

3. The stall angle. This is an important consideration because this is the angle at which the flow detaches from the foil. When the flow detaches the drag increases substantially and the lift drops off. This will be speed dependant and appears to be between 7 and 10 degrees on most foils. It is visible in the graph above as the Cl/Cd drops rapidly.

The graphs above show that the Cl/Cd profile for the NACA63-412 (blue lines) has a high peak but it is a very pointy peak. This means that the foil will be very good operating at exactly that peak but performance reduces rapidly away from the peak. The performance for the AG17 (red lines) is more rounded and in pretty much all cases better than the NACA2408.

**Stall angle definition (Wikipedia)**

A stall is a condition in aerodynamics and aviation wherein the angle of attack increases beyond a certain point such that lift begins to decrease. The angle at which this occurs is called the *critical angle of attack*. This critical angle is dependent upon the airfoil section or profile of the wing, its planform, its aspect ratio, and other factors, but is typically in the range of 8 to 20 degrees relative to the incoming wind ("relative wind") for most subsonic airfoils. The critical angle of attack is the angle of attack on the lift coefficient versus angle-of-attack curve at which the maximum lift coefficient occurs.[4]

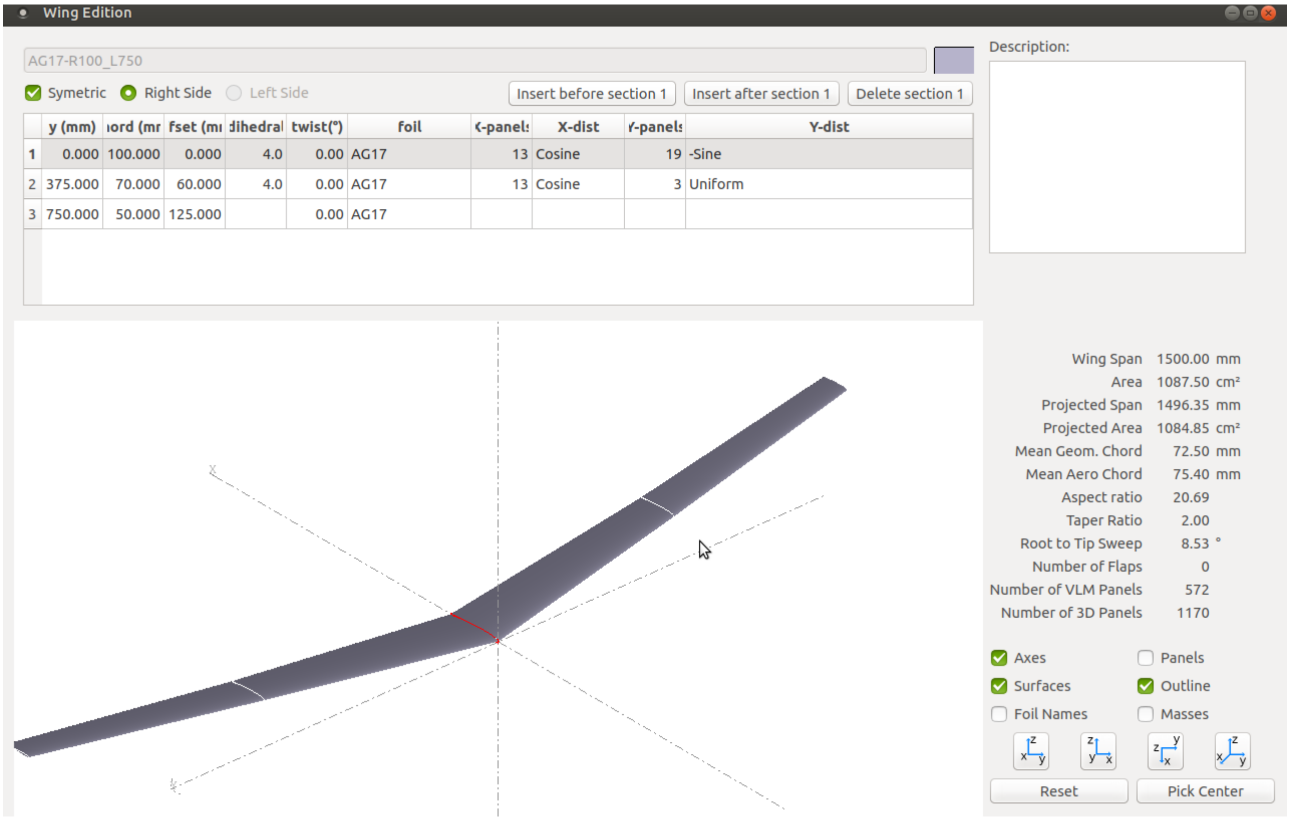



Flow separation begins to occur at small angles of attack while attached flow over the wing is still dominant. As angle of attack increases, the separated regions on the top of the wing increase in size and hinder the wing's ability to create lift. At the critical angle of attack, separated flow is so dominant that additional increases in angle of attack produce *less* lift and more drag

