8.5 FINAL REMARKS

The methods and ideas discussed in this short chapter generally represent the state-of-the-art and state-of-technology in hull design. Because performance trade-offs are involved in virtually every aspect of hull design a rational approach using modern computational tools and scientific methods will help find the balance. Understanding the key issues related to each design project, and how the hull parameters and form affect these key issues are crucial to a successful design. Although the accuracy of the predictive tools is quite good, it leaves a very small margin of error that is still critically significant to race boat design. For complex issues related mostly to dynamic effects, including seakeeping, and manoeuvring, the tools are not as well developed. What still remains vitally important is the development of an 'eye' – the visual aspect, sense of proportion, powers of observation, as well as attention to overall present and past trends, discussions with sailors and customers, and sailing as much as possible.

CHAPTER 9

THE DESIGN OF APPENDAGES

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9.1 INTRODUCTION

The need for appendages that provide stability and sideforce as well as directional control is the principal underwater feature which distinguishes the sailing yacht from the motor boat.

This chapter does not attempt to revisit the whole field of general appendage design and the basic mechanisms of force generation which are covered in Chapters 2 and 5 of *Sailing Yacht Design: Theory* and elsewhere,[1] but takes a brief look at the basic issues and at recent developments in aerofoil, bulb and winglet design.

While the function of appendages remains unchanged, since the 1960s the proportions and configurations of both racing and cruising yachts has undergone a revolution. Figure 1 from reference 2 illustrates the keel characteristics of yachts of that era, and inset also for comparison are those of some current racing yachts that might be considered typical of the new breed.

So dramatic has this change of proportions been, that much of the research work that has been carried out over the last thirty years on appendages is of little application to the current breed which have considerably more in common with model racing yachts and racing dinghies than keelboats of the past. Highly swept low aspect ratio fins have been replaced by fins of higher aspect ratio supporting heavy lead bulbs. Despite the current prevalence of these types very little has been published concerning the three dimensional effects of these configurations.

The highly publicised success of the winged keel on 'Australia 11' in 1983 focussed attention on the application of non planar lifting surfaces to yacht keels and led to much concentrated research for the following America's Cup. Consideration is thus given to the development of the keels in the International Twelve Metre Class for keels of these proportions remain of particular interest in the design of high performance cruising yachts where moderate draft is valued.

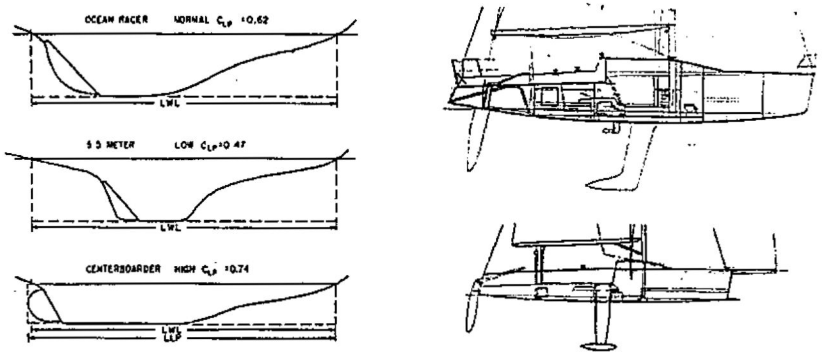

Figure 9.1 *Then and now, 1965 to 1998. How the proportions of appendages have changed. Modern profiles are the Farr 40 OD and Melges 24 OD.*

To obtain an indication of the relative characteristics of widely varying appendages in real life, the author's personal keel developments which have taken place since 1981 in the comparative stability of the International Six Metre Class (Rule established 1906) are reviewed. In this Class, as perhaps in no other, hull forms have remained remarkably unchanged over that period. It is one thing to demonstrate on paper that a better keel has been designed but the only hard evidence for such improvement is to be found on the racecourse or in the improved handling of a cruising yacht. Even in close boat for boat racing or two boat tuning it is all too hard to judge small speed differences when gains made in viscous and induced drag may easily be lost in the general noise of yacht performance associated with sails and balance let alone the human factor in the shape of the crew.

Finally, a look is taken at a form of winged bulb keel development that has proved particularly well behaved in cruising applications.

9.2 BACKGROUND TO MODERN APPENDAGE CONFIGURATIONS

In a sense the past is being revisited in that the fin and bulb configuration developed by Nathaniel Herreschoff for full scale yachts in the 1890s has been 'rediscovered' and is now regarded as the obvious and universal solution as to the best disposition of ballast and minimisation of wetted surface, hence performance.

This has occurred because of the tacit acceptance by the Rulemakers that Racing boats of the 1990s need have no useful afterlife as cruisers, and that the logistics of operating with weed catching keels of deep draft are of little concern to modern racing craft and their owners.

It might be just be worth recalling that the fin and bulbers of the 1890s, though reportedly well mannered and fast, were later ruled against in favour of boats with at least some scope for accommodation and built to sensible scantlings. Yacht racing does have a habit of going in cycles.

Lightweight one piece hull constructions employing advanced materials have permitted offshore yachts to be driven ever faster and have led to new expectations of handling capability. In the past the rolling and consequent broaching of these craft was perhaps erroneously laid at the door of the separated fin and rudders by some commentators. Likewise the ultimate seaworthiness and safety of the type was sometimes brought into question rather than attention being paid to the proportions and VCG position of the yachts in question.

A sailing craft has to operate in a large variety of conditions: upwind, downwind, reaching, heeled and unheeled, also from zephyrs through to heavy airs. As it must also operate in smooth and rough water the problem of optimisation is evidently highly complex so it is not entirely surprising that experience and good judgement in addition to science is generally essential to a successful result.

In a parallel field the progress of the design of gliders/sailplanes has been most marked and far more readily quantifiable – lift/drag (L/D) ratios (the glide angle), has increased from around 30:1 in 1950 to 63:1 in the 1990s for the highest performance machines.This has been brought about primarily by the design of more efficient wing sections but the use of these has only been made possible by the advent of composite materials which can provide the stability of shape and the smooth surface required to maintain laminar flow as well as allow the construction of wings of extreme aspect ratio.

