AMERICA'S CUP YACHTS - RECENT DESIGN DEVELOPMENTS

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SUMMARY

In this paper a review is presented of recent trends in the design of America's Cup Class (ACC) yachts , in particular with respect to the design of the canoe body and the appendages. These trends are presented as a logical result of the continuing search for more speed. For example, it is shown that the search for designs with better all-round performance has resulted in narrower hull forms. Likewise, the quest to find higher speeds sailing upwind, at relatively large angles of heel, has resulted in the adoption of extremely U-shaped sections.

After critically examining the America's Cup Class Rule, an overview of some notable design trends and innovations during the 1992 to 2003 period is presented. More recent developments in the design of ACC yachts, both those that are apparent to the trained eye and some that are perhaps not so apparent, are then examined. Aspects of the canoe body and the appendages, to which a lot of attention is now focused, are discussed.

Many experienced designers are of the opinion that further design innovations, leading to a significant jump in performance, are no longer possible within the constraints of the existing ACC Rule. This topic is also discussed.

1. INTRODUCTION

The use of the America's Cup Class (ACC) Rule for the design of the yachts for the America's Cup events in 1992, 1995, 2000 and 2003, has led to a very specific yacht, both with respect to its dimensions and its geometric details. Although the trained eye will have acknowledged differences between the boats in the 2003 event, the untrained eye will not have noticed many significant differences. The present-day ACC yacht is about 24.5 m long, about 3.6 m wide on the deck, displaces about 25000 kg, has a fin keel to which is attached a long torpedo-like bulb with a mass of about 20000 kg, to which are fitted high aspect ratio winglets. A single, relatively deep rudder, with a very small chord, completes the configuration, as shown in figure 1.

America's Cup yachts are today designed by a large team of qualified persons, in number ranging from 4 to more than 12 or so. In these teams the yacht designer-naval architect usually plays an important role in ensuring that the many elements of the yacht are integrated into the overall design in a way leading to optimum performance, while hydrodynamicists, aerodynamicists, people fluent in the process of applying and understanding Computational Fluid Dynamics (CFD) software, structural engineers, sail and spar designers, etc, all play an important role in researching the many detailed aspects of the design.

Most designers and specialists involved in the design of this type of yacht are likely to agree that it is now no longer possible to define design improvements leading to major performance gains. Only relatively small performance improvements remain to be identified within the configuration that is now almost universally adopted. While this may seem comforting to some competing for the America's Cup because of the fact that it is not very likely that a design team today will design a yacht totally "off the pace", it is at the same time - for those seriously wanting to leave no stone unturned in the search for a performance edge - still a very intensive design project, requiring considerable man-power and budget.

After critically examining the America's Cup Class Rule in paragraph 2, this paper first gives an overview of some notable design trends and innovations during the 1992 to 2003 period in paragraph 3. More recent developments in the design of ACC yachts, both those that are apparent to the trained eye and some that are perhaps not so apparent, are then examined. Aspects of the canoe body and the appendages, to which a lot of attention is now focused, are covered in paragraphs 4 and 5. The possibility of identifying further design innovations, leading to a small or large jump in performance, is then discussed in paragraph 6. Conclusions and final remarks are listed in paragraph 7.

The mast, rig and sails are not addressed in this paper. There are others associated with the design of ACC yachts that are more capable to address these topics.

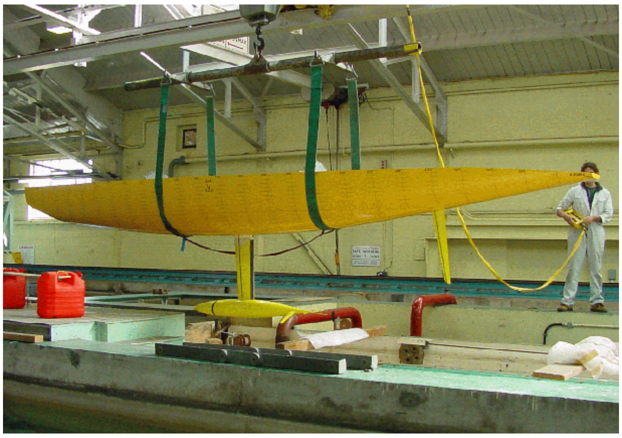

Figure 1: Tank testing model of a typical 2003 ACC yacht

2. THE AMERICA'S CUP CLASS RULE

In this paragraph the main design constraints as listed and described in the America's Cup Class Rule are discussed. Version 4.0 of the Rule (see the list of references in paragraph 8) is adopted for this purpose because of the unavailability of version 5.0, at the time of preparing this paper.