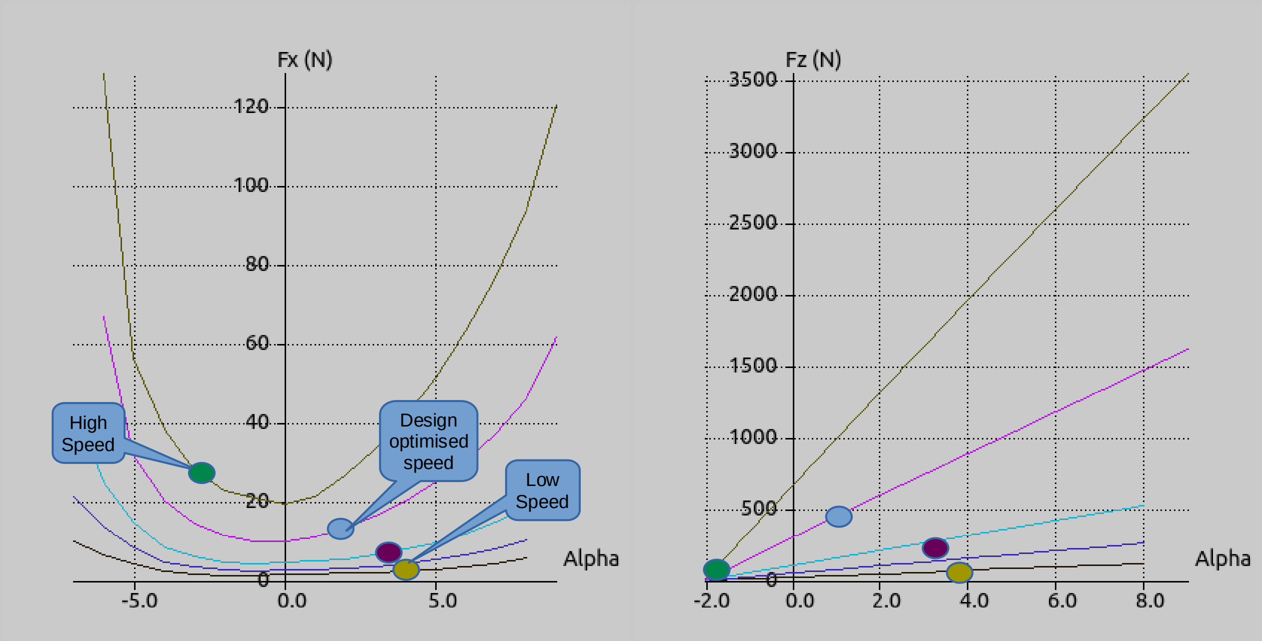
## 2.4 Designing the wing planform

The Cl/Cd graphs are a good aid to help select a candidate foil section but the analysis needs to move to the next stage to work out the right planform. It is the combination of aerofoil section and planform that will provides the actual lift and drag. The XFLR5 software will calculate actual lift and drag forces as shown in the graphs below (Fz – lift and Fx – drag.

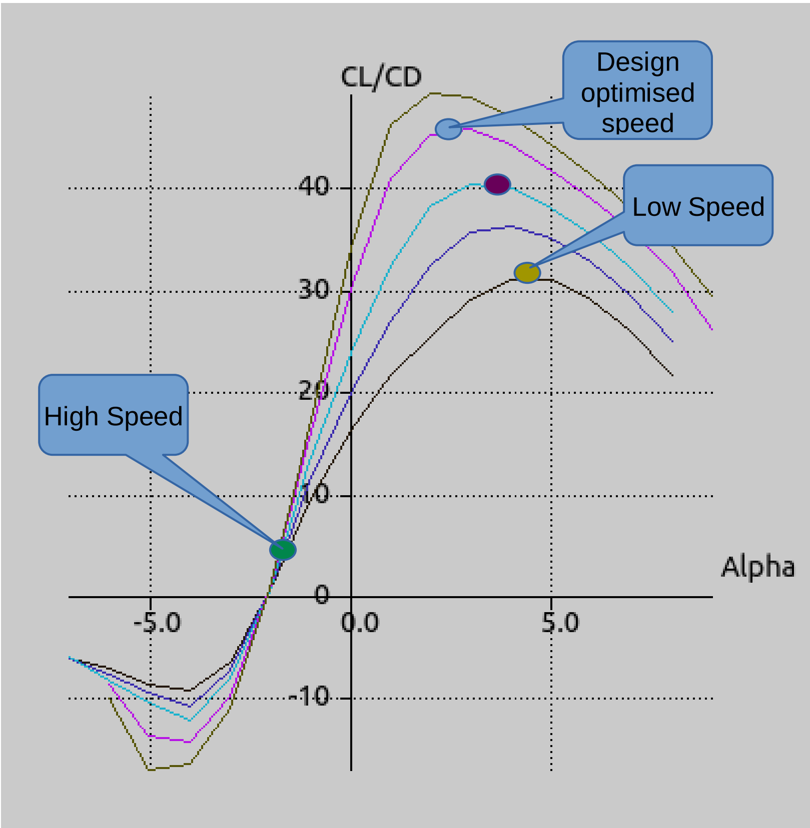
You can play with wing shapes to change the area and aspect ratio to trade-off lift with handling and efficiency. The dimensions to adjust are the wing span, root chord, tip chord, amount of sweep back and the way the foil tapers from root to tip. The screen shot below shows the modelled wing having defined the wing span and the chord at various positions along the length.