9.3 APPROACHES TO APPENDAGE DESIGN

In planning a new set of appendages a designer would normally consider the modification of an existing design, attempting to make a logical gain from a known successful base or putting right known deficiencies relative to the competition.

The *best conventional ballast keel* is that which will provide the highest stability i.e. lowest VCG with the least drag at the required sideforce over the operational range or in any case the best trade-off of those two variables. For good performance to windward a ratio of sideforce:resistance of the order of 3.5:1 is to be expected at optimum velocity made good (VMG).

When models are tested in the towing tank resistance (R) is generally plotted against sideforce (S) or sideforce^2 (S^2) hence from testing a range of keel sizes it may be deduced that a keel is too large or too small for the boat characteristics for the chosen conditions. Unlike the design of sails the vertical position of the CLR is comparitively unimportant as the variation is small relative to mast height.

The *best rudder* is one which provides the necessary control in all conditions, allows the helmsman a sensitivity and feedback as to the transients in the performance of the boat and also enables the CLR of the boat to be shifted over a considerable fore and aft range in order to maximise the useful horsepower available from the rig over a range of heel angles.

The following areas might be expected to be the subject of the attention of a designer.

9.4 THE FIN KEEL

Choice of foil section – the reduction of viscous drag

Until the 1980s, standard aeronautical data as in the remarkable reference 3. intended for the aircraft industry was considered 'state of the art' for the design of the foil sections of keels and rudders. By this time however, the design of aerofoil sections for Gliders had made remarkable progress and a summary of the characteristics of the sections resulting from some of this work is to be found Althaus *et al.*[4] Further developments along such lines continued the essential methodology, this being to design a pressure distribution to optimise laminar effects at the desired Reynolds number (Rn) for the anticipated Cl value and thickness/chord (t/c) ratio and then organise the section shape to produce that pressure distribution taking account of the boundary layer.The resultant sections were subsequently evaluated in a Laminar Wind Tunnel over a range of Rn. Experiments have also been carried out in the operating environment using wake analysis on a section flown 'piggyback' above the wing of another glider.

The atmosphere itself is said to allow even more laminar flow than may be found in the laminar wind tunnel and Obara *et al*[5] suggest that the same will occur in the denser medium of the ocean.

Most of this development concentrated on wing sections (the principal performance factor) which were cambered and flapped, sailplane wings operate at a Cl value of the order of 1.0 and a Rn in the range 0.7–3.0 Million.

Some work was also however carried out on symmetrical sections generally of 15% t/c ratio with flaps (chord lengths 0.2–0.3 C) for use as elevators and fins operating at Rn 0.5–1.5 Million.

Where a flap (or trim tab) is not required it would seem reasonable that a section of lower drag might be designed. Figure 9.2 shows the predicted performance of a Wortmann section designed for 20% flap compared with that section refined in its rear part where no flap was required.

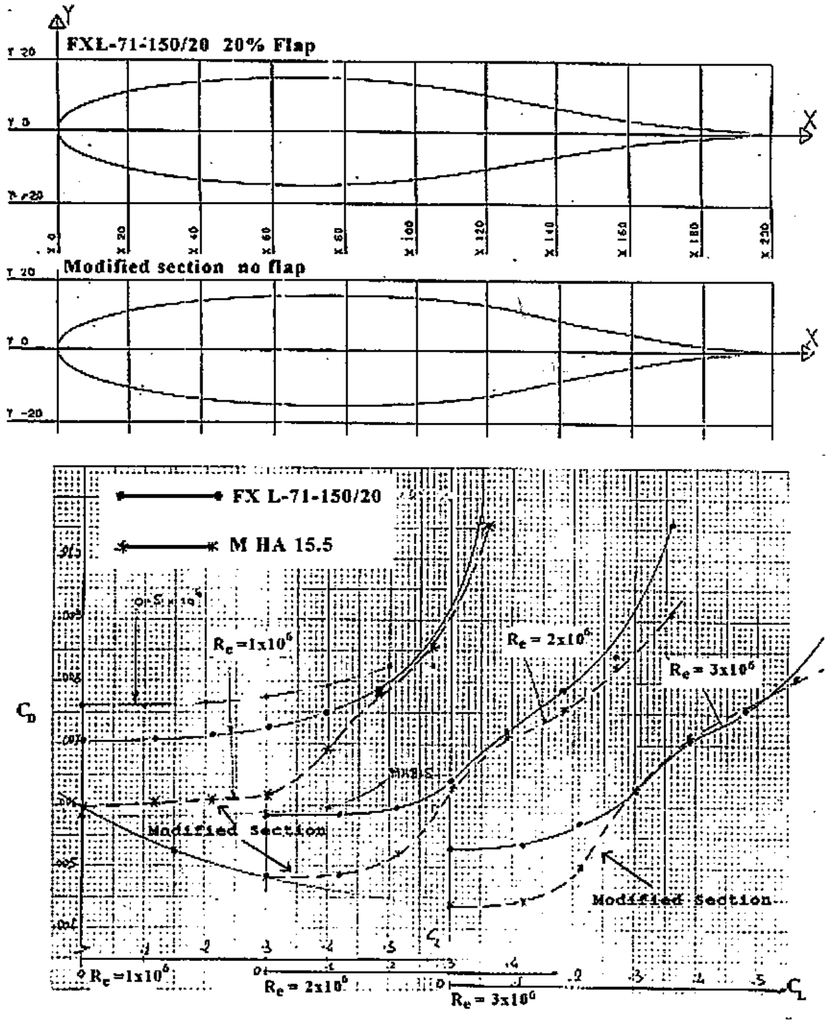

Figure 9.2 *Wortmann FX L-71-150/20 modified section and predicted performances of these sections over a range of Rn.*

This latter section has been used extensively by the author for International Six Metre rudders and canard foils since1989 with encouraging results.

For the sake of completeness Figure 9.3 shows the predicted effect of just using the aft section of a standard foil section as a flap without modifying the shape and hence the pressure distribution immediately preceding the flap.

