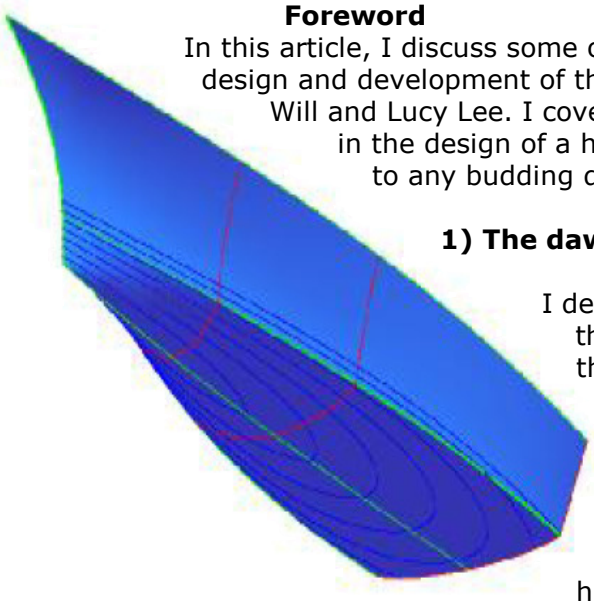
Behind the E numbers - a look at some of the design analysis for the E5 Cherub



Foreword

In this article, I discuss some of the design issues and features considered during the design and development of the E5 Cherub, commissioned by 2x National Champions, Will and Lucy Lee. I cover some of the basic naval architecture principles involved in the design of a high performance skiff and I hope this may be of interest to any budding designers out there.

1) The dawn of computers

I designed my first Cherub at the age of 16 in 1974. Design then was very much a question of feel, eye, aesthetics and the extensive use of drawing boards, set squares and a slide rule (calculators had not then been invented!).

The Deeley 5 (Amber Dragon) and the E4, designed in 1984, were to my knowledge, the first computer aided Cherub designs. Here the computer (a Sinclair Z80, programmed by Bill Deeley) was used to ensure that the hull shape was fair by using a progression of simple mathematical curves to derive the shape. The computer also allowed the calculation of some simple hydrostatics.

The design of the SK4 skiff in 2006 was rather more scientific. I used a program called Hullform 9 Professional (1) to design the hull. This program allows the hull to be designed, faired, the hydrostatics to be computed as functions of fore and aft trim and heel and designs to be overlaid and compared. It also allowed simple drag predictions based on hydrostatics to be made for each design. Over 50 different design iterations were evaluated before opting for the final design - a task which would have proved impossible without CAD.

The drag predictions were then entered into a velocity prediction program (VPP) which allows the boat's speed to be calculated at any true wind speed and angle. By analysing other boats with known PN numbers (e.g.. our Slug Cherub, Dangerous Beans), it was also possible to predict the boat's possible PN number. This worked out to be around 815 in 5-8 knots, reducing to 750 from around 10 knots. Once we had learned the rudiments of sailing this beast, this is what the SK4 sails to; we adopted 780 as our club handicap. This exercise proved that it was no longer necessary to build a boat to see how it would perform - reasonable predictions could now be made using analytical techniques.

The SK4 skiff sailing at 11 knots in just 6 knots of wind

The drag predictions used for the SK4 are based on yacht hull forms (e.g. Gerritsma (2)) and simple prismatic planing hulls (Stavitsky and Stavitsky Brown) (3)). The SK4 skiff and Cherubs, being both short and light, spend a lot of time in the semi planing (about 7-11 kts) and full planing (>11kts). Experience with various Cherub designs over the years has provided practical evidence of the profound influence that transverse panel curvature and especially longitudinal curvature (rocker) has on

performance in these speed ranges. The Howlett 1b of about 1984 was, by Cherub standards, very round and rockered , with about 125mm of rocker. It looked like an ISO or BOSS, which were also Howlett designs. In drifting conditions it was unbeatable and won a couple of light wind nationals. As soon as downwind planing conditions prevailed, it was pretty slow.

In the summer of 2007, I was approached by Will Lee about a new Cherub design. The Bieker IC cherub (AKA GT60) had hit the water and shown good speed, particularly in lighter winds. This hull, although low rockered, is relatively round. It was clear that an analysis technique to quantify the effects of chine rise, panel curve and rocker would be an extremely useful tool to hone a Cherub design for the reigning national champion. After a lot of web trawling, I finally located a commercial program (BOAT3D 2007 (4)) to do just that. After working with the program designer to adapt the program to work with Cherub style skiff hulls, the design process could begin.

Will and Lucy Lee in their Cherub 'Atum Bom'

The E5 design has evolved from the combination of practical experience with both Cherubs and the SK4 skiff, and detailed numerical analysis. I believe the numerical analysis may be a first in skiff design.

2) In search of the Holy Grail

Cherubs sail at a wide range of speeds from 0-20+kts. There are 3 basic speed regimes; displacement, semi planing, and full planing. For each speed regime, there is a hull type which will give least resistance.