Having modelled the wing planform it is possible to analyse the actual lift and drag that the wing will produce at different speeds (Reynolds numbers) and angles of attack. The graphs below show lift (Fz) and drag (Fx) for the AG17 wing at various angles of attack. From this it is possible to work out the angle of attack you need to achieve the desired lift and from there you can measure the expected drag. You can also check that the angle of attack is not too close to the stall angle. You can analyse models for various planforms, comparing lift and drag at the angle of attack required. From this it is possible to work out which planform best meets the design goal.




The lines in the charts above represent the different speeds, brown being low speed and green the highest speed. From the graphs it is possible to read off the angle of attack required to achieve a desired vertical lift force (Fz) at a specific speed. The actual drag force (Fx) at that AoA and speed is found by reading Fx at the angle of attack required.




Ideally the wing would be operating at the peak of the lift:drag radio at all speeds, but inevitably the angle of attack will need to be adjusted to achieve the desired lift at the different speeds. The graph here shows the progression of lift:drag at the operating speeds along the lift:drag curve (see coloured dots). One of the optimisation decisions is how to overlay this progression onto the curves.

The aim should be to try and position the operating point at the speed you wish to optimise at the top of the Cl/Cd chart. This means the wing is operating in its most efficient manner at the desired operating point.

Note: All forces are in Newtons (N). To get the force in Kg divide by 10 (roughly)

At low speed it is best for the wing to be horizontal with a zero degree AoA as this position produces the least drag and in very low speed mode we are typically looking to minimise overall system drag and are looking for no lift from the wing.

To compare the performance of different wings (both the planform and aerofoil section combined) a table can be created with the operating points of interest. The lift and drag at those points can be measured off the graphs and then compared between wings. In the table below three wings are being compared to a NACA2408 reference foil – this was the existing section on my DCB. For the analysis the target lift is identified at each speed, then the angle of attack required to achieve this lift is read off the graph. The drag at that AoA can then be measured of the Fx/Alpha graph. The colour coding below indicates better (green) or worse (orange) drag at the same lift force.

| Wing | Speed | Low | Moderate (below hull speed) | Moderate (below hull speed) | Moderate (above hull speed) | High | Very High |
|---|---|---|---|---|---|---|---|
| | **Target lift (N)** | **92.0** | **200.0** | **256.0** | **395.0** | **460.0** | **0.0** |
| | **Speed (knots)** | 3 | 4.2 | 4.2 | 6 | 10 | 15 |
| | **Reynolds number** | 145,200 | 201,667 | 201,667 | 290,400 | 484,000 | 726,000 |
| **REFERENCE** | | | | | | | |
| **1 NACA 2408** | **Root: 115, Mid:100, Tip:45, Length: 585** | | | | | | |
| | AoA | 6 | 6 | 9 | 6 | 1 | -2.5 |
| | Drag (N) | 3 | 7 | 13 | 13 | 13 | 23 |
| **2 NACA 2408** | **Root: 150, Mid:110, Tip:65, Length: 650, Area: 1413cm2, Dihedral: 4** | | | | | | |
| | AoA | 4.3 | 4.3 | 6 | 4.2 | 0.6 | -2 |
| | Drag (N) | 3.2 | 6 | 8.5 | 11 | 13 | 29 |
| **3 AG 17** | **Root: 150, Mid:110, Tip:65, Length: 650, Area: 1413cm2, Dihedral: 4** | | | | | | |
| | AoA | 4.3 | 4 | 6 | 4.1 | 0.5 | -2.1 |
| | Drag (N) | 3.1 | 6 | 9 | 11.5 | 13 | 21 |
| **4 NACA 63-412** | **Root: 120, Mid:100, Tip:65, Length: 650, Area:1251cm/2 Dihedral:4** | | | | | | |
| | AoA | 4.2 | 4.1 | 6.1 | 4.1 | 0 | -2.2 |
| | Drag (N) | 4.3 | 7.3 | 9.5 | 13 | 16.5 | 26 |

The results above are a limited selection from the scenarios I ran but they help to demonstrate the sort of analysis that can be done. The figures show that when increasing the size of the NACA2408 wing (2) it is possible to reduce the drag at moderate speeds relative to the reference wing (1). The penalty however is a significant increase in drag at very high speeds (highlighted orange)

The NACA63-412 (4) exhibits good drag performance at moderate speed but is not so good at either very high or low speeds (yellow). Increasing the wing area will only make the drag at high speed worse as the AoA will have to be reduced further into negative numbers.

The AG-17 (3) wing shows improved drag across the board with the largest improvement at moderate speeds which was the design goal. The area for this wing is about right to achieve the target lift at the AoA for moderate speeds is between 4 and 6 degrees which means the aerofoil section is operating at the peak lift:drag ratio.

# 3 Making the wings

## 3.1 The need for a mould

When making a normal rudder it is fairly easy to start with a sheet of wood or foam to make the core. It is possible to plane and/or sand this to shape and then lay carbon over the top for some extra strength. This method works fine on a normal rudder profile as it is reasonably thick. Wings on the other hand are a much thinner section and because they are thinner the profile needs to be accurate to a fraction of a millimetre so small differences matter. For this reason I'd recommend making a mould first rather than trying to shape the core material. It is easier to get the shape of a male plug right when using a material such as poly-filler or plaster – it is also much lower cost and easier to patch if you make a mistake.

Having said that accuracy is important, there are a wide range of aerofoil sections out there that vary in shape quite a bit and the performance doesn't appear to varying hugely. The most important parts of the wing to get right are the lead edge radius and achieving a smooth and continuous curve over the other sections.