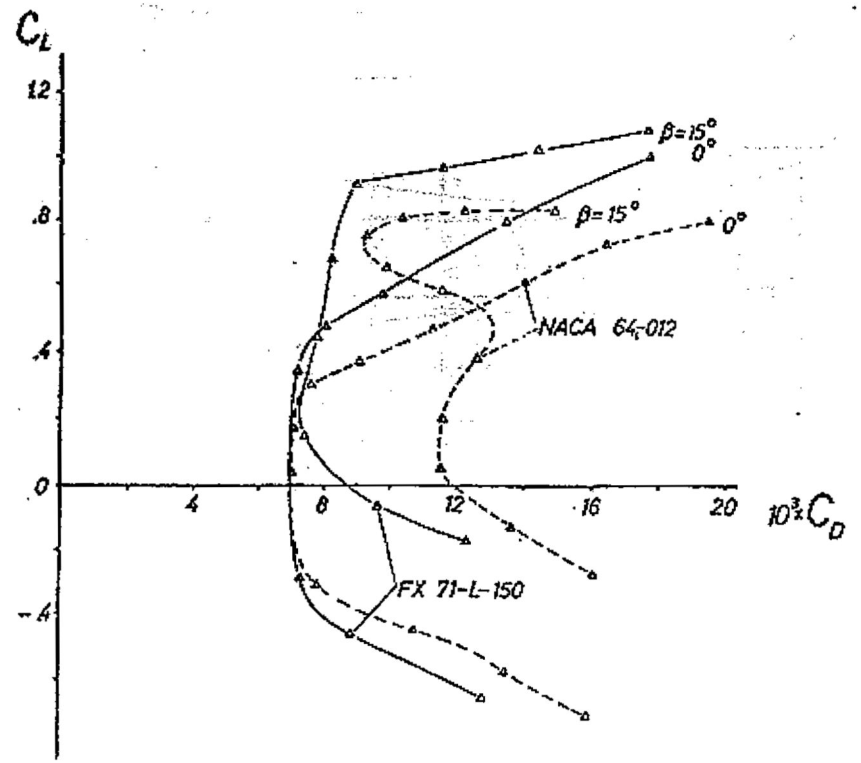

Figure 9.3 *Comparison of NACA 64012 section with Flap and Wortmann (designed for flap) at a Rn of 1.0 Million.*

As of today (1998) however, it is probably reasonable to suppose that with all the theoretical techniques and computational power that has been available for some time for such analysis, a plateau of development has been reached in 2D foil design for yachts as in gliders. That is to say that for a given Rn, t/c and desired Cl value a current 'best section' is unlikely to be bettered without the use of boundary layer control by suction, which may, as in the case of the IACC, be prohibited by Class Rules.

Such 'best' sections are not generally published and often regarded by designers as valuable proprietary items. Obara[5] provides good considerations of the issues involved however.

In the case of both keel and rudder sections desire for a high Cl max, at the expense of drag, in order to enhance manoeuvring and ultimate broach control may be misguided. In steady state sailing, keels normally operate within the Cl range 0.3–0.5 on the wind, and substantially below this when reaching or running, while rudders, the roots of which tend to be close to the air/water interface will normally ventilate well before any likely stall angle.

Interference drag

While sections of typically 15% t/c ratio may have suitable characteristics in 2D and open water, they might be expected to benefit from modification at the junction where they meet the hull and or bulb and a reduction of t/c to 9% or thereabouts via fairings on the leading edge (LE) and trailing edge (TE) would seem good practice.[6]

Section thickness

Today less than 9% t/c might be considered thin for yacht appendages, more than 15% would be regarded as thick. The principle difficulty with laminar prone sections of higher t/c thickness/chord ratio appears to be avoiding laminar separation at the rear of the foil hence loss of performance especially at lower Rn. The effect of this on a foil of 13.5% t/c may be seen in reference 7 as may be the corrective effect of turbulation strips.

Thickness however is the mechanism to provide the pressure gradients favourable to promoting laminar flow (thicker foils allow wider drag buckets) and so is not necessarily to be discouraged even when the volume or structural aspect is not required.

At low Rn however, thin foils will invariably yield the best performance and model racing yachts[8] are reported to use sections which are structurally limited of around 7% t/c while racing dinghy foils may also be expected to be less than 8% t/c.

Keel planform – minimisation of induced drag

Wavemaking from the keel root means that a reduction in root chord is generally desirable from the air/water hydrodynamic aspect especially when heeled but not from the structural requirements of stiffness in bending and torsion.

That hydrodynamic benefit is not necessarily the case with deeper bodied yachts such as those of the International Twelve or Six Metre Classes where the region of the canoe body close to the keel junction makes a considerable contribution to the generation of pressures that generate sideforce.[9]

References 1 and 10 treat extensively the effects of sweepback and taper ratio on planar keels and offer good guidance for an initial approach.

Sizing the keel

To windward high performance successful keels generally operate at a mean Cl range 0.3–0.5 as evidenced by the sailing leeway angles.

Pierre de Saix[11] made tests on a then contemporary International 5.5 m design and established that the fin keel contributes approximately from 80% to 62% of the sideforce as heel increases from 0–30°. The changes that have occurred in the International 5.5 m class may be seen in Figure 9.4

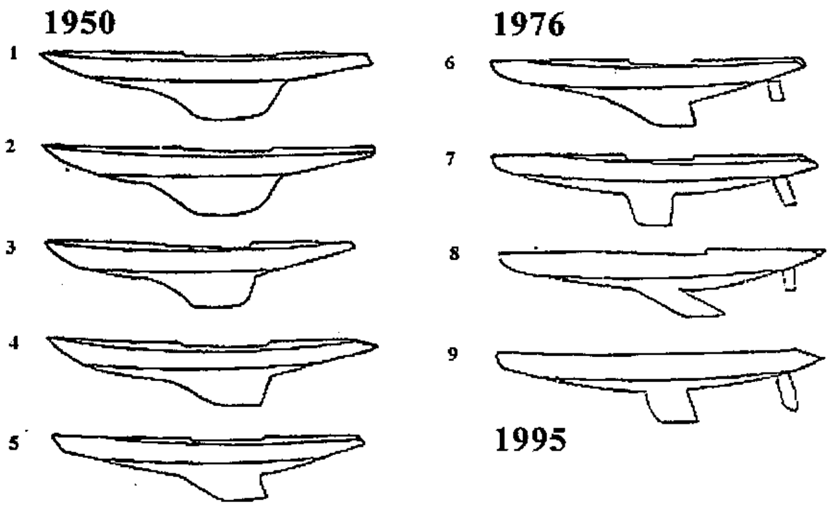

Figure 9.4 *International 5.5 m developments from 1950 to 1995. (From a student design project by R. Stadelmann 1995, Southampton Institute.)*

On modern racing boats of shallow canoe bodies the keel might be expected to carry a higher proportion of the sideforce, though the percentage carried by a typical deep modern rudder will have increased to compensate. 70% on the keel, 20% on the rudder and 10% on the canoe body might be expected to be a reasonable 'division of responsibility' for obtaining a sensible 'engineering solution' for typical conditions.