The main formula of the Rule requires a trade-off between length of the canoe body, sail area, and displacement, as follows:

$$\frac{L + 1.25 \cdot S^{1/2} - 9.8 \cdot DSP^{1/3}}{0.679} \leq 24\,metres$$

In this formula:

L	=	rated length;
S	=	rated sail area;
DSP	=	displacement in cubic metres in the so-called measurement condition.

Rated length is defined as:

$$L = LM\left(1 + 0.01(LM - 21.2)^8\right) + FP + DP + WP + BP$$

in which:

$$LM = LBG + G$$

where:

LM	=	measured length;
LBG	=	length between girth stations;
G	=	girth component of LM;
FP	=	freeboard penalty;
DP	=	draft penalty;
WP	=	weight penalty;
BP	=	beam penalty.

The length between girth stations LBG is measured at a height of 200 mm above the measured waterline MWL. MWL is the plane of flotation of the yacht in sea water with a density of 1025 kg/m^3 in the measurement condition.

The girth G is the sum of a transverse girth measurement at the forward girth station FGS, situated at the forward extremity of LBG, and at the aft girth station AGS, situated at the aft extremity of LBG. The hull form is nowadays shaped so as to be able to adopt the minimum values of 0.3 m at the FGS and 1.6 m at the AGS, without penalties. Accordingly we can write:

$$LM = LBG + 1.9\,metres$$

and

$$L = (LBG + 1.9)\left(1 + 0.01(LBG - 19.3)^8\right)$$

This relationship is today strictly adhered to so as to be able to maximum LBG. The 8th power of the term (LBG - 19.3) will allow an LBG value approaching 20.3 and, usually, a value of LBG is chosen of about 20.2, yielding a value of L of about 22.2. Table 1 shows the effect on L when LBG approaches the value 20.4.

The rated sail area S is defined as:

$$S = SM\left(1 + 0.001\left(SM^{1/2} - 16.9\right)^8\right)$$

where:

$$SM = MSA + \frac{(I \cdot J)}{2}$$

in which:

SM	=	measured sail area;
MSA	=	mainsail area;
I	=	height of foretriangle;
J	=	base of foretriangle.

The maximum value of SM without appreciable penalty, is about 18^2 = 324 m^2. This follows from the same consideration as described above for L, see table 2.

The displacement DSP is simply the mass of displacement in kg divided by 1025 and, in salt water with a density of 1025 kg/m^3, corresponds to the volume of displacement in m^3. The minimum value of DSP without penalty is 16000/1025 = 15.61 m^3, and the maximum value of DSP without penalty is 25000/1025 = 24.39 m^3.

Table 1: The effect on rated length L on increasing the length between girths stations LBG

LBG (m)	L (m)	Increment in L for 0.1 increase in LBG (m)
19.8	21.701	0.101
19.9	21.804	0.103
20.0	21.913	0.109
20.1	22.037	0.124
20.2	22.195	0.158
20.3	22.422	0.227
20.4	22.778	0.356

Table 2: Table 2. The effect on rated sail area S on increasing measured sail area SM

$\sqrt{SM}$ (m)	$\sqrt{S}$ (m)	Increment in $\sqrt{S}$ for 0.1 increase in $\sqrt{SM}$ (m)
17.5	17.500	0.100
17.6	17.601	0.101
17.7	17.703	0.102
17.8	17.808	0.105
17.9	17.918	0.110
18.0	18.039	0.121
18.1	18.178	0.139