## 3.2 Making the mould

The basic approach for making the mould is to start by making a male plug out of an easily formed material such as plaster or poly-filler. From this male plug a female mould can be created that is robust enough and stiff enough for you to lay up the carbon fibre into. The female mould will need to be able to stand a temperature of around 40 degrees without distorting whilst the carbon is being cured under a vacuum and with heat applied.

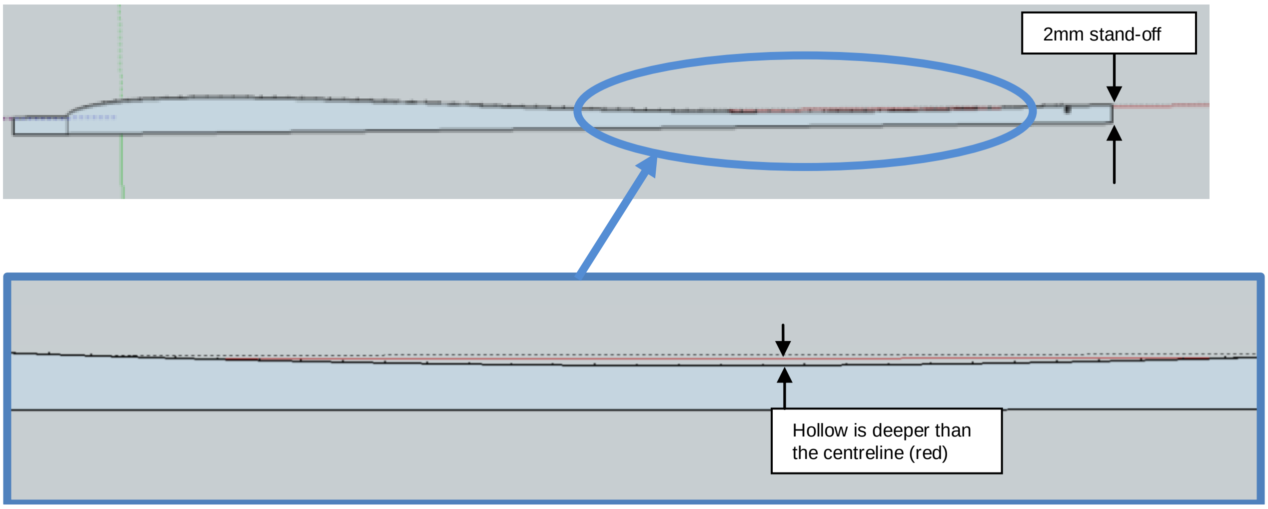
If making a mould sounds like a bit of an ordeal but you still want to have a go at making some wings then contact Graham Camm or Tom Lee, we are happy to loan out our moulds. Alternatively it is possible to make wings by fashioning the core from a piece of ply-wood and numerous National 12 wings have been successfully made this way.

**Step 1. Create the male plug**

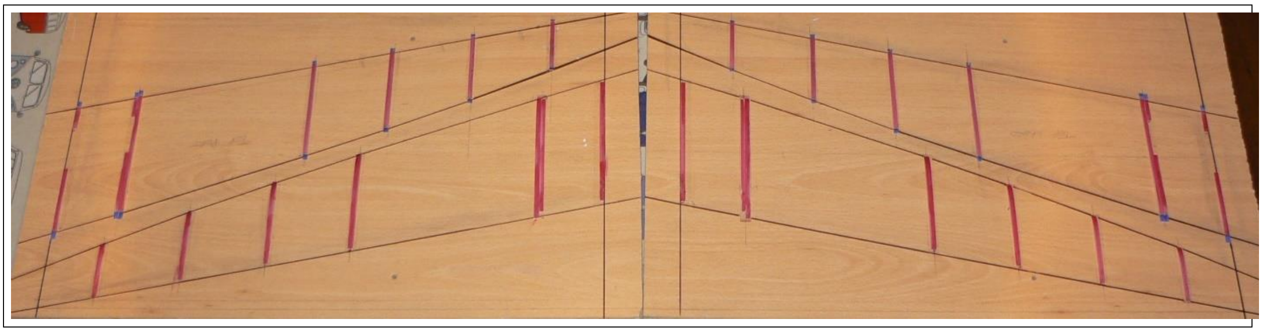
1.1 Create templates at sections

Having done your design work (see section above), transcribe the profile sections onto templates for a number of stations along the aerofoil. It is possible to make wooden templates by printing out the aerofoil profiles on paper and sticking these to the wood (MDF is best) then cutting and sanding the shape. But it is difficult (although no impossible) to cut and sand to 0.2mm. As an alternative the templates can be 3D printed, this involves using a modelling package such as Google Sketch up to create the 3D model. Note that depending on the aerofoil section you choose you may find that the lower side of the section has a hollow that is deeper than the centre-line of the section. If this is the case then you will need to allow a stand-off to cater for the hollow.

This diagram shows the template of the male mould for the lower section. The red line indicates the centre line. The second picture is a close up of the hollow area and shows the hollow going past the centre-line more clearly. To accommodate this, the mould has a 2mm stand-off all over.