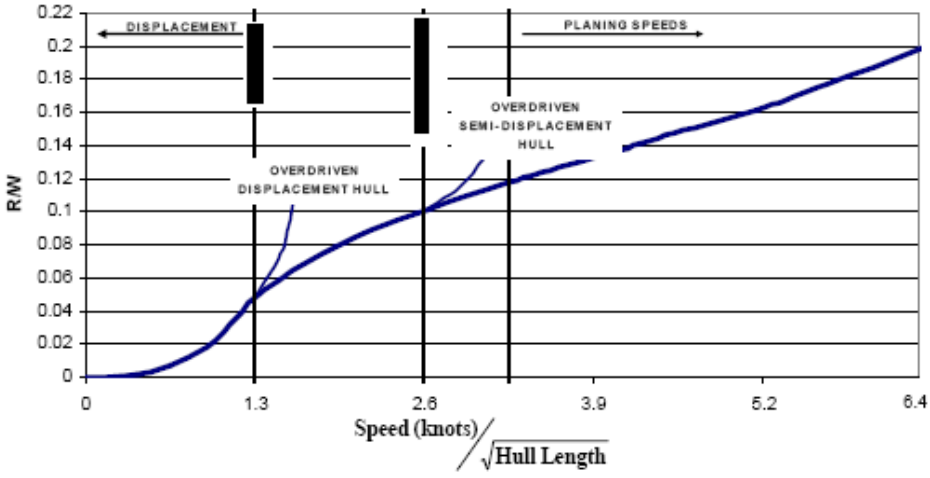


Figure 1 (ref Stavitsky) shows how the drag per unit sailing weight typically varies as a function of speed to length ratio (SLR), where SLR is speed to length ratio = speed (kts)/(waterline length(ft))^0.5.

Figure 1: Variation of drag to lift ratio of typical hulls as a function of speed to length ratio.

a) Displacement (0 - 4.5kts, SLR 0-1.34) The design is all about avoiding flow separation from the hull. The rocker and buttock lines behind mid length should be arcs of circles. The water planes should be pointed at both ends, so the transom will be narrow. The prismatic coefficient (CP), which for skiff

hulls is basically a function of rocker, should be <=0.58

Examples of this type of hull shape is exemplified by traditional yacht hulls, rowing skiffs. Dinghies with some of these characteristics: RS200 / 400, Firefly

This type of hull would be a light wind flyer, but if you tried to sail it in a breeze, it would probably not go much faster than 5 or 6 knots. This is because the curvature in buttocks aft of mid length, combined with the narrow transom, would cause it to suck down into the water giving it a huge resistance hump at so called 'hull speed'. Hull speed occurs at a SLR of 1.34 when the length of the wave produced by the bow is equal to the waterline length, as shown below.

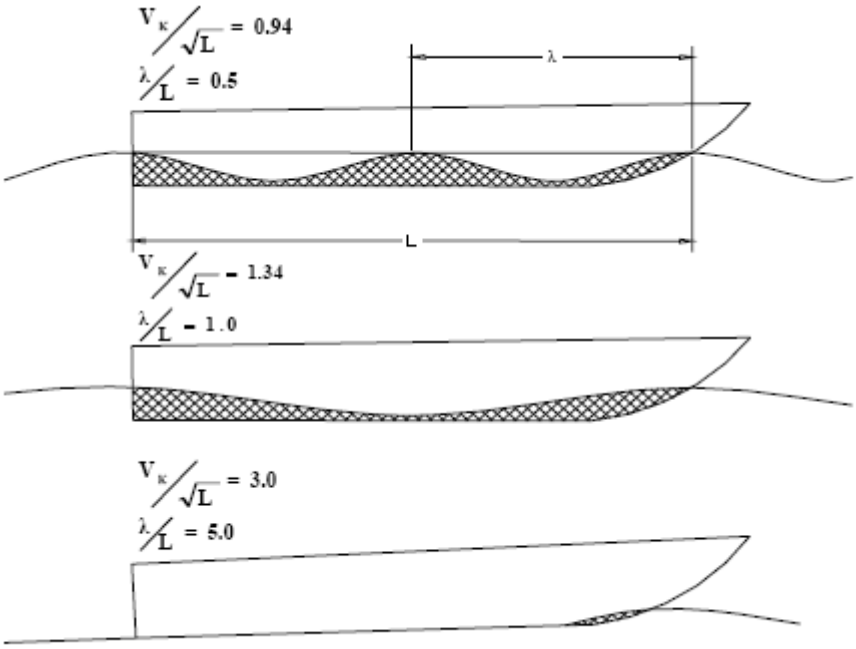


Figure 2a: Wave patterns as a function of SLR

Figure 2b: 49er at hull speed (about 5.3 knots) - note the coincidence of the second peek of the bow wave at the stern. Picture courtesy of Bethwaite Design.

b) Semi planing (SLR 1.5 - 2.8)
Here the boat is effectively trying to sail up its bow wave. To minimise resistance, the bow should be fine and veed, leading to a narrow mid section so that little lift is produced. The transom should be of a similar or greater width to the mid section and flat towards the centre line to overcome the tendency of

the bow trying to push it down into the water. The water planes should be wedge shaped. When sailing, the transom will be below the water surface and the water will separate cleanly at the vertical transom.

The prismatic coefficient for this type of hull should be 0.62 - 068.