From a knowledge of:

1. The stability of a boat at an appropriate heel angle and an assumed height difference between the CE and the CLR the sideforce requirement for that heel angle may be deduced, that is the 'sailing sideforce' described in *Sailing Yacht Design: Theory*.
2. Its likely windward speed (the maximum V (knots)/√LWL on the wind is likely to be no more than 1.2)
3. A nominal design average Cl value of for example 0.3

we may derive as a first approximation a keel area appropriate for the purpose. This would then be refined by either past data, towing tank tests or by access to powerful computational methods.

The design of bulbs

A body of revolution, being of least wetted surface would be expected to provide the form of least drag at zero sideforce.

Guidance as to the drag and likely optimum proportions of diameter/length (d/l) for a given Rn are to be found in Hoerner.[6] It might be noted that airships have the same requirement as bulbs in terms of minimum drag for a given volume so data from these may be of interest if a high proportion of laminar flow is not sought or is deemed unrealistic.

Section shapes for airfoils are of course defiined for two dimensional (2D) forms and the pressure gradients associated with the same geometry, however, a technique for modifying these for 3D use was proposed in Galvao[12] whereby a 3/2 power modifier is used to generate equivalent favourable pressure gradients to the 2D. The effect of such a transformation shown in Figure 9.5 is to produce a sharper nosed section.

Figure 9.5 *Bulb designed using 3/2 power law transformation.*

Bulb/keel interaction

A body of revolution will invariably be a poor source of lift hence fitting a bulb of circular cross section within a fixed keel span will reduce the effective aspect ratio of the keel and hence its efficiency in generating sideforce. A longer bulb will have a smaller cross section hence have less detrimental effect on the production of lift. Likewise transforming the cross section to a flattened ellipse will do the same as well as having a lower VCG. Ellipse ratios for the cross section of the order of 2:1 might be considered normal.

Some of the bulb tip loss may be recovered by reshaping the form of the bulb especially by developing width (span) and/or chines, or by the fitment of wings. For both Twelve Metre and Six Metre Class yachts, where there is substantial wavemaking and proximity of bulb to canoe body, the author's bulb designs were cambered so that they contoured the streamline flow past the body. The curvature for these was derived experimentally in the towing tank with wool tufts on a flat plate grid in the region of the keel.

If winglets are to be fitted the afterbody of the bulb would generally be expanded in width to suit a natural blending of the joining surfaces. The drafting of cambered and twisted bulbs on a drawing board would be very onerous, and the advent of PC based fairing systems has made this work considerably easier.

Design of winglets

For minimum offwind drag winglets would be oriented to operate at zero Cl along their span at the chosen speed and in order to achieve this they may require twist as well as a particular incidence in order to conform to the 3D flow around a yacht hull with its attendant wavemaking or indeed the bulb itself. Wool tufts on wires set out from the centreline has again been the author's experimental method to get a feel for the best geometry to suit this requirement but no doubt computational methods would be very effective for this work.

On the Twelve Metres typically some 2° twist was used in the first metre of half span. As they produce such a powerful effect winglets can be expected to be highly loaded upwind and will require inverse camber, for it is the leeward winglet that is producing the desired result.

High span is most effective in promoting high performance, but such will be limited either by Class Rules or operational limitations. A root chord length of 25% of keel Chord would correspond with aircraft practice.

The effect of a trim tab

Contrary to popular belief leeway angle per *se* is not important to the performance of a yacht which may be considered as a black box with speed, a course direction and characteristics of stability, sideforce and resistance. The yachts orientation within the black box is thus of little consequence.

A trim tab is principally intended to increase chances of laminarity, effectively adding camber to a foil. Section shape should be such as to to provide the best pressure distribution with the tab set to 5°. It should be noted that tab deflection increases fin incidence which may result in a lower lift curve slope for the whole vessel[6] which may be why tabs rarely test fast in the towing tank.

On a Six Metre more than a certain angle of trim tab tends to make the boat feel directionally unstable (no available 'groove' – 'squirrely'). One interpretation of this effect might be that the extra loading on the fin and reduced leeway leads to balancing on a small edge rather than the longer distribution of pressure that would exist along the hull. As the yacht pitches it may be that the centre of pressure on the sail and that on the hull move about so that the craft begins to behave as a see saw so that a harmony of balance between hull and rig is unachievable.

Deep draft rudders – sharing the sideforce load between foils

Generating a significant proportion of the sideforce on the rudder blade reduces the required keel Cl value hence may mean a considerable gain in predicted induced drag. Panel calculations on a Maxi yacht suggested that the latter could be reduced to some 80% of its original value by so doing. When the writer first experimented in this area (1973) he was unaware of previous experiments of the same type, but Figure 9.6 shows a 1925 MOCAT design by Andre Mauric.

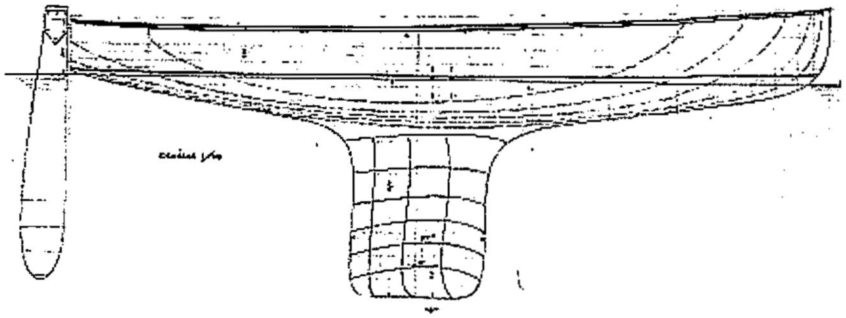

Figure 9.6 *1925 MOCAT design by Andre Mauric.*

Installing deep high aspect rudders means however, that the potential loads and bending that these rudders may experience can be considerable and even be a significant fraction of the displacement of the craft themselves.