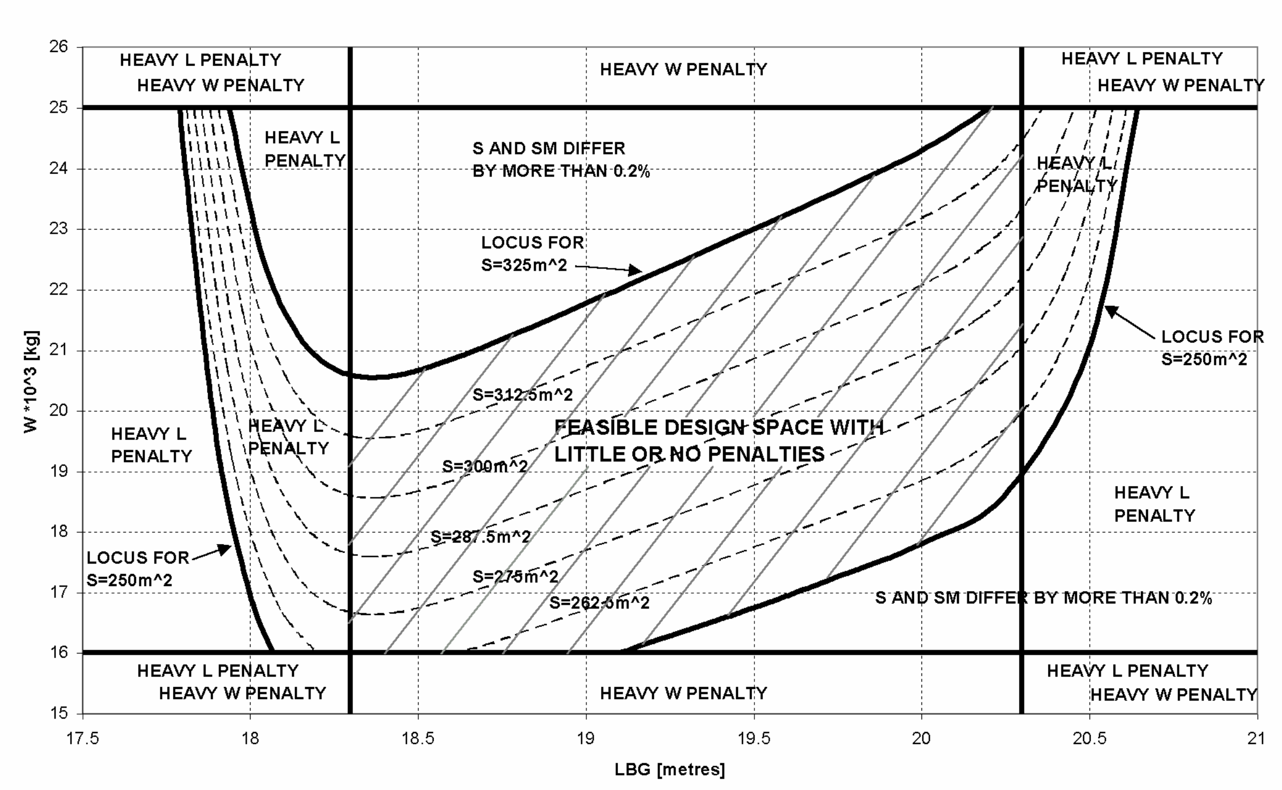

Figure 2: Graphical representation of the main formula of the ACC Rule.

With few exceptions, ACC yachts that have either raced in the Luis Vuitton Cup or in the actual America's Cup, are positioned in one specific corner of the ACC Rule. This is the corner where rated length L is maximum, rated sail area ($\sqrt{S}$) is maximum, and displacement DSP is maximum, without appreciable penalties. These values, as seen above are about 22.2, 18.0 and 24.39 respectively. Substituting these in the ACC rating formula gives a value of 23.976, which requires little fine-tuning to obtain 24 metres.

The main formula of the ACC Rule is graphically represented in figure 2.

In both Cup venues to date (San Diego in 1992 and 1995, in predominantly light winds, and Auckland in 2000 and 2003, in a wide range of wind conditions), the best performing designs were in this corner of the Rule. It is clear that the group of designers and racing rule developers, responsible for the first version of the ACC rule and this rating formula (developed in 1988 and 1989), in which sail area, length and displacement are traded-off, failed to develop an equitable formula in which more than one combination of these 3 factors leads to similar performance in certain wind conditions. The Wolfson Unit (see the list of references) was tasked to develop this rule formula by the America's Cup Class Technical Committee, charged with developing a new class of yacht for the America's Cup event to replace the International Twelve Metre Class that had been used for this purpose for so long. The Wolfson Unit used a Velocity Prediction Program (VPP) and some model tank test data to analyse 85 different designs. Effects of length, displacement and sail area were looked at in detail. Most of these 85 yachts, understandably, did not rate according to the formula that was subsequently drawn up. Knowing how difficult it is to develop a VPP that is able to rate the performance of a wide range of designs fairly, it is not surprising that the developed expression was found to be biased towards one corner of the design space.

Nevertheless, the existing ACC Rule has well-served the America's Cup event ever since its introduction. The resulting ACC yacht has allowed for close racing and a supremely good performance to windward. Altogether 82 ACC yachts have been built up to 2003.

The ACC Rule allows for a wide range of appendage configurations. Nothing is specified in this regard except that there may be only 2 movable (i.e. rotatable) appendages. The axis of rotation of each movable appendage must be in the symmetry plane of the yacht at an angle not exceeding 45 degrees to the vertical. It is further stipulated that appendage rotation must not influence the righting moment or the fore and aft trim of the yacht. It is also required that appendages are attached to the canoe body in a narrow region, 250 mm wide from the forward end of the measurement trim waterline to a point 0.25 x LBG further aft, and in a region 500 mm wide, aft of that, to the aft end of LBG, both regions being positioned symmetrically along the centre line. It is

in this region only that the canoe body may have hollows (and then only in conjunction with fitting an appendage).
Different types of appendage configurations have been adopted on ACC yachts. Over the years, however, a majority of the design teams have opted for the traditional fin keel with trim tab, to which are fitted a long bulb and winglets. A single, conventional rudder completes the appendage configuration.