Examples of this type of hull: fast patrol boat
Dinghy hulls where these features predominate: Tornado cat, International Moth. 29er, L3 design NZ R Class.
This type of hull can readily pass through hull speed, but is not the most efficient above a SLR of around 3.

Figure 2c: 49er hull at a SLR of about 1.9 (7.6kts). Note that the boat is effectively sailing up its bow wave. The trough of the bow wave is now approximately coincident with the stern. Picture courtesy of Bethwaite Design.

c) Planing hull (SLR >2.8)
Here the boat's weight, rather than being supported by the displacement of water, is supported by dynamic lift. The hull skims on the water like a water ski. The hull will have a straight rocker line and the sections will be a straight V or even concave. Convexity in sections and particularly rocker, need to be avoided to prevent dynamic suction. The hull will have hard, sharp chines and a vertical transom such that the water separates cleanly at both the transom and chines. The prismatic coefficient will be over 0.7.

Examples - formula windsurfer, speedboat
Dinghy hulls where these features predominate : Slug, Pasta and Jennifer Julian Cherubs

The planing hull can pass freely through displacement and semi displacement regimes and on into full planing. The resistance of a planing hull in displacement and semi displacement sailing is greater than displacement / semi displacement designs at SLR of less than around 3. This is mostly due to wetted surface and flow separation at the chines and particularly the transom if immersed.

The 'best' hull shapes for each speed range are quite different and to certain extent, mutually exclusive. It is impossible, therefore, to design a hull which will be optimal at all speeds and thus dominant in all wind conditions. There is, therefore, no Holy Grail. A blend of characteristics is required and the design will always be a compromise. The blend depends upon how fast we expect the hull to sail at for most of the time. This, in turn, depends upon how windy it is.

3) How windy is it?
Studies of the wind at recording buoys in the Solent indicate that the wind, at the times we can go sailing, has an approximately normal distribution with a mean of 11 knots and a standard deviation of 5 knots. For over two thirds of the time (68%), the wind will be within 1 standard deviation of the mean, that is between 6 knots and 16 knots. For 80% of the time the wind will lie within 1.28 standard deviations of the mean, that is between 4.6 knots and 17.4 knots.

Behind the E numbers - a look at some of the design analysis for the E5 Cherub

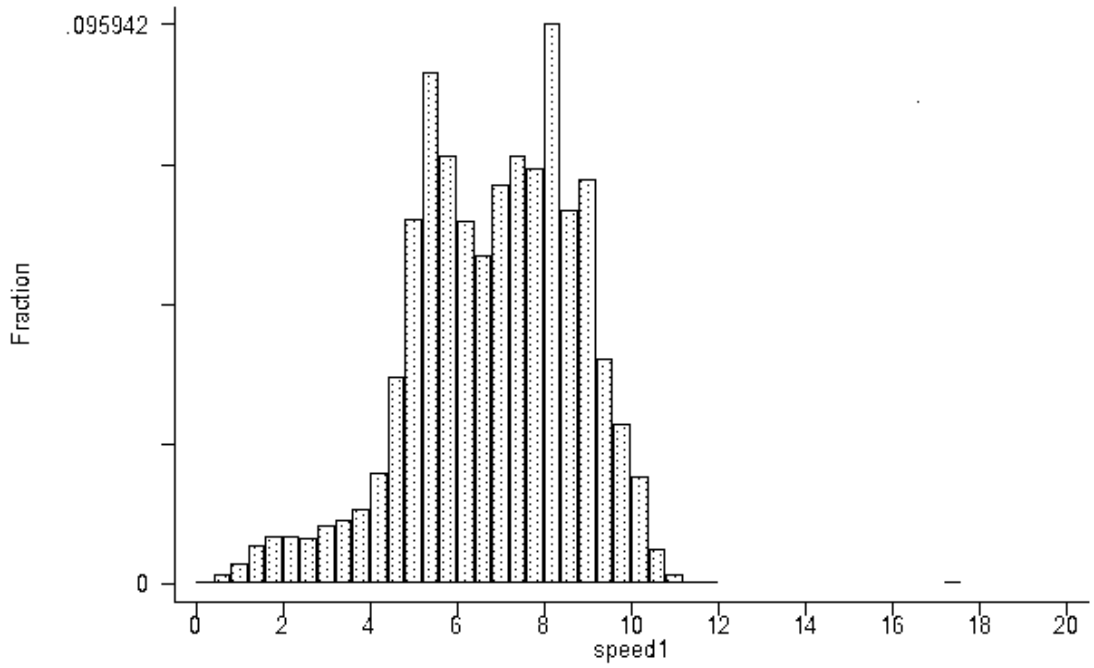
4) How fast do we sail

This is where the GPS and the VPP come in. Upwind, Cherubs sail at a speed equivalent to 70% - 80% of the true wind speed over the range 5 - 14 knots. Above 14 knots of wind, the speed is limited by leverage or sea state. This means that upwind, the hulls will sail at speeds of between about 4 knots and 10 knots for 70% of all races

Downwind the Cherub typically achieved a speed of around 110% - 120% of true wind speed. So over the 6 - 16knot wind range, the downwind speeds would be around 7 - 18kts for 70% of all races.

We spend about twice as much time sailing upwind as down. Using this weighting, we need to design for a speed of 5kts in 6 knots of wind, and around 13 knots in 16 knots of wind.