1.2 Stick the templates onto a base board



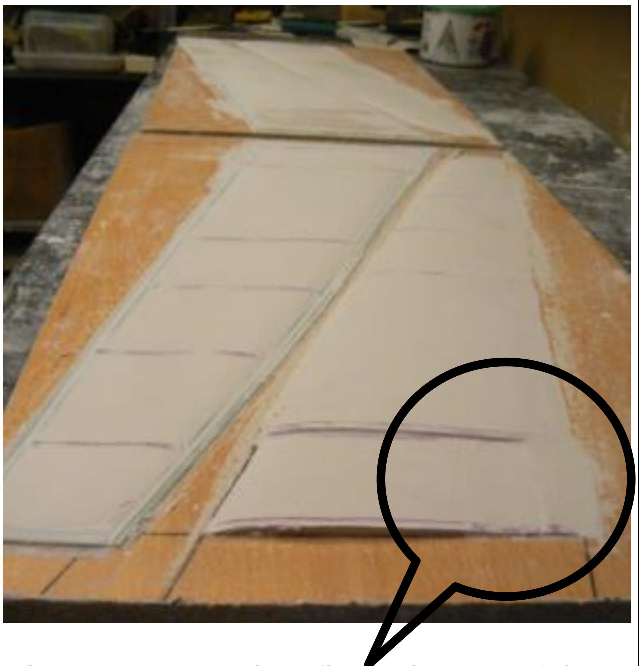
**Above**: Plan view of the templates attached to the base board using double sided tape. Note the desired shape (plan view) of the wing has been drawn out as an outline for the templates to be positioned into.

**Left**: Side view of templates taped to the base board

**TIP**: Check and double check that you have the correct pairs marked up. You need both starboard and port topsides and both bottom sides. This means that each of the four pieces will have a different shape. It is a pain if you get this wrong as it means starting again.

1.3 Fill the space between the sections

Fill the space between the template sections using plaster or poly-filler. Run a straight edge along the templates in order to scrape the poly-filler to the contour of the templates



**Above**: Recessed profile at the root of the wing

**Above**: Plan view of male plug with template sections filled. The white powder/residue on the work surface shows this is a bit of a messy job.

**Left**: Side view of male plug. The recess at the root of the top wing section can be seen here. This recess will allow the wings to be joined together and also joined to the rudder without the joint building proud of the desired profile.

1.4 Allow the filler to set

1.5 Sand to a smooth and fair finish

1.6 Check the profile

Check the profile using separate templates placed along a number of stations. The aim is to ensure that the plug is smooth and even along the chord. Next check the profile along the length of the wing using a straight edge. Again the aim is to ensure that the plug is smooth and even. To do this, rest the straight edge on the section templates to check for low spots and high spots. Add additional filler or sand down until there are no high or low spots.

**Step 2. Make the female mould**

The female mould is made using the male mould as a plug

<table>
<tr>
<td>
2.1 Apply a mould release wax to the plaster male plug. Follow the instructions on the tin. Apply at least 4 layers to ensure the mould won’t stick.<br><br>
2.2 Lay-up cheap chopped-strand glass fibre and a polyester resin over the plug. Lay the fibre matting over the mould then wet-out using the resin. Chopped strand is good for following a shape and getting into corners but it might need some encouragement with a brush to make nice tight edges.<br><br>
TIP: Fastglass car repair GRP can be used for this. The mould should be at least 5mm thick so it is rigid enough that it won’t distort when laying up the final wings.<br><br>
2.3 Once set, pop the plaster male plug out of the female mould. I had to chip some of the filler out but it came out fine without damaging the female mould.<br><br>
2.4 Using fine wet and dry sand paper, fair the mould then polish
</td>
<td>
<br><br>
Above: Finished female mould. The brown filler is where the mould was a bit rough and needed a little filling to smooth it off.
</td>
</tr>
</table>

## 3.3 Laying up the wings

When laying up the wings it is possible to change the stiffness of the wings. The two layups I've tried are described below. There is a lot of force around the joint of the wing with the rudder blade. For this reason I'd recommend filling the aerofoil section with a solid epoxy filler mix within 30mm of the joint on both the rudder blade and wings. If this area is left as foam there is a risk that the foam will be crushed and joint weakened.

| Flex properties | Lay up |
|---|---|
| Very stiff | 100% 200g/m2 carbon weave<br>100% 200g/m2 carbon uni-directional x 3<br>40%  300g/m2 carbon bi-axial |
| Moderately flexible | 100% 200g/m2 carbon weave<br>90% 200g/m2 carbon uni-directional x 2<br>40% 300g/m2 carbon bi-axial |

* The percentage indicates how far down the blade the material went, starting at the head.

**The steps for wing manufacture are**

1. Wax the mould using a mould release compound. Apply at least 4 coats as you really don't want the wings to stick into the mould permanently!
2. Lay in the carbon weave and wet out
3. Lay in the carbon uni-directional  to achieve the desired flex (see table above for inspiration)
4. Vacuum bag and allow to cure
5. Apply epoxy filler mix to the profile 30mm at the root of the wings to create a solid joint

**Right Top:** Peel ply being removed from the wing skin

**Right Bottom:** The wing skin, laid up and still in the mould

6. Fill the wings with foam

There are two options for filling with foam the first is to fill each side (top and bottom) separately, allow the foam to set then flatten the foam and bond together. The second method is to fill each side with the foam mixture then clamp the two sides together before the foam sets. Both methods work. The first method has more steps and is more time consuming but allows time to position the top and bottom correctly when you bond them together. Whereas the second method is quicker and cleaner but it is not possible to tell if you have bonded the two sides in the correct position until the foam is set by which time it is too late to do anything about it.