Other notable limitations in the ACC Rule is a maximum overall beam, without penalty, of 5.5 m, a maximum draft without penalty of 4 m (in the measurement condition), a minimum set of freeboards, a set of prescribed construction materials, specifications on the size and position of the cockpit, hatches and other openings, etc.

3. OVERVIEW OF SOME NOTABLE DESIGN TRENDS DURING 1992 - 2003

3.1 WATERLINE BEAM

The most marked design trend over the years has been that of a reducing waterline beam. Early ACC designs had waterline beam values of between 4.0 and 4.5 metres. Now, this typically varies between 3.3 and 3.5 metres. It is remarkable that it took till the year 2000, for the majority of the competing teams to discover this. Most experts will agree that America[3]'s successful defence of the Cup in 1992 was for a large part due to having discovered the importance of a smaller waterline beam. Il Moro di Venezia (ITA 25), the Italian challenger, was markedly beamier than the defending yacht (USA 23). America[3]'s huge research effort (probably the biggest ever undertaken in America's Cup history, see reference 3) was not successful in pin-pointing the optimum value. It was the New Zealanders (NZL 32 and NZL 38) and the Australians (the ill-fated AUS 35), in the 1995 event, that homed in on the correct value for the first time.

The search for stability was considered paramount in the early years of ACC design. The opinion amongst the designers that participated in formulating the ACC Rule in 1988 and 1989 was that beam should be maximized, not minimized, and the 5.5 metre limit, still part of the Rule, was then formulated.

3.2 BOW SHAPE

Where bow shape in 1992 varied from the typical destroyer-type bows of the IOR and IMS Classes, to the so-called spoon bow with a significant overhang, similar to that of the International Metre Classes, the bow geometry now seems to be settled in favour of that first introduced by Team New Zealand (TNZ) in 2000 on NZL 57 and NZL 60. The spoon bow is recognized to be more effective in generating slightly lower wave drag values in specific Froude number regions, due to differences in trim and sinkage. When sailing in waves, these differences are more significant. The TNZ bow retains most of these characteristics, while generating a longer waterline length when heeled and a more effective curve of sectional areas in connection with reducing wave drag.

3.3 TOPSIDES FLARE

Early ACC boats had considerable topsides flare. Again, the reasoning for this was that it was necessary to maximize stability. Today, we realize that topsides flare increases both viscous and wave resistance when the leeward side of the canoe body is heeled into the water. Careful testing has shown that flare such as incorporated on the 1992 and some 1995 designs is more harmful to performance than the reduction in stability associated with little or no such flare.

3.4 APPENDAGE CONFIGURATIONS

The appendage configuration universally adopted for 2003 was that of the standard fin keel with trim tab, with bulb and winglets, often denoted as the T-keel configuration. Only the second British yacht - that has been quoted as "being off the pace" - had a different appendage set. In 1992, the tandem keel was popular (used by New Zealand and Australia) but although NZL 20 was fast, narrowly missing out on winning the Louis Vuitton Cup, this concept was not to re-appear again (not counting the keel of GBR 78 which has been reported to have a tandem keel). Since then, the conventional T-keel configuration has been used, with the exception of the yacht used by the first Swiss entry in the America's Cup in 2000 (see reference 4) and the second British boat in 2003. An overview of the appendage sets used on ACC yachts to date is shown in Figure 3.

4. RECENT DEVELOPMENTS IN CANOE BODY DESIGN

4.1 IMPROVEMENTS WITH RESPECT TO REDUCING HYDRODYNAMIC RESISTANCE

The present search for the optimum canoe body is concentrated on relatively small geometric details. Optimum length, beam and displacement values are well established. With the exception of beam, these values appear to be little influenced by wind speed or venue. For the conditions prevailing at San Diego (predominantly light conditions) and at Auckland (predominantly moderate to heavy conditions), the choice of waterline length and displacement are basically the same. Design details are now focused on deriving a shape that will generate the least hydrodynamic resistance in the heeled condition while retaining the required stability, and the best interaction with the appendages to generate the highest effective appendage span, producing minimum induced drag.