Feel and smoothness of control is essential to the machine interfacing, MMI and on large craft such has only been made possible by the availability of self aligning roller bearings and advanced composite materials for the construction of the shaft and blade.

9.5 BALANCE AND STABILITY – THE EXISTENCE OF AN UPWIND 'GROOVE'

As well as the theoretical advantages of reduced drag, a deep aft rudder enables a greater movement of CLR without significant drag penalty. There are quite a few highly popular One Design Classes where sails have to be sheeted and/or designed to best match the poor initial balance of the craft.

The power variations available from sails and sail trim (as evidenced from wind tunnel tests) are such that the underwater appendages should attempt to give best scope to the same. Overloading the aft foil may give rise to a longitudinal instability, and it might be noted that free flying model aircraft are set up with a 'longitudinal dihedral', which is in the opposite sense to a loaded aft rudder in a sailing craft. In a stable mode a definite 'groove' may be felt and the widening of this as well as a more precise handling may be the most useful attribute of deep rudders.

9.6 EFFECT OF ALIGNMENT, SYMMETRY AND ACCURACY OF FOIL SECTION

Experimenters in towing tanks and high level One-Design Sailors will be conscious of the powerful effects of the above. Keels cast on their sides with subsequent differential cooling rates or those aligned without the greatest care seem to affect performance considerably and the the anecdotal stories of Solings etc which are taken into boatyards for reworking and come out substantially faster are legion.

Where the budget permits, NC machining may be used with advantage to guarantee both accurate section shape and symmetry.

On dinghies the characteristics tack to tack may also be quite different if the centreboard and rudder are out of alignment in the vertical plane and/or with the rig and this is an important check for best performance. In terms of achieving section accuracy, experiments with Standard Class gliders have shown that the overall L/D ratio may be reduced from 40:1 to 30:1 with 'production' sections that do not carefully correspond with the designed section.

9.7 FOILS FOR RACING DINGHIES

Design of the planform and areas employed is almost invariably by experiment[13] and modification of past successful practice. Likewise the centreboard is positioned from successful past practice, modern dinghies with asymmetric spinnakers often have the board further forward than would have been the case in order to mimimise lee helm with that sail up in light airs. Tipping the boat to leeward is another technique employed to cope with the problem of lee helm.

Gybing boards have from time to time been popular in the Development Classes but Hoerner,[6] as with trim tabs, suggests a reason why such may not be overly successful.

An interesting description of a practical method of section development to maximise laminar effects is described in Bethwaite[14] but sadly the section offsets are not published but no doubt could be readily derived from examples in the dinghy park.

A dinghy experience that many will have encountered is that of the board humming or singing. This is normally caused by a trailing edge (TE) of excessive thickness and thinning or cutting the trailing edge off at an angle will normally effect a cure.[1]

This type of high frequency vibration may also be encountered on larger craft (from keels, winglets and rudders). In fact disturbing high frequency resonant responses of the whole rig under power have been reported. Such vibrations have been eliminated by the removal of the concave regions in the rear of the keel sections, which would in any case be standard practice for most dinghy foils.

9.8 APPENDAGES FOR MODEL RACING YACHTS

The most competitive type of Model Racing Yacht has long been the 50 inch Marblehead Class and the popularisation of radio-control racing further accentuated this. Modern examples of these craft have high aspect ratio keels of extreme draft and therefore use advanced composite materials to avoid excessive bending and torsional effects, the latter being minimised through the siting of the bulb LCG close to the twist centre of the keel fin. This is a feature which also allows the rig to be moved aft in the boat.

The planforms are reported[8] to be derived primarily from structural considerations while the areas employed have been developed to suit tactical transitional sailing whereby most races are won or lost. The foil sections employed are typically 7% t/c, no doubt thinner would be preferred at these low Rn but stuctural requirements again dictate practical limits. Young's Laminar bodies are generally used for the shaping of the bulbs which typically have diameter/length ratios of 1:6. More recent experiments have suggested that finer forms with ratios as extreme as 1:10 may have a performance advantage.

9.9 KEEL DEVELOPMENT IN THE TWELVE METRE CLASS

Developments in Yacht Design are almost always made within the context of the Rules of a Racing Class. In the 1980s the then America's Cup Class yachts, the International Twelve Metre, was the hotbed for the development of a new breed of shallow draft keel and a description of these developments should help to explain how some current configurations have evolved.

In 1964 the definitive Twelve Metre yacht was considered to be the full keel Cup Defender 'Constellation', but in 1967, 'Intrepid' came out with a fin keel of substantially reduced chord fitted with a trim tab and aft rudder. It might be noted that several experiments had previously been made with such a configuration in the Six Metre Class, by W.J. Daniels ('Josephine' 1926), John Stevens ('Maida' 1939) and Uffa Fox ('Noroda' 1950), but these were without exception disappointing in performance. The W.J. Daniels design in both its original and modified and more successful form with full keel were described in Yachting Monthly[15] see Figure 9.7.

Subsequent to 1967 and despite extensive tank work at scales as large as 1/3 (after some backward steps in 1970 with oversized hulls of excess afterbody fullness developed from small model tests) further development in the Twelve Metre Class became very slow, indeed many commentators believed that (as they had in the 1960s) the Class was 'played out'. The America's Cup in1983 however, saw the arrival of 'Australia 11' in Newport R.I., her dominating performance over the other Challengers and her historic victory over the NYYC defender.