The graphs below show the upwind and downwind speed distributions recorded from Championship winning boat, Atum Bom, during the 2007 Cherub nationals at Weymouth. The distributions confirm the validity of the of theoretical design speed analysis.



Behind the E numbers - a look at some of the design analysis for the E5 Cherub

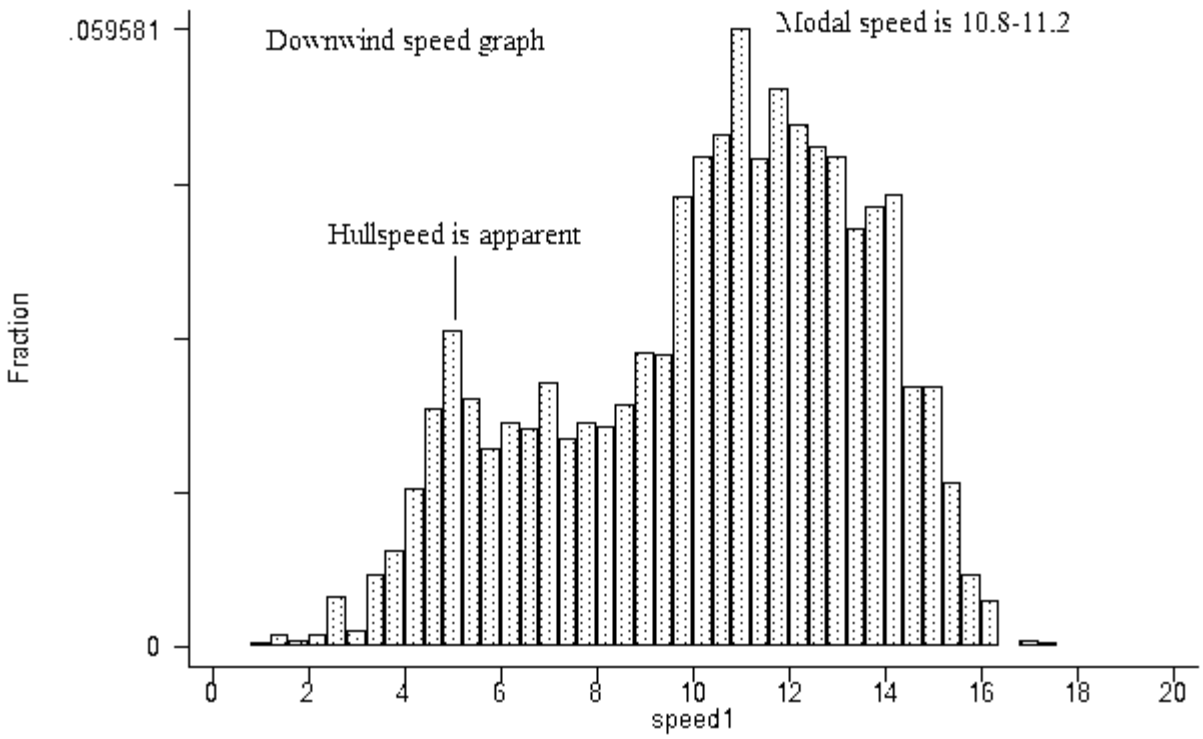


Figure 3 - Upwind and downwind speed distributions from Atum Bom during the Weymouth 2007 Nationals

5) E5 design parameters

5.1 Prismatic coefficient (CP)
The starting point is to select a prismatic coefficient appropriate to the design speed range. This, in effect, determines how much rocker the hull will have.

The figure 4 shows the optimum CP as a function of SLR.