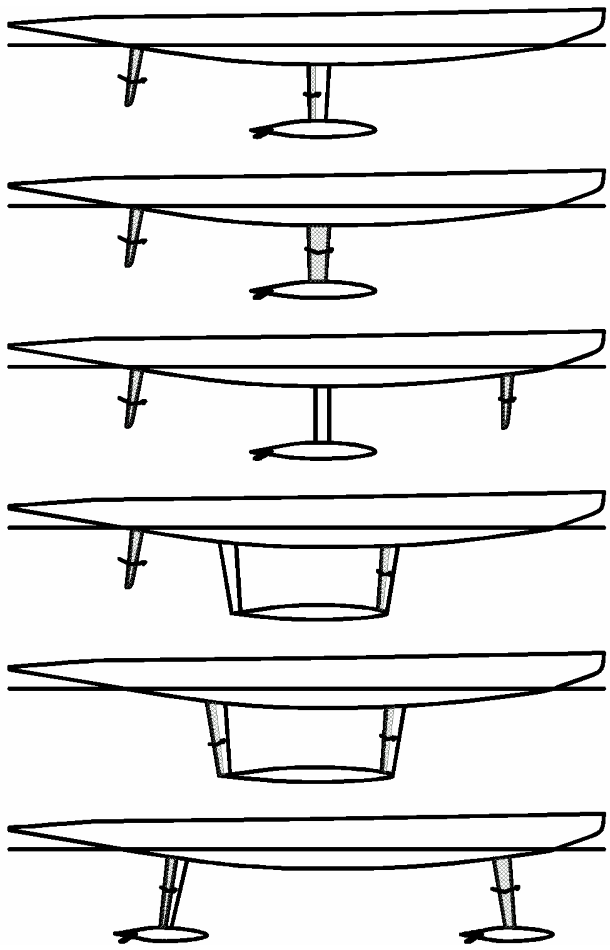

Figure 3: *Types of appendages used on ACC yachts to date (configurations used for experimentation purposes and not for racing are not shown).*

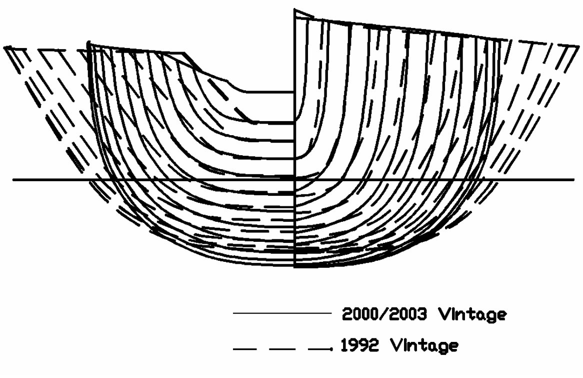

Figure 4: *Body plan of two canoe bodies, one with section shapes as adopted in 1992, and one typical of the present ACC design, revealing how the ACC yacht has evolved.*

The search for the optimum canoe body shape in heeled conditions is totally a result of the priority placed on performance upwind. To achieve a long waterline length when heeled, U-shaped sections are now utilized over the total length of the hull. This can be seen in figure 4 in which the body plans of two canoe bodies are overlaid, one with sections as used in 1992, and an ACC yacht typical of the 2000-2003 crop, both scaled to the same LBG length. The associated change in heeled waterline length is shown in figure 5.

The hull of a sailing yacht with moderate to heavy displacement will sink further into the water at speeds in excess of a Froude number of about 0.30, because of the presence of a relatively deep wave trough amidships. When the yacht has bow and stern overhangs such as ACC yachts have, extra waterline length is thereby created. This fact, amongst others, warrants a detailed study of the curve of sectional areas, i.e. the distribution of volume along the length. Model test results indicate that it pays to distribute volume from the middle of the boat to the bow and stern region, more so than what would be considered normal in the case of other design classes. The TNZ bow allows such a volume distribution more effectively in the bow region. The “Hula” as adopted by TNZ in 2003 (to be discussed further below) and bustles, as adopted in the International Metre Classes, allow such a volume distribution more effectively in the aft-body region.

The ACC type of bow and stern overhangs, together with the typical U-shaped sections utilized today, with little or no topsides flare, will allow a 2003 ACC yacht to sail to windward at boat speeds as high as 10 knots. This corresponds to a Froude number, based on the static waterline length at zero heel, in excess of 0.38. Other classes of yachts with similar length-displacement ratios, will not exceed Froude number values of about 0.34 when sailing to windward at an optimum VMG point-of-sail.

The sum of all of these improvements, including those associated with the appendages, sail fabric and sail and rig design, between 1992 and 2003, have led to an increase in boat speeds, sailing to windward, of about 0.7 knots.

It is also interesting to note that, because of the above-mentioned canoe body features, the modern ACC yacht is now actually more hydrodynamically efficient sailing at relatively large angles of heel than when sailing upright. The reduction in resistance with heel is the primary reason for this. In figure 6, this decrease in resistance of a modern ACC canoe body is shown.