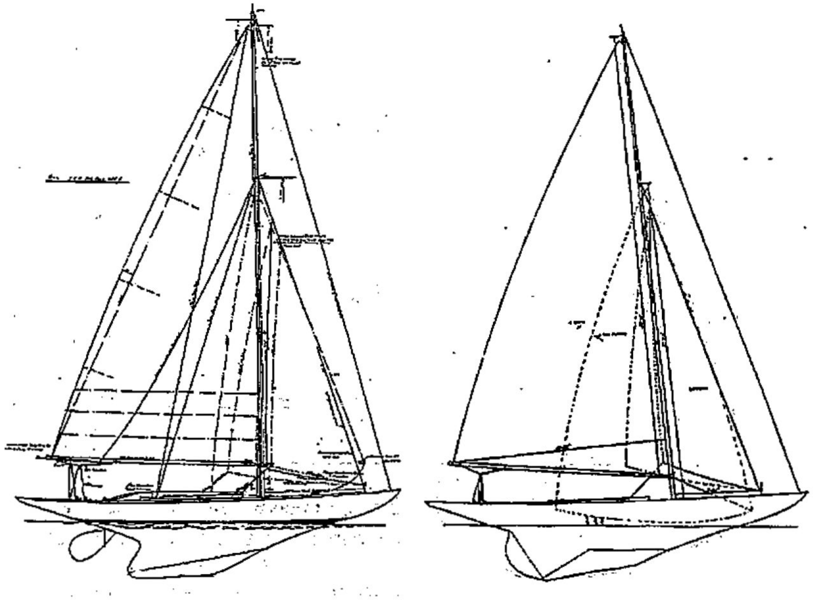

Figure 9.7 *The 1926 Six metre Josephine, before and after modification.*

While Australia 11 was not dramatically faster in a straight line (particularly in water other than smooth) than the best of the other boats of that year, she was fitted with perhaps the best sails in the regatta and had an excellent and experienced crew. The manoeuvrability and speed out of tacks conferred by her short chord wingletted keel was remarkable, both these characteristics being a great asset in the match racing format of that event.

A simplification and summary of the thinking behind Joop Sloof's/Ben Lexcen's concept for the 'Australia 11' keel was perhaps as follows:

1. An inverse taper keel would be more efficient because it would move the lift/sideforce away from the interface of air and water and hence save the drag associated with this
2. The centre of gravity would thereby be lowered thus equivalent stability might be achieved with a lighter boat; hence better acceleration for match racing
3. The low sweep angle (the 25% chord line was unswept) would promote laminar flow over the keel, sweep being the enemy of such a propensity and the forward sweep of the leading edge would prevent boundary layer contamination from the canoe body
4. Edge losses across the long tip chord could be minimised with the use of winglets while these being of substantial volume would again further lower the VCG

At that time winglets were a fairly recent development in aircaft though they have been apparent on the primary feathers of some soaring birds since time immemorial.

This authors' work in the field came from a rather different direction. Winglets were tested in the wind tunnel in 1981 on a double model of a 'conventional' 12 m keel 'flown' in a wind tunnel as part of tests on a series of sections, devices and tip shapes. The indicated gains were considerable as per Figure 9.8 which suggested that of the order of 9% of total upwind drag might be saved by their use. These winglets however were intended purely to reduce induced drag and did not carry any significant proportion of the ballast.

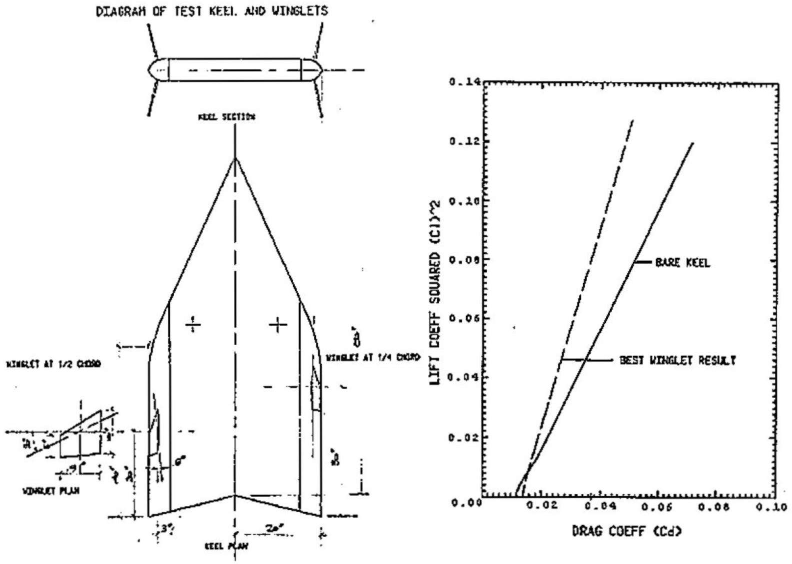

Figure 9.8 *Wolfson double model wind tunnel tests on Winglets.*

In later model testing in the tank at 1/10 scale the following effects were indicated with an 'Australia 11' type keel. With no winglets on this keel the hull's ability to produce sideforce at low drag cost was inferior to the conventional keels. Fitting the winglets caused the VCG to be lowered and the keel efficiency to be considerably improved, while perhaps of major significance the centre of pressure of the boat would be moved back some 1.0 m full size which was equivalent to some 4° of rudder angle.

Despite the gains with the winglets the predicted upwind performance of this boat (tested it should be emphasised at 1/10 scale and employing normal scaling procedures) was slightly inferior to the best conventionally keeled model. From experience in real life and later tests at larger scale this had to be ascribed to scale effects with the model size employed.

Later developments in the Class leading up to the Cup races in Fremantle1987 brought about the development of keels of higher t/c ratio especially in the lower regions and high span wings mounted on bulbs of various forms in way of the trim tabs. These wings which were typically of 3.2 m span, not only significantly reduced the induced drag but also moved back the CLR by a further metre or so. The great advantage of this effect being such that it occurs as the boat heels which is just when it is most required by the position of the rig forces. Likewise when tacking, the mainsheet did not require easing to anything like the same extent as previously, hence speed out of the tacks was much improved.

The development of these 12 m keels led to a much greater understanding of the possible mechanisms for making improvements to low aspect ratio keels and has had considerable impact on the design of keels for cruising yachts.

Another major lesson from Fremantle was that it is rare to have too much stability when the breeze fills in but again, of course as any dinghy sailor will attest, stability is coupled to balance.