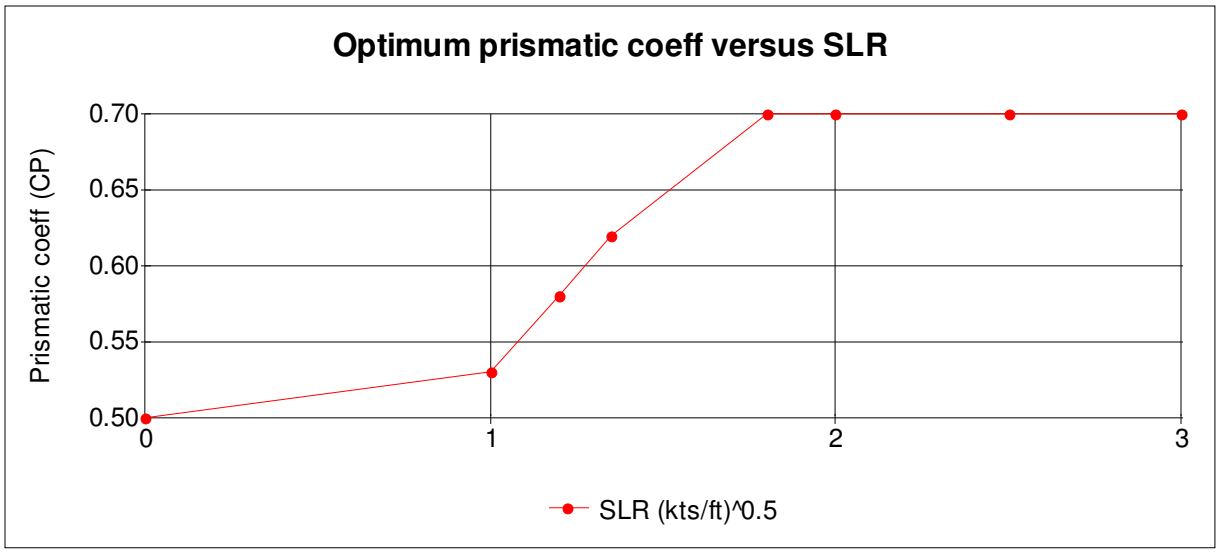


Figure 4: Optimum prismatic coefficient versus speed:length ratio

Behind the E numbers - a look at some of the design analysis for the E5 Cherub

From the speed analysis in Section 4, the minimum design speed was 5 kts., corresponding to the mean time averaged speed achievable in 6kts of wind. The hull speed of 5 knots corresponds to a SLR of 1.44. The optimum CP for this speed is about 0.65. The maximum design speed was 13kts, (SLR of 3.75) corresponding to the time average speed in 16kts of wind. Here a CP of 0.7 would be required. Cherubs, because of their short waterlines, large sail area to weight ratios and large power to weight ratios spend a lot of time sailing at high SLR ratios. In consequence, the hull designs require higher Cps (lower rocker) than in many other classes.

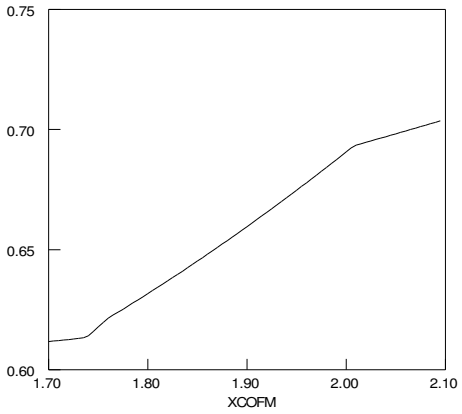
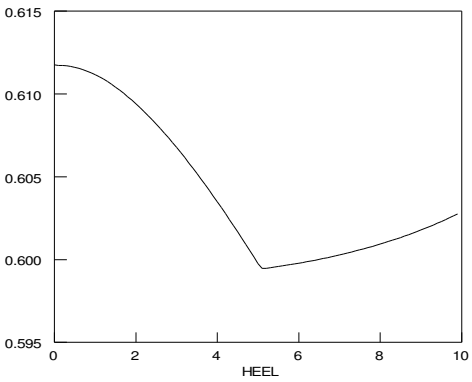


Figure 5 shows the CP of the E5 design in upright trim. It can be seen that due to the wedge shaped water planes, the CP increases from about 0.62 with the crew weight right forward (1.8m from the bow) to 0.7 as the crew move farther aft.

Figure 5 - Variation of prismatic coefficient (CP) versus centre of mass (XOFM) on the E5 hull



The plan and elevation of the chines have also been designed so that the CP can be still farther reduced by introducing leeward heel. Figure 6 shows the effect on CP of heel. It can be seen that forward trim, combined with heel of about 5 degrees can reduce the CP to below 0.6, which would be near optimum for upwind sailing in about 5.5 knots of wind.

Figure 6: Variation of CP with heel on E5

5.2 Wetted surface

The hull resistance is dominated by skin friction resistance up to a SLR of about 0.9 (about 3 knots). The E5, although a low rocker / high CP design has been designed to give a low wetted surface when in light wind trim with the bow well in and the boat heeled to leeward. Figure 7 shows how the wetted surface is reduced as the boat heels. Figure 8 shows the water planes for the hull when the boat is

trimmed for light weather. It can be seen that the water planes look similar to those required for a displacement hull; pointed at both ends. This is the 'fourth mode' referred to in Frank Bethwaite's book High Performance Sailing.

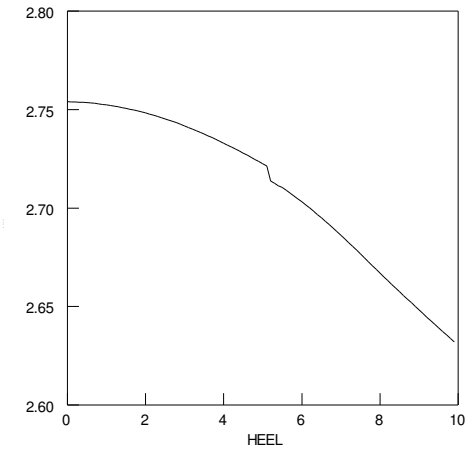


Figure 7 : Variation of wetted surface with heel angle

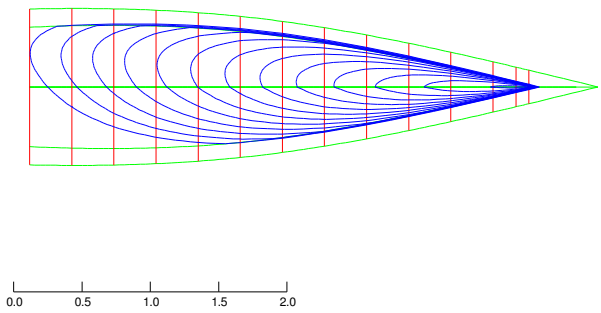


Figure 8: E5 water planes for light wind trim.