4.2 IMPROVEMENTS WITH RESPECT TO INCREASING EFFECTIVE APPENDAGE SPAN

Attention is now also focused on the influence of the shape of the canoe body on the effective span of the appendages and how the effective span (also termed effective draught) can be maximized. The effective span is related to side force and the associated induced drag, as follows.

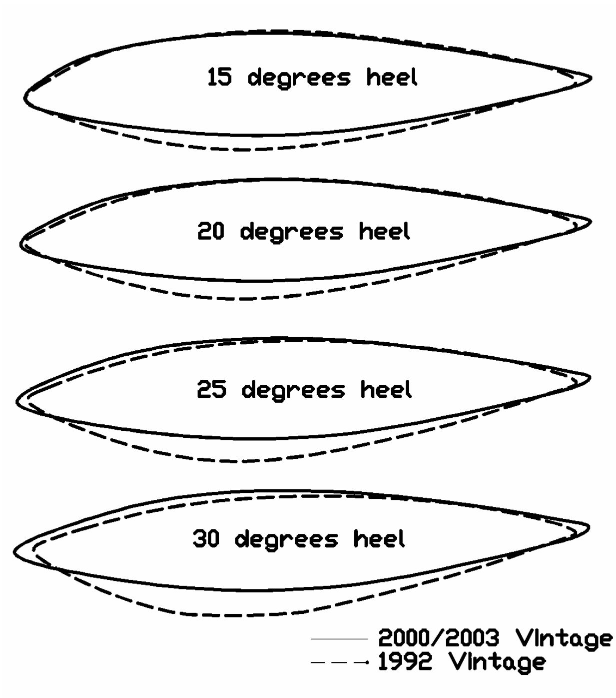

Figure 5: Waterlines at 15, 20, 25 and 30 degrees of heel of the two canoe bodies shown in figure 4, revealing the longer (and more symmetrical) waterlines associated with the narrower and more U-shaped canoe body.

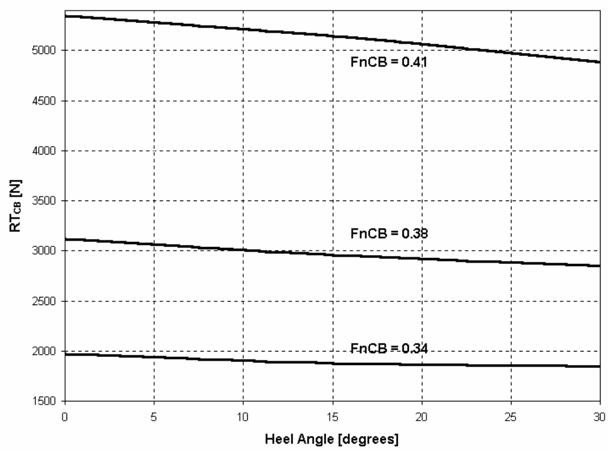

Figure 6: The resistance of a typical 2000-2003 ACC canoe body, at 3 speeds, from 0 to 30 degrees of heel (Froude numbers are based on static waterline length).

The induced drag can be written as:

$$R_I = \frac{1}{2}\rho V^2 C_{DI} A_L$$

in which the induced drag coefficient is:

$$C_{DI} = C_L^2 \frac{(1+\sigma)}{\pi AR}$$

In these equations:

- ρ = density of water;
- V = velocity of yacht;
- A_L = lateral area of side-force producing body (canoe body, keel and rudder);
- C_L = lift coefficient associated with the total lift produced on canoe body, keel and rudder = $L / (½ \rho V^2 A_L)$;
- L = total lift produced on canoe body, keel and rudder = $SF / \cos(\phi)$;
- SF = total side force;
- ϕ = heel angle;
- $1+\sigma$ = (aerodynamic) induced drag factor accounting for the fact that the span-wise loading is not elliptical;
- AR = geometric aspect ratio of total lifting surface (canoe body, keel and rudder).

It follows that:

$$R_I = \frac{1}{2}\rho V^2 C_{DI} A_L = \frac{1}{2}\rho V^2 C_L^2 (1+\sigma)\frac{A_L}{\pi AR}$$

The geometric aspect ratio can be written as:

$$AR = \frac{T_{\max}^2}{A_L}$$

where $T_{\max}$ is the maximum draught of the hull (for ACC yachts this is 4 metres in the measurement trim condition). Substituting this, and re-writing the equation in terms of side force, we obtain:

$$R_I = \left(\frac{SF}{\cos(\phi)}\right)^2 \frac{(1+\sigma)}{\pi \frac{1}{2}\rho V^2 T_{\max}^2}$$

The factor 1 + σ, for airplane configurations varies between 1.2 and 1.4. For the underwater configuration of an ACC yacht, this usually varies between 1.2 and 2.0, depending on geometry and Froude number (the amount of wave-making in particular).

