The Iambus2 Footy Design – David Wilkinson

Fin Design

The design parameters here are the fin span, chord, taper ratio, sweep angle, thickness/chord ratio and section shape. It's fairly obvious, but sometimes overlooked, that the fin is a wing flying under water. Its job is to balance the side force from the sail. As it has to be a symmetrical section with no moving parts, this means it develops lift by travelling at incidence, the leeway angle, to the direction the boat is pointing. The hull travels through the water slightly sideways by the leeway angle rather than in the direction of the hull centre line. Leeway angles are typically 3 or 4 degrees but the actual value depends on the sail area, wind speed, boat speed and fin area.

The lift and drag producing properties of two-dimensional aerofoils for a wide range of NACA sections of different thicknesses are given in Abbott and von Doenhoff's book “Theory of wing sections”. This contains much useful data but its application to Footys is limited by it only going down to a Reynolds Number of $3 \times 10^6$. Reynolds Number is a measure of the ratio of dynamic to viscous forces in a flow and for an aerofoil is defined as $Re = \frac{V \times c}{\nu}$. Where $V$ is the flow speed, the boat speed in the Footy case, $c$ is the chord and $\nu$ is the kinematic viscosity of water, which is $1.15 \times 10^{-6}$ m$^2$/s for fresh water at 15 C.

The hull speed of the boat is at a Froude Number of 0.4 giving $V = 0.4 \times \sqrt{(LWL \times g)} = 0.4 \times (0.305 \times 9.81)^{0.5} = 0.69$ m/s.

A typical fin chord is about 40 mm = 0.04 m, so $Re = \frac{0.69 \times 0.04}{1.15 \times 10^{-6}} = 24,000 = 2.4 \times 10^4$, which is non-dimensional. This is some 100 times lower than data in Abbott and von Doenhoff and is so low that there is very little experimental data available for wing sections in this type of flow. Model aircraft data is nearer the correct $Re$, as in “Model Aircraft Aerodynamics” by Simons, but nearly all of it is for cambered rather than symmetrical sections. Otherwise I do have some low $Re$ data for symmetrical sections at zero incidence, from an Open University Course T331. At low $Re$ there is mainly laminar flow but the drag coefficients are higher than at high $Re$ where the flow is mainly turbulent. The drag is also more sensitive to thickness/chord ratio, rising more rapidly as $t/c$ increases than at higher $Re$. Compared to a flat plate at zero incidence there is about twice as much drag at $t/c = 10\%$ and 4 times as much drag at $t/c = 20\%$. Since fin drag is quite a large fraction of total boat drag there is an obvious benefit of using a thin section, less than $t/c = 10\%$.

At the other extreme of zero thickness, like a flat plate or an old fashioned razor blade, this would work well on the run where there is no lift but would fail on the beat where the flow would separate at the sharp leading edge giving a high drag. Somewhere between zero and 10% $t/c$ is an optimum, but lack of experimental data means one can only guess at the best value. The SuperBug family of boats uses $t/c = 6\%$ and, as always with this designer, that is a good value to use. It is physically quite thin and needs to be made very accurately and to use a high strength material like carbon fibre to make it stiff enough to avoid bending and torsional deflections. Very thin fins can easily develop torsional oscillations of the fin with the lead as the mass and the fin as the spring. As a test, hold the hull and flick the end of the lead sideways to see if it vibrates much. It does then travel through the water can excite this and cause extra drag and a stiffer fin is needed.

Choice of wing section to use is easier. The choice is between something like NACA0006 or NACA0008 or the more modern NACA63A006 or NACA63A008. The 63A series are laminar flow aerofoils designed to try to preserve laminar flow over a small range of lift coefficients, the “drag bucket”, to about 30% chord. The A means
there is no cusp at the trailing edge, which is a feature of the 63-series. The 006 indicates 6% t/c.

Abbott and von Doenhoff give the surface velocity distribution at zero lift and the incremental velocity due to lift so it is easy to find the upper and lower surface velocity distributions at any lift coefficient. The drag and probability of separation can then be estimated by calculating the boundary layers on each surface. This can best be done using Thwaites’ method for the laminar boundary layer, Michel’s transition criterion and then Head’s method for the turbulent Boundary layer, together with the momentum integral equation and the Ludwig-Tillman skin friction equation.

These are all available on the internet if you want to investigate different sections, but it is not really necessary as I have done the sums. It turns out that the 6-series sections although good for aircraft Re are not as good at Footy Re as the old-fashioned four-digit sections like the NACA0006 or NACA0008. Of these two, the 6% one gives less drag on the run but has a sharper leading edge and so is likely to stall at a lower incidence on the beat or when tacking in those low boat speed moments before it picks up speed on the new tack. Footys have very little momentum and there are always times during a tack when the boat speed is low but the full force of the wind is still present, giving a high leeway angle, which may cause the fin to stall, requiring the boat to bear away to pick up speed, losing ground to windward. The Iambus2 therefore uses a NACA0008 section, or as near as I could construct it. This slightly thicker section also gives a fin that is stronger in bending and torsion, which is useful if it is made of wood, as in the Iambus2, rather than carbon fibre.