It should be emphasised that the author's keel developments in this era were all made experimentally in the towing tank using 1/10 and 1/4 models, sadly no CFD or other proper numerical theoretical calculation methods being employed.

The other interesting development of the 1987 Cup races was the advent of 'USA' designed by Gary Mull which employed a canard configuration. Here the sideforce (a low VCG and hence stability was provided by a lead bulb) was intended to be shared primarily between the highly separated front and rear high aspect ratio foils in order to take advantage of the theoretical aerodynamic advantage. (See 1989 design Figure 9.10.)

Curiously this form of configuration was not uncommon on model yachts at the turn of the century and in fact was tested by the author at 1/12 scale in 1973. At this scale with its attendant low Rn however the performance of the tiny foils was unsatisfactory and that model showed no special promise in the tank. Later tests in 1987 at 1/4 scale demonstrated however, the extraordinary characteristics of the type with the reduction in wavemaking when heeled being quite remarkable. The waves at 9 knots boatspeed being equivalent to those which might be expected at 8.5 knots due to the favourable interaction of the wave system from the lifting foils with the canoe body wave pattern.

The ability of foils with a horizontal component to interfere destructively with hull surface waves (also to control trim) is surely an area requiring greater research attention, particularly in an era concerned with the development of low wash forms for powercraft. As with high span winglets the performance evidenced itself in the towing tank as an insensitivity to heel angle (i.e. the models efficiency to develop sideforce did not decline with heel angle in the normal way) driven by the above effect.

The 1987 Cup was the last to be sailed with the Int 12m Class of Yacht and since 1992 the new IACC Yachts have been employed with an allowed draft of 4.0 m (rather than 2.75 m) producing appendages of an effective aspect ratio (waterline reflection surface) of the order of 9 rather than the 1.5 of the Twelve Metre.

9.10 INTERNATIONAL SIX METRE CLASS

Racing development of the shoal draft winged keel form has continued however in the Six Metre Class which following a moribund period after 1956 has enjoyed a revival of interest from the early 1970s. In the period of this rebirth, which closely followed the building of 'Intrepid', a type of keel intended to produce the smoothest possible section area curve became 'state of the art' and rudders were made miniscule to minimise wetted surface. Such a form is shown in Figure 9.9 alongside an early design of Six Metre.

However by the mid 1970s forms with more separated fins and more workmanlike rudders had appeared as real life testing emphasised the need for accurate control and gust response.

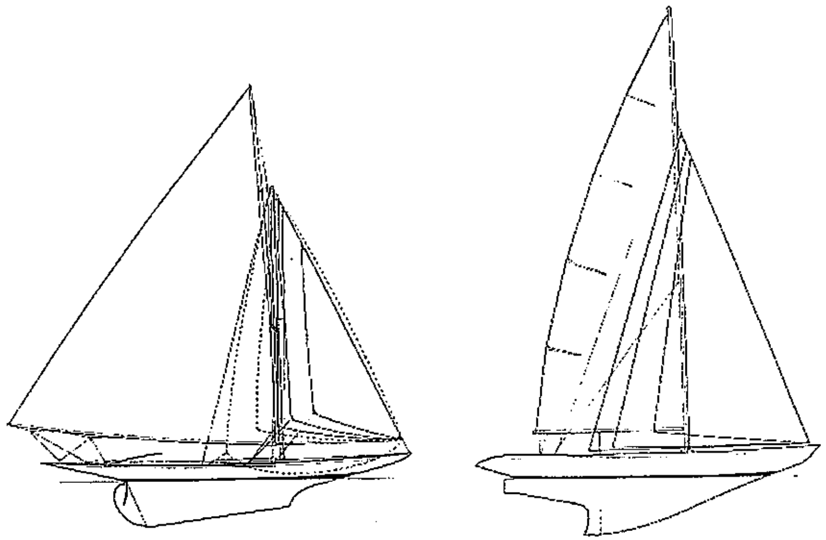

Figure 9.9 *An S&S designed Six Metre from the 1970s and an early Six Metre.*

Figure 9.10 shows the changes tested over a seventeen year period by the author. It might be noted that the Canard (1989) configuration won the World Cup in 1993, while the 1986/7 configuration won the Seawanhaka Cup in 1987, the European Champs in 1988 (indeed this keel type won every race at this event) and 1996, and the Worlds in 1995 and 1997.

No significant advances appear to have been made in hull design over that period but real performance gains have come about from developments in keel design and the consequent ability to derive more power from the rigs to suit. These developments took the following form and were supported by 1/5 scale model tests by the Wolfson Unit MTIA.

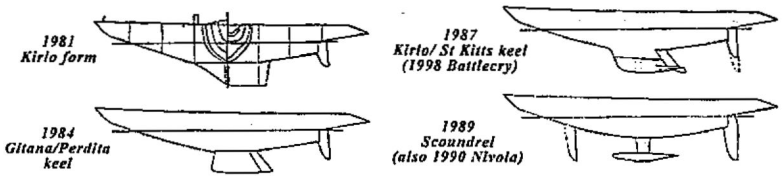

Figure 9.10 *Sequence of Six Metre keel developments by the author from 1981 and 1989.*

1981 'Kirlo' form

This keel is not untypical of the era with a hint of the influence of the IOR which taxed stability in an indirect attempt to control scantlings. Perhaps of special interest was the development of this keel planform which was used in 1983/4. This minor variation had the rake of the bottom removed and the tip made square in line with tunnel tests and a desire for greater stability. The result was significantly slower on the racecourse and later tank tests indicated that the leading edge toe of the keel was producing a substantial drag increase at least at that scale while having a minimal effect on lift curve slope... a reminder that sometimes it is important to test the whole craft and not just individual elements.

1984/5 inverse taper keel

These were tested at 1/5 scale, it had been found difficult to make Australia 11 low aspect type winglets work on the higher aspect ratio of a Six Metre keel. This keel, which was without winglets, was intended to encourage laminar flow tendencies and produce a 12% stability gain but overall the arrangement was probably slower than the original 1981 keel. Sections employed were Wortmann based but modified in t/c ratio and for a flap angle of 5° (by Rule of Thumb an attempt was made to make the suction side physically smooth at 5° by employing flats in the section) rather than the 10° which seemed to be the design value for the section in its intended role for glider tailplanes.