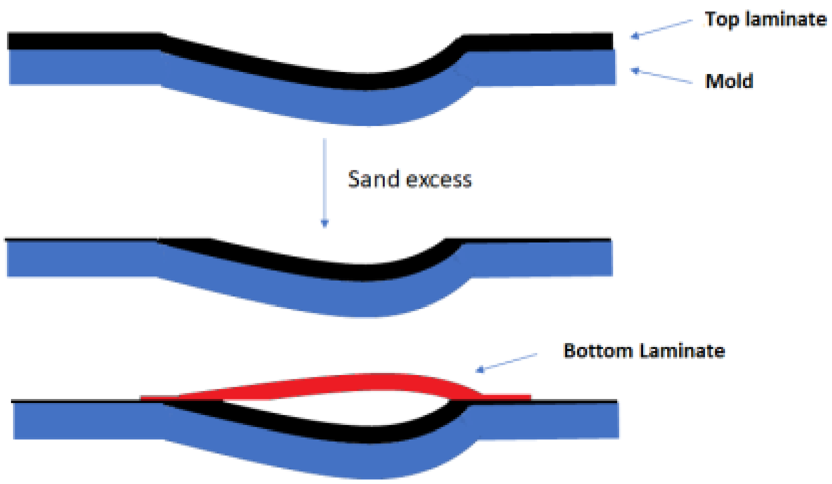
6a Filling the wings method 1 – fill the wings separately and bond later

a) Fill the four sides (top and bottom pairs) with epoxy foam
b) Allow the foam to rise and set
c) Sand the foam flat
d) Check flatness with a straight edge looking for bumps and hollows
e) Bond the top and bottom pairs together using an epoxy bonding mixture (including micro fibres) and allow to cure
f) Before doing the final cure, check the profile is the correct shape. Look along the leading and trailing edge and check these are straight. Use a section template to check the profile is correct at a few stations along the wing. If the profile isn’t quite right in places then it is possible to heat the area up to say 80 degrees briefly, the carbon and epoxy should soften allowing you to correct errors. Hold in the correct position until the material has cooled
g) Heat the wing to 40 degrees for 6 hours to allow the foam to full cure. If you don’t do this then the foam won’t be fully set and there is a risk that the wing will deform.

6b Filling the wings method 2 – fill the wings in one operation

The wings can be filled with foam in one operation which saves time and probably a bit of weight as it removes a bonding operation.

a) First thing is to measure the internal volume of the wings. This can be done by filling each half wing with fine sand, the sand is levelled using a straight edge
b) Then pour the sand into a measuring jug to find the volume.
c) Calculate the amount of the two components of the foam needed using the expansion factor given in the instruction and add 20%. For example, if using PB170, the expansion factor is 6.2 so for a volume of 1L, we need 1/6.2=0.161Kg, add 20% so we need 193g of mixed resin.
d) Put the two halves in their respective moulds and sand the excess laminate on the edge flat; go as thin as you dare while still leaving some material.




e) Most of the excess material is trimmed from the bottom half (make sure there is still a bit of excess left all round).
f) Carefully align the bottom laminate onto the top laminate and make some marks so the alignment can be reproduced easily and accurately.
g) Place the top laminate level on the bench in its mould.
h) Mix the two components of the foam and pour into the top laminate through a sieve, evenly over the whole length of the wing. Do not attempt to spread it once poured as this interrupts the foaming process!
i) Put the bottom laminate on top using the alignment marks and tape in place with parcel tape
j) Carefully put the bottom mould on top and clamp the two halves all the way along the edges. I used lots of bulldog clips for this.
k) Apply heat and leave to cure.
l) Once cured (6-12hr @40C) the wing can be taken out the moulds and trimmed.

**Tip:** once you have started to mix the foam, you have approx. 4 min to finish pouring if this is exceeded you are likely to end up with a very sticky mess.

7. Finishing the trailing edge

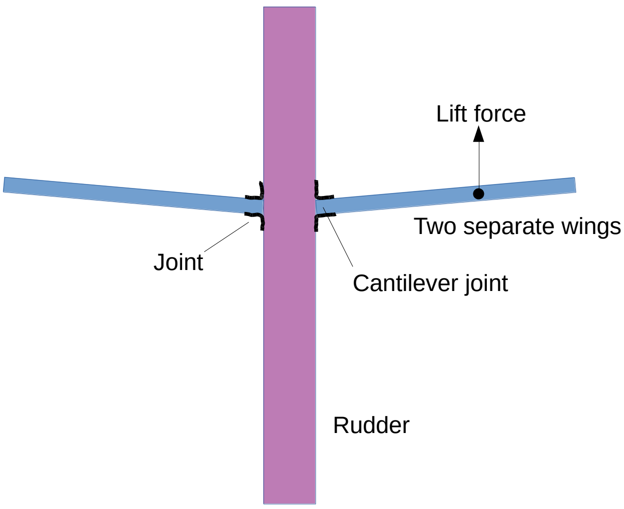
A good quality trailing edge is important in order to ensure the flow separates cleanly and avoid vibrations. The trailing edge should be less than1mm (1mm is good for strength) and should be nice and square. The trailing edge should not be rounded as this encourages the flow to leak between the high pressure (underneath) and low pressure (top side) and often results in vibrations. A square edge can be achieved by using a file.