The fin span obviously needs to be the maximum that will fit in the measuring box to give the maximum possible righting moment in heel due to the lead. This is most easily determined after constructing the hull and lead and fitting an over-length fin in the hull. The fin can then be trimmed down so the whole boat just fits in the box when the lead is in place.

Fin taper is sometimes used to minimise induced drag from the fin. This drag component is due to the energy spent shedding trailing vortices from the fin, due to varying lift along the span. Its value is $C_{di} = k \times C_l^2 / (\pi X A)$ where $A$ is the Aspect Ratio of the fin, $A = 2 \times \text{Span}/\text{Chord}$, and $k$ is a number close to but greater than one. This expression derives from finite wing theory for aircraft wings, which was one of the earliest successes of aerodynamics applied to aircraft, using lifting line theory. The main results of this were the induced drag expression above and the optimum planform shape for minimum drag, which was an ellipse. This is the well-known Spitfire wing shape. However this needed double curvature and was difficult to make. It was soon realised that a taper ratio of about two to one between wing root and wing tip chords gave almost as little induced drag as the elliptical shape and was much easier to make. This is the case for a tapered fin, but the analogy of the Footy fin with an aircraft wing is not complete.

The differences are at the ends of the fin. On an aircraft there are two wings and in level flight the load is zero at the wing tips and a maximum at the centre where there is reflection in the side of the fuselage. On a Footy there is only one “wing” and a relatively large body at the bottom end which has an end-plate effect which stops the load going to zero there and gives partial reflection. At the hull there is almost complete reflection when the hull is nearly upright but the side force is so low in this condition that the induced drag is small and does not matter. The important case is on the beat with heel angles of 30 to 45 degrees when the side force is large and the induced drag significant. Then, due to the heel, the fin/hull junction is very near the surface, which is exaggerated by the trough in the wave pattern. This makes it difficult for the fin to carry much load at the top of the fin. It also means that any load carried disturbs the water surface producing extra wave drag due to lift. A large chord tends to increase this drag.
component. Reducing the chord at the top of the fin will reduce the wave drag. Some 40 years ago some Stollery Marblehead designs used fins with an inverse taper, narrow at the top and wider at the bottom, possibly for this reason. This seems to have died away since then and the SuperBug uses a conventional taper. However, I can’t see the rationale for either taper, as described above, and the Iambus2 uses a straight untapered fin as probably being as near optimum as anything and the easiest to make accurately.

With the fin span, section and taper fixed the remaining item is the chord. This determines the fin area. Too little and there will be a high Cl, a lot of leeway and a tendency to stall in tacks. Too much and there will be a lot of drag and the slow boat speed will offset low leeway and reduce speed to windward on the beat. As there is an optimum heel angle on the beat of around 30 degrees, the side force that can be carried will be proportional to the lead weight, roughly. The higher the side force the more fin area needed so fin area is directly related to lead weight. The SuperBug with a total weight of 475gm and a lead of 275gm has a chord of 60mm at the hull and 45 mm at the lead, giving a mean of 52.5mm. The Iambus2 with a total weight of about 425gm cannot support that much lead and has a 215gm lead. Scaling would indicate a chord of 52.5 x 215 / 275 = 41mm, which is almost exactly the value chosen, which was 40mm. Later VPP sums for the Iambus2 showed that increasing the chord to 50mm would reduce the leeway on the beat but slow the boat enough to give a lower speed to windward. Obviously the higher drag on the run also slowed the speed downwind.

There is one other fin parameter to choose, the sweep angle. Low speed aircraft all have zero sweep and there has to be some reason to use anything else. Sweep was introduced on high speed aircraft that operate near the speed of sound to reduce shock waves and the drag they produce by reducing the Mach Number normal to the leading edge. It has a further effect of reducing the load near the wing root and increasing it near the wing tip, making stall more likely near the tip and giving an undesirable pitch-up moment at stall tending to make it worse. None of this is relevant to Footys or yachts in general which have completely incompressible flow. Sweep can, in fact, be seen to be harmful in slowing tacking.

The ideal fin, as used on the Iambus2, has zero sweep, with the fin centre of pressure, which is at the ¼-chord station, the LCB of the hull and the Centre of Gravity of the lead all on a vertical line, with the hull at its static water line attitude. This minimises the rotational moment of inertia of both hull and lead, by the parallel axis theorem, and avoids any aerodynamic damping or resistance to rotation while the boat is turning. This latter effect will happen if the fin is swept either forward or backward or even if the fin centre of pressure is displaced from the vertical axis of rotation. Vector diagrams of the fin velocity components due to boat forward motion and rotation for any part of the fin show that for an off-centre centre of pressure there is an incidence and hence aerodynamic force that acts to resist the rotation. The Iambus2 alignment avoids this effect and means the boat can turn on a sixpence and there is never a problem tacking.