When planing at optimum trim angle, the friction resistance and the induced drag (i.e. the drag produced by creating dynamic lift) have about equal value. Low planing wetted surface is ensured by having low, sharp, chines with a low exit angle.

5.3 Wave making resistance

As SLR increases above 0.9, wave making resistance becomes and important factor. In addition to CP, the entry angle of the water planes and the distance aft of the longitudinal centre of buoyancy (LCB) to the longitudinal centre of floatation (LCF) are key factors. To achieve narrow entry angles and to place the LCF well aft of the LCB, the E5 has wedge shaped water planes, with the maximum width occurring close to the transom. This wedge shape is also characteristic of the 49er and 29er Bethwaite designs.

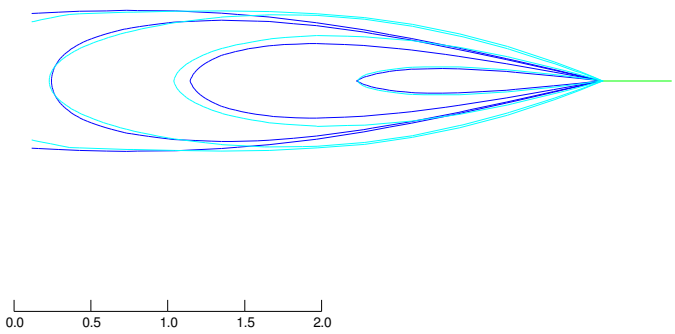


Figure 9: Comparison of E5 (dark blue) and Slug (light blue) water planes.

5.4 Planing resistance

The E5 has a scoop rocker line as found on sailboards (though very much flatter). It also has low chines and relatively flat sections. There is minimal curve in the buttock lines aft of mid length to avoid dynamic suction. Detailed drag analysis using Boat3D showed these factors contribute to early planing, low resistances in the 8 -10 kt range, and high top speed. It was also found that a difference in rocker of only 7mm could make a significant difference to drag.

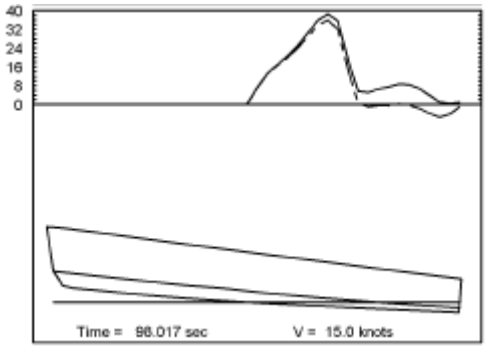


Figure 10 shows the predicted trim and forces acting on the E5 hull at 15 knots of boat speed. The solid line is the total lift force, the dashed line the dynamic lift force. The difference between the two lines is the buoyant force. It can be seen that the boat is supported mostly from the dynamic lift. There is very little suction (negative dynamic lift).

Figure 10: Planing analysis of E5 hull using Boat3D program.

6 Comparison with other designs

In order to assess the various hydrostatic parameters, it is useful to compare them with those for other designs which have known performance characteristics.

Behind the E numbers - a look at some of the design analysis for the E5 Cherub

Design	Bieker 1C	Slug	P7	E5b	E5e
Parameter					
Upright Cp (Big range is good)					
Min	0.62	0.62	0.58	0.61	0.61
Max	0.675	0.69	0.622	0.69	0.7
Upright wetted surface (m^2) (low is good)					
Min (bow down trim)	2.66	2.89	2.75	2.67	2.75
Max	2.74	2.95	2.89	2.82	2.85
Bow entry half angle (degrees) - low is good					
Bow down trim	18.5	23.3	17	13.8	14.1
typical	13.5	20	16.4	13.3	13.3
Distance of LCF behind LCB (mm) - big is good					
XOFM at 2.0m	230	160	190	300	290

Table 1 - Hydrostatics of various UK Cherub designs
Notes:
1) Values for Bieker are approximate
2) The E5e is the design being built by Bloodaxe Boats. The E5b was an earlier iteration which has xx mm more rocker

The P7 has a proven to be a formidable light wind performer, especially when sailed against the Slug design. The P7 design has a lower CP, smaller wetted surface, and much finer bow entry angle. From these numbers, the P7 would be expected to be quicker than the Slug at displacement speeds (i.e. at boat speeds less than about 6 kts). With the smaller sails and single trapeze of the pre 2005 rule Cherub, these speeds would often be encountered upwind.

The Bieker has a very low wetted surface due to its essentially round bilged form. Combined with its low entry angle, it would be expected to be a good upwind performer, especially in lighter winds.

The hydrostatics of the Slug suggest that its hull form will come into its 'sweet spot' when hull speeds of 7 knots or so are exceeded. With the 2005 rules rig, this would suggest a minimum wind strength of around 10 knots for sparkling upwind performance.

7 Comparative drag predictions

Drag predictions have been made for each design. The drags are at optimum trim and heel for each speed. The drags are shown in Figure 8. Despite the very different shapes of the hulls, it can be seen that the differences in drag are relatively small; poor sail trim, incorrect hull trim etc. would make a greater difference to drag than the differences between the hull shapes themselves. Nonetheless, the E5e design is predicted to have less drag then the Slug as all speeds.