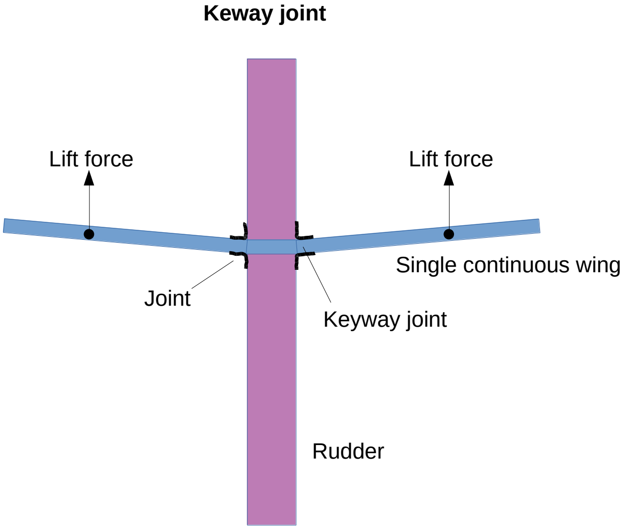
## 3.4 Options for bonding the wings to rudder blade

Obviously before embarking on this step you'll need to make the rudder first. There are some good instructions on the National 12 website [www.national12.org](http://www.national12.org) for making rudders. Note significant carbon reinforcement is needed from the head of the rudder blade through to 50mm below the wings; this is because the wings create a significant additional load on the blade which peaks at the waterline. Below is the layup I've used for the rudder blade, the percentage indicates how far down the blade the material went, starting at the head.

- 100% 200g/m2 weave
- 100%  200g/m2 uni-directional
- 80%  200g/m2 uni-directional
- 60%  200g/m2 uni-directional
- 50%  200g/m2 uni-directional - along a 100m band from head to 50mm below wing joint
- 50%  200g/m2 uni-directional - along a 100m band from head to 50mm below wing joint
- 50%  200g/m2 uni-directional - along a 100m band from head to 50mm below wing joint
- 50%  200g/m2 uni-directional - along a 100m band from head to 50mm below wing joint
- 25%  300g/m2 bi-axial * this should go 50mm below the wing joint
- 20%  300g/m2 bi-axial

There are a number of methods for joining the wings to the rudder and a variety of positions for wings. The joining methods include 1) cutting a keyway and slotting the wings into the rudder, and 2) bonding the wings on to the blade each side as a simple cantilever. The table below illustrates these methods and describes the trade-offs.

| | |
|---|---|
| **Method 1 - Cantilever joint**<br><br>The diagram illustrates the cantilever attachment method. This method doesn't weaken the rudder blade but has the downside that the wing joint is weaker. The lift force acts as cantilever force and tries to peel the wing joints off the rudder blade. This peeling action can be limited by "sewing" the wing joints onto the rudder blade as described later in this guide. | **Cantilever joint**<br> |

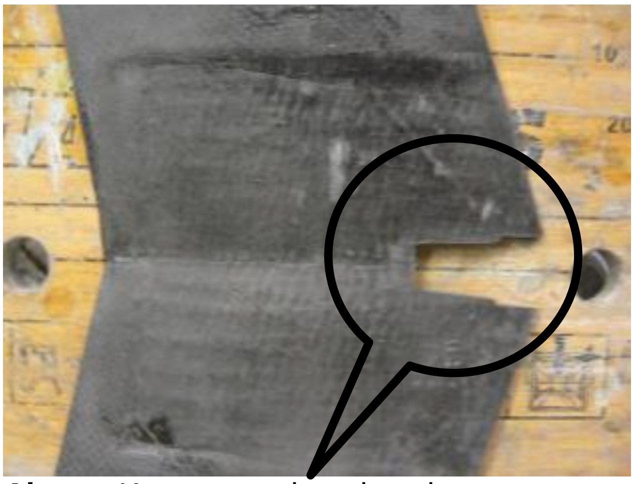
| | |
|---|---|
| **Method 2 - Keyway joint**<br><br>The diagram illustrates the keyway attachment method. This method weakens the rudder blade slightly but has the bonus of making the wing joint much stronger. The joint is stronger because the lift force is transmitted and balanced from both wings through the joint. So the wing is being “bent” evenly around the rudder joint.<br><br>There is less of a peeling action with this attachment method compared to the cantilever method.<br><br>Having had a homemade pair of wings rip off a rudder in the past I’m in favour of method two (keyway) for the additional joint strength it provides. |  |

## 3.5 Bonding the wings to the rudder

**Step 1 If using a keyway joint then start off by bonding the wings together**.
If using the cantilever method then skip this step and go straight to step 2.

| | |
|---|---|
| The steps for joining the wing together are:<br><br>1. Position the wing at the angles required; correct sweep back and dihedral<br><br>2. Bond the two sides together using an epoxy bonding mixture (including micro fibres) and allow to cure<br><br>3. Laminate 4 layers of Carbon UD 200g/m$^2$ across the top and bottom for at least 80mm either side of the joint as shown in the diagram to the right<br><br>**Right:** Close up of the Wing sides bonded together with carbon UD reinforcing the joint. The recess for the wing to rudder reinforcements can be seen | <br><br> |

4. Cut the key slot in the rudder blade at the correct angle down (toe down)
5. Cut key slot in the wings
6. Check the two pieces slot together