Feedback from one of the boats fitted with this keel described that it was very hard to find a 'groove' upwind, and doubts were cast on the somewhat 'bullet nosed' leading edge. This was modified more in line with a NACA 63 series section and an improvement was subsequently reported by one of the helmsmen.

Further experiments with the type included 'filling in' above the forward swept LE to produce a vertical LE and a keel of increased area and this was considered a further improvement in the conditions prevalent on Lake Geneva, so would presumably have been better again in wave conditions at sea.

A substantial change of form was evaluated in 1986 after further model tests on a variety of keel forms at 1/5 scale in the towing tank. A bulb form (bulb carrying 40% of total ballast weight) enabled stability to be increased by a further 12% and this keel with a vertical leading edge did seem slightly faster in real life.

Its full potential was only realised however, when the winglets for which it was designed were added in 1987. A wing bulb keel whereby 60% of the ballast weight was sited in the bulb also tested well but was felt slightly too extreme, this was later to become the basis of a new breed of cruising keel.

1987 development of the 1986 keel

This utilised the same bulb but with increased fin area after reports of performance questionability in large lumpy seas and most importantly winglets in way of the trim tab as described above. Interestingly even at 1/5 scale the upright drag of this keel was reduced relative to the thinner and shorter 1986 keel, and the VCG was further lowered.

In real life testing quite aside from the racing success of the yachts fitted with these keels, trialling with hulls of identical design indicated no downwind speed difference between a traditional swept keel and a winglетted keel of the 1987 design, while upwind the difference was quite marked.

1989 developments

These saw the addition of rudders of maximum draft (later tank tests indicated an equivalent reduction in induced drag to that achieved by the addition of wings) and refinements to the wings. These latter tested to have a drag of only 1.5% of total upright drag at 1/5 scale, which was readily recovered by an improved sideforce drag slope.

1989 'Canard' keel

Class Rule changes in 1987 allowed only a fixed forward foil to be employed so it was most interesting to discover how this arrangement would perform upwind in real life and how it would steer.

Remarkably it felt docile to handle in the manner of a long keeled steady cruiser and was quite without vice.

At 1/5 model scale it was notable that the upright drag of a bulb and strut was greater than that of a bulbed keel form, again, with a larger model size this order was reversed. 1/4 scale towing tank tests on the Twelve Metres had indicated that light air performance might be suspect and that performance would be best when allowed to foot off rather than pinch, and this seems to have been borne out in practice, though the effects as ever are masked by other factors.

9.11 DELTA WINGED BULB KEELS FOR CRUISING YACHTS

A development that has been most interesting has been the design of delta winged bulb keels which have been fitted to a range of yachts from 9–24 m LOA in order to achieve high performance with moderate draft. An example of some 8 Tons fitted to a 20 m cruising yacht of 2.3 m draft is shown in Figure 9.11.

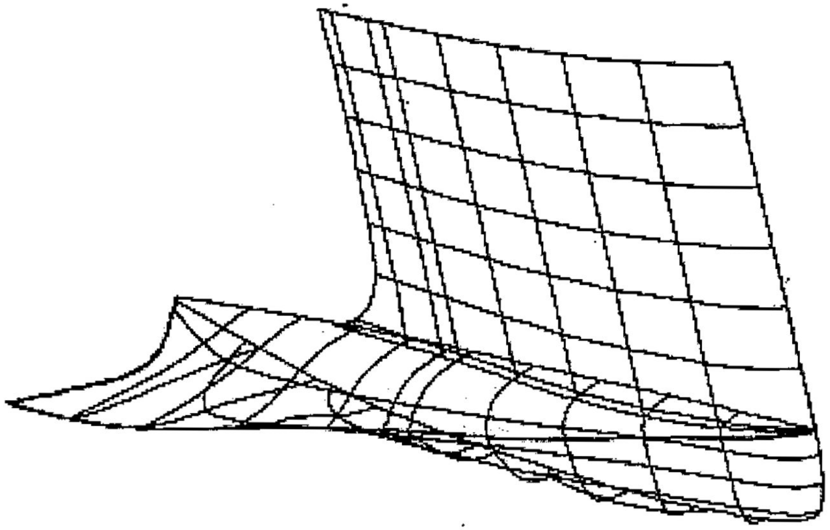

Figure 9.11 *Example of Winged Delta Bulb cruising keel by the author.*

These keels generally comprise an iron fin fitted with a lead bulb carrying a high proportion of the ballast and having significant span.The bulb achieves a low VCG and its short length permits a form without a weed and line catching prognathious leading edge while the span of the wings pulls back the CLR when the boat heels.The bulbs are twisted and cambered to suit the flow and the wings raised above the maximum draft position to make these less vulnerable to grounding damage.

One unexpected benefit is that the heave response of boats fitted with these keels appears to be substantially modified and comments that the boats feel larger than they are and have improved motions have been common, especially on retrofits where a direct comparison may be made. Yachts fitted with these keels also seem to be particularly well mannered in their handling.

9.12 USE OF COMPUTATIONAL FLUID DYNAMIC METHODS

Conspicuous perhaps by its absence in the above notes is any mention of CFD methods in the design of 3D appendages. We live in an age where computational power is multiplying at a remarkable rate so there can be no doubt that such methods will prove invaluable in times to come when they have been fully tested against experimental results. The author's experience with these methods and consequent opportunity to assess results in real life has so far been rather limited so

9.13 CONCLUSION

The attainment of optimum balance between hull and rig may generally be expected to have greater effect on performance to windward than any other single factor. This is however, one of the most difficult of all areas to analyse so there is first and foremost the need for experience and judgement as is the case in most other areas of design and engineering.

Rating Rules which influence all aspects of yacht design may be less than helpful to general progress, encouraging unwise features – the IOR rewarded excessive beam and taxed stability hence safety while outlawing potentially desirable cruising developments such as bilge boards. Likewise as has been described winged keels may also provide real advantages so the discouragement of these may be misguided.

If it is one of the intended functions of a Racing Class to improve the breed, as declared by the International America's Cup Class Rule for example, (Ref IACC), then those who administer future Rules should perhaps consider carefully the rationale behind particular restrictions and limits of proportions.

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