Usually, an effective draught is defined as:

$$T_e = \frac{T_{\max}}{\sqrt{1+\sigma}}$$

so that:

$$R_I = \left(\frac{SF}{\cos(\phi)}\right)^2 \frac{1}{\pi \frac{1}{2}\rho V^2 T_e^2}$$

A good value for the effective draught of an ACC yacht, at maximum speeds sailing to windward, is anything in excess of 3.0 metre. Effective draught decreases with increasing heel angle and increasing Froude number. Side force augmentation due to trim tab and rudder angle increases effective draught substantially. Particularly the trim tab is very efficient in increasing the side force without a significant increase in induced drag.

The effect of the canoe body on the level of the induced drag is a complex matter, requiring studies using both CFD and model testing. The keel fin generates additional lift on the canoe body and the canoe body generates additional lift on the keel fin. The induced drag associated with these lift carry-over components is different, one being more efficient than the other. When keel draft is limited such as on an ACC yacht, the optimum canoe body is now recognized to be relatively deep and flat-bottomed in the vicinity of the keel fin, and in front thereof.

Here we must make the observation that both tests in a wind tunnel and in the towing tank are required to be able to determine the level of the induced drag at specific heel and leeway angles, and specific settings of the trim tab and rudder. This is because in the towing tank it is difficult to subtract the inevitable change in wave resistance from the total increase in resistance that occurs when the side force is increased on the model (see reference 5). In the wind tunnel the real level of the induced drag can be ascertained (i.e. separate from the increase in wave resistance), and a good design will attain effective draught values in excess of 3.3 metre (at maximum speeds when sailing to windward). For this purpose the complete underwater configuration (preferably on a large scale to avoid scale effects associated with Reynolds number differences between model and full-scale) needs to be modelled in the wind tunnel. A photograph of the set-up used in the wind tunnel for the study of the appendages of SUI 59 is shown in figure 8.

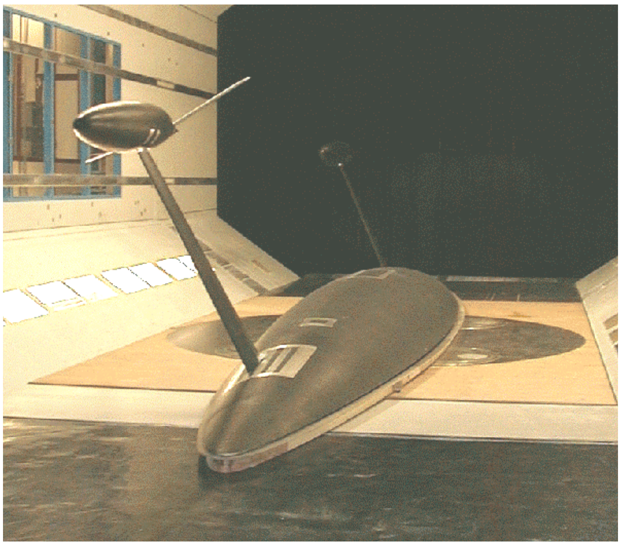

Figure 7: *Photograph of the set-up in the wind tunnel (at half scale) of the underwater configuration of SUI 59.*

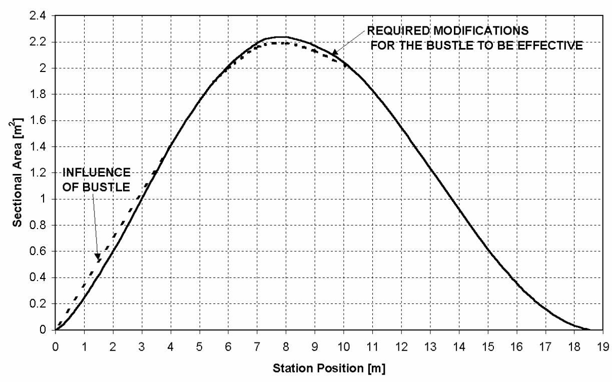

Figure 8: *Effect of a moderate bustle, such as the "Hula", on the curve of sectional areas of a modern ACC.*

4.3 THE EFFECT OF A BUSTLE

The bustle[1], first developed by Olin Stephens for the Twelve Metre "Intrepid" in 1967 (see references 6 and 7), consists of the addition of volume to the canoe body between the keel and the rudder, thereby obtaining a curve of sectional areas with less hollow in the aft-body, increasing the effective waterline length. The "Hula" (an acronym for "hull appendage"), as fitted to the aft-body of NZL 81 and NZL 82, is in fact a bustle. Figure 8 shows the influence of an appendage such as the Hula on the curve of sectional areas.