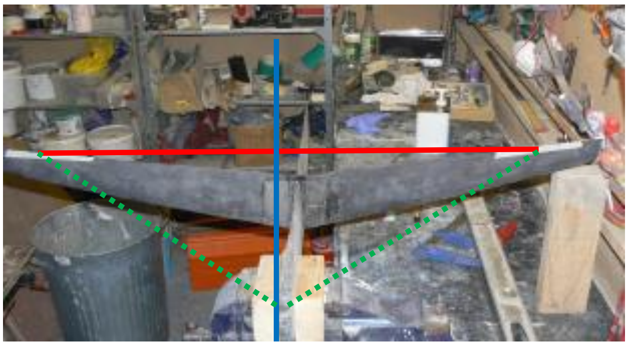


**Above**: Keyway cut into the wings

**Above**: Keyway cut into the rudder blade

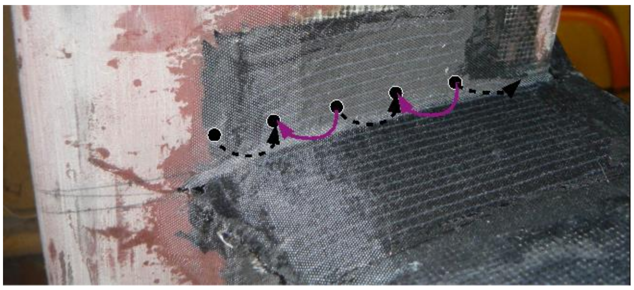
**Step 2 Join the wing to the rudder blade**

1. Bond the pieces together using an epoxy bonding mixture (including micro fibres). Ensure the wings are horizontal and even.
    - Measure from wing tips to the head of the rudder blade and ensure this measurement is the same both sides.
    - Use a spirit level to ensure the wings are horizontal and perpendicular to the rudder



**Above**: Aligning the wings to the rudder.

The blue line indicates using a spirit level to set the rudder head to vertical.

<table>
<tr><td></td><td>The red line indicates using a spirit level to set the wings to horizontal.<br><br>The green dotted lines indicate using a tape measure to align the wings so the tips are the same distances from the centre of the rudder head.<br><br><br>Above: Wing to rudder blade joint.</td></tr>
<tr><td>2. Laminate 4 layers of Carbon Bi-axial 300g/$m^2$ on each of the four joints for at least 50mm either side of the joint.<br><br>Note bi-axial is a great cloth for this job as it goes around corners well giving a nice tight radius and is also excellent for resisting the twisting forces trying to separate the wings from the blade</td><td></td></tr>
<tr><td>3. Stitch the wings onto the rudder blade. The force on the wings tends to try and peel the carbon off the rudder blade, this peeling starts at the radius where the wing meets the rudder blade and then works away from the wing along the rudder. The wings can be “stitched” onto the blade to stop the peel action from</td><td></td></tr>
</table>

| | |
|---|---|
| propagating.<br>a) Drill 4 or 5 3mm diameter holes through the rudder above and below the wing joint. Holes should be spaced around 15mm apart.<br>b) Tape a slither (5mm wide) of 200g/m2 uni-directional carbon to a pin to make a string.<br>c) Poke epoxy resin into the holes and spread epoxy over the carbon strings<br>d) Sew the carbon string through the holes<br>e) Allow to cure<br>f) Fill holes and smooth the joint using an epoxy filler<br>g) Sand smooth | **Above**: illustration of how to “sew” the wings onto the rudder. The dotted black line and purple lines represent a single piece of uni-directional carbon fibre that is passing through the blade.<br><br>The purple has been sewn through working from the trailing edge of the rudder towards the leading edge and the dotted black line shows the return journey back to the trailing edge |
| 4. Cover the joint area by laminating carbon weave 200g/$m^2$ over the joint on the rudder blade. | |

Finishing; filling and painting. Advice on this can be found on the National 12 website www.national12.org instructions for making rudders.

# 4 Materials

Epoxy: Ampreg 21 as a good all-round epoxy with a slow hardener
Foaming epoxy: PB170 DM02 for the epoxy foam
Carbon uni-direction: 200g/m2
Carbon weave: 200g/m2
Carbon bi-axial: 300g/m2
Peel ply
Woolly stuff
HPE – Single coat,120g per coat
Undercoat – Two coats, 60g per coat
Topcoat – Single coat, 60g per coat
Mould release wax
Laminating brushes
Latex gloves
Wing moulds. Graham Camm & Tom Lee are happy to load their moulds out.

# 5 Reference

UIUC AirFoil Coordinates Database http://m-selig.ae.illinois.edu/ads/coord_database.html

XFLR5 user guide
https://engineering.purdue.edu/~aerodyn/AAE333/FALL10/HOMEWORKS/HW13/XFLR5_v6.01_Beta_Win32%282%29/Release/Guidelines.pdf

Hydrofoils book: Hydrofoils Design Build Fly by Ray Vellinga. ISBN 978-0-9822361-1-6
https://www.amazon.co.uk/s/ref=nb_sb_noss?url=search-alias%3Daps&field-keywords=+ISBN+978-0-9822361-1-6

Source of carbon , epoxy and vacuum bagging materials. Marineware:
http://www.marineware.com/

Epoxy foam source: matrix composites http://www.matrix-composites.co.uk