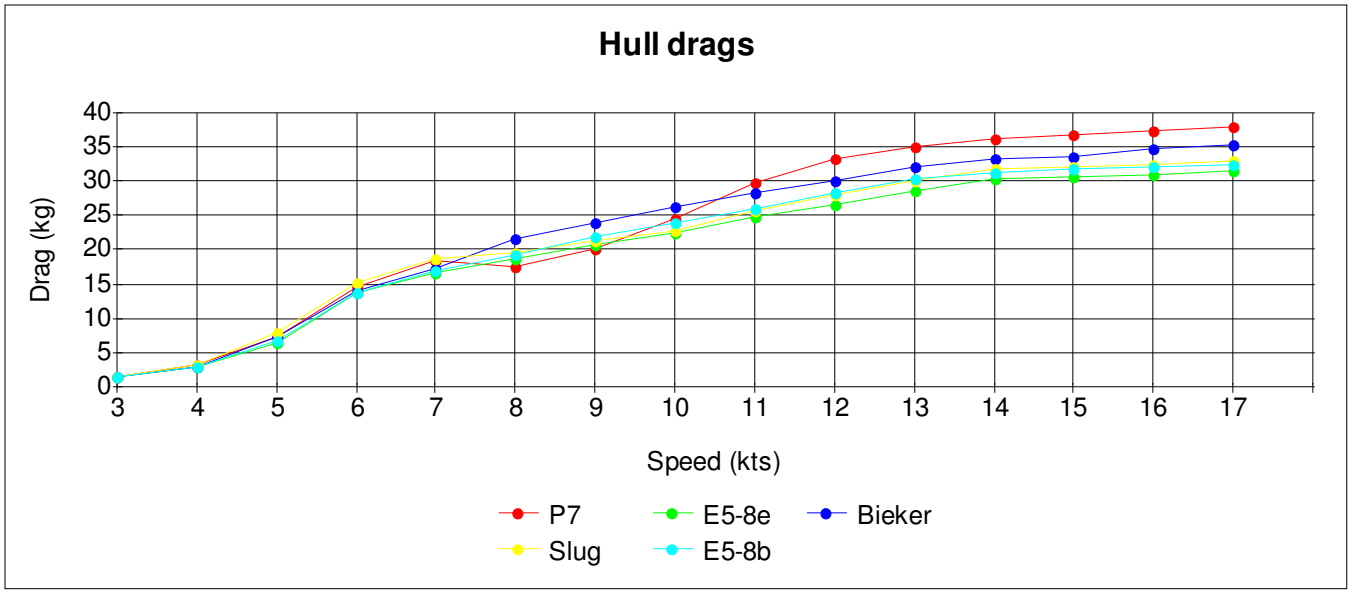


Figure 11: Predicted hull drags at optimum trim and heel, displacement is 210 kg

The drags have been expressed as a percentage of the Slug drag curve in Figure 12. It can be seen that all the designs have lower predicted drags then the Slug at speeds below 7 knots. This lends some credence to the opinion that the Slug is not at its best in light winds.

All of the designs have a dip in relative drag compared with the Slug at around 5 knots, which is close to hull speed. Referring to Table 6.1, it can be seen that this reduction in drag is essentially a function of entry angle and the separation between LCB and LCF which affects wave drag.

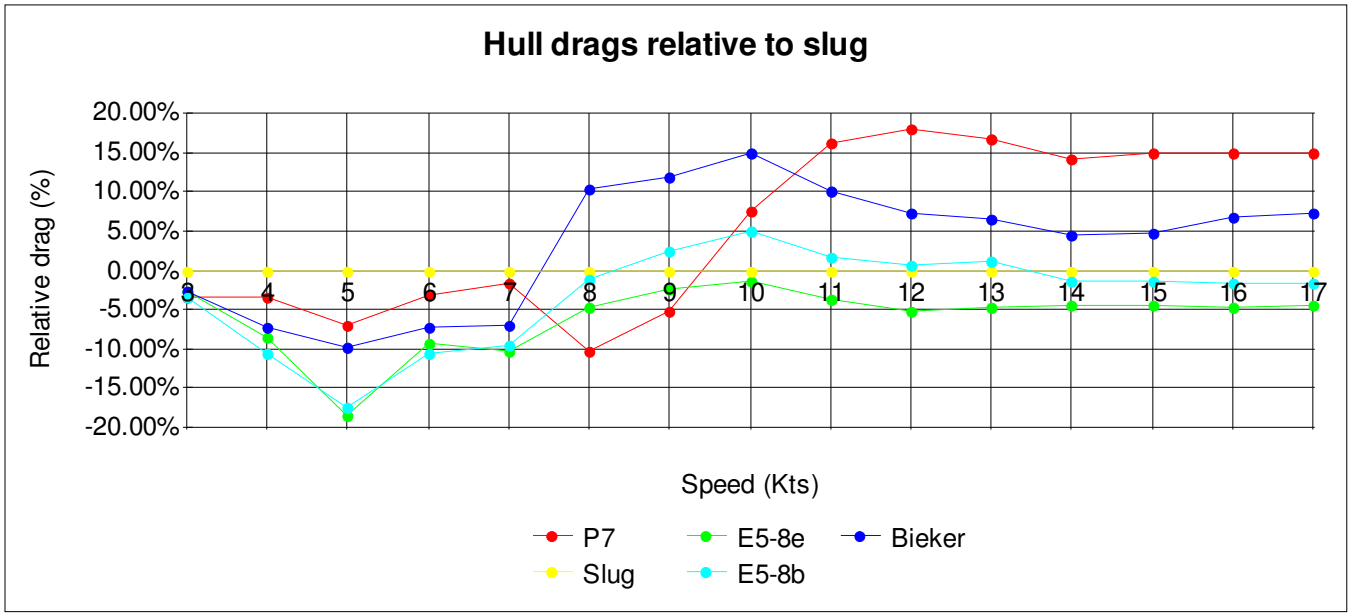


Figure 12: Drags of cherub hull designs relative to the Slug

The difference between the E5-8e and E5-8b is that the 8e has 15mm less rocker than the 8b. The higher rockered 8b is predicted to have less drag at low speeds. From about 7 knots up, where dynamic lift and the associated induced drag become dominant, the lower rockered 8e has the lowest predicted drags.

8 Foil design

The foils represent about 25% of the total hydrodynamic drag when the Cherub is sailed upwind in about 11 knots of wind. A fast boat is the sum of a good crew, a good, well set up rig, and good foils. There is little point in trying to reduce the hull drag by a few kilograms if the foils are poor.

The foils for the E5 have been designed with the aid of computational fluid dynamics (CFD) package. The package can look at the effects of sections, plan forms and must importantly, the interaction between the various lifting surfaces (e.g. the centreboard and rudder, rudder and T foil, hull and centreboard etc.).

The Figure 13 shows an example of the type of analyses being undertaken which may well be the topic of a future article.

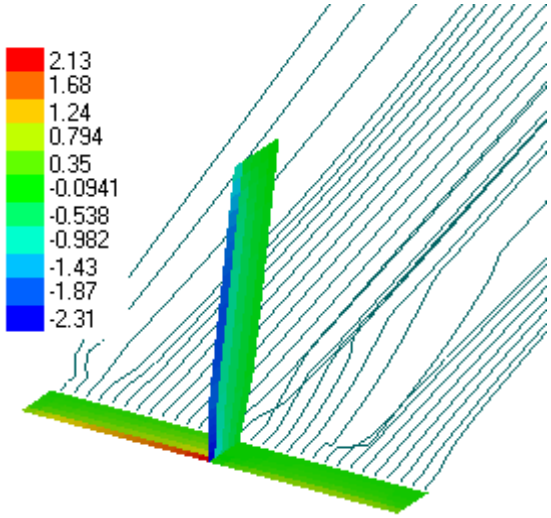


Figure 13 - Interaction of rudder and T foil lift. Colours show mean delta presssure coeff Cp and streamline. Rudder AOA is 10 deg, T foil 5 degrees

9 The proof of the pudding

The design analyses undertaken for the E5 suggest that existing cherub designs can be improved on.

The key area of change is the much finer bows and entry lines compared with existing boats, combined with a low rocker and low rise of floor aft. The chine line, rocker and top sections have also been designed to allow the boat to be 'tuned' by trimming. This should allow reasonable light wind performance with the bows buried deep in the water and about 5 degrees of heel. The hull has been optimised for sailing in about 10 knots of breeze which is indicated to be the mean wind strength.

With the exception of the Beiker 1C, the existing designs were developed for the 1997 rules, which allowed only a single wire, 12.5m^2 of upwind sail. In consequence, these hulls were designed for

lower average sailing speeds than can be obtained working to the 2005 rule set. The P7 design, in particular, seems well suited to this.

The mathematical modelling undertaken predict flat water resistance and with the hull at optimum trim. Incorrect trim (i.e. too bow up or down) can produce a greater change in a hull's resistance then the differences between the hull shapes considered. Sailing in chop will also produce a major effect on hull resistances.

3 No. E5 designs have now been ordered from Bloodaxe Boats; I am even thinking of getting one myself! The design should offer some performance advantages. However, the real world has much more complexity than can be handled by a mathematical model. I thus print the following warning: 'past performance is no guide to future performance; performance may go down as well as up'.

Good sailing.

The E5 being built at Bloodaxe Boats - www.**bloodaxeboats**.co.uk

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References:

1) Hullform 9 Professional Blue Peter Marine Systems Pty - boat design software

2) Daniel Stavitsky 1963 - extensive work on the behaviour of planing hulls

4) Stavitsky and Brown 1974 - empirical study on the pre planing resistance of planing hulls

3) Gerritsma et al 1997 - empirical drag prediction method for yacht hulls

4) Boat3D - 3 degrees of freedom time domain planing boat simulation by Peter Payne and Dail Singleton. C Digital Analytics, Houston Texas

5) Bethwaite design

6) Frank Bethwaite 'High Performance Sailing'

Cherub designs
Howlett 1b - Ian Howlett 1984
Slug - Simon Roberts 1997
Patterson 7 - Andy Patterson 1999
Beiker 1C - Paul Bieker 2007