Unlike the International Metre Class Rules, it is difficult to add an effective bustle to the canoe body of an ACC yacht. This is because the ACC Rule requires that the hull has no hollows anywhere (except in conjunction with fitting an appendage) and that the slope of the buttock, 250 mm from the centre plane, between the aft end of the measurement waterline plane and the aft girth station, shall not be greater than 12.5 degrees to the horizontal. The Hula was contrived to be an appendage, in that it was separated from the hull by the slightest of gaps, and only attached to the hull within the 500 mm band centred along the centre line, allowed for the attachments of appendages in that area of the canoe body.

For a bustle to lead to an improvement in resistance it needs to be properly integrated in the sectional area curve, and the effects on prismatic coefficient and the longitudinal centre of buoyancy need to be studied. The change to the area curve required is approximately as indicated in figure 8. It is hoped that the new version of the ACC Rule (version 5.0), to be used for the next America's Cup, will not allow this type of an

[1] The maritime meaning of the word "bustle" has not yet been acknowledged by dictionaries. According to the dictionary a bustle is: "a pad or framework formerly worn by women on the back part of the body below the waist to fill out the figure".

"appendage" again. Most designers see this as an unhealthy development. After all, the Hula is not an appendage, as such. The people that drafted the first version of the Rule intended for the canoe body to have a smooth and convex shape, without "irregularities" such as bustles and "bumps". If the 12.5 degree buttock limitation is considered to be too severe, it could perhaps be modified. This too is unlikely however since the parties responsible for drafting the new version of the Rule have a vested interest in the Rule basically staying unaltered.

4.4 THE HULL VANE

The author has, on and off for the last 10 years, been working on an alternative approach to favourably influence the flow around the aft-body. This approach consists of fitting a wing transversely below the hull in the region where the flow is directed upwards and inwards the most. Besides favourably affecting the wave resistance, this device, when its dimensions and shape are well chosen, also develops a modest thrust force, depending on the steepness of the buttocks in that region.

This concept was tested in the tank by the author in 1990, in 1995 and on an ACC model in 2001. The configuration in 2001 yielded a lower overall drag for all tested speeds, particularly at angles of heel. A patent for this concept has been applied for and obtained. Research into the optimum integration of this concept in the design of different hull forms is currently underway.

The hull vane is an appendage but because of its influence on the characteristics of the canoe body (a total change in the wave profile along the canoe body in that region), it has been included in this paragraph rather than in the following.

5. RECENT DEVELOPMENTS IN APPENDAGE DESIGN

5.1 BULBS

The most talked-about development in 2003, on the subject of appendages was the TNZ bulb. This bulb was significantly longer (and hence more slender) than the bulbs used thus far. The reason for this choice is not altogether clear. It has been suggested that a longer, more slender bulb will lead to a reduction in wave resistance. According to our studies, this reduction in wave resistance is rather modest and only greater than the associated increase in viscous resistance (due to the increase in wetted area), at Froude numbers associated with sailing downwind, not upwind. Initially, our studies revealed that a much longer bulb would also be beneficial upwind but, on correcting our viscous resistance stripping method for those appendages that are situated below the middle of the canoe body for the excess flow speed associated with the displaced volume of the canoe body and wave trough, we found that this was not the case.

The determination of the optimum bulb length and shape is one of the most difficult subjects left to tackle. This is apparent when viewing the bulbs used by the 3 fastest boats (SUI 64, USA 76 and NZL 82). They are significantly different, revealing that the 3 different design teams have arrived at different conclusions (see figure 9). The difficulty of assessing the amount of viscous drag of a particular bulb is compounded by the fact that a significant amount of laminar flow exists on the forward part. During model testing, the boundary layer on the bulb is stimulated to become turbulent at a location at which it is thought that, on the full scale, natural boundary layer transition will take place. This location is difficult to determine accurately without actual full-scale observations. Most CFD tools will also not allow calculation of this location. It follows that an accurate determination of the trade-off between viscous and wave bulb drag is a complex issue.

Other effects need to be considered before a significantly longer bulb can be adopted, such as the performance at lower speeds (when wave resistance is less dominant), the slightly greater viscous resistance during manoeuvring (caused by the increase in local speeds at the front and back of the bulb) and the associated loss of laminar flow, the greater longitudinal inertia, the increase in complexity of the already critical keel - bulb structure, etc. These effects might not weigh up against the few good points, such as the decrease in wave resistance, the slight lowering of the centre of gravity of the bulb, and the slight increase in the aspect ratio of the fin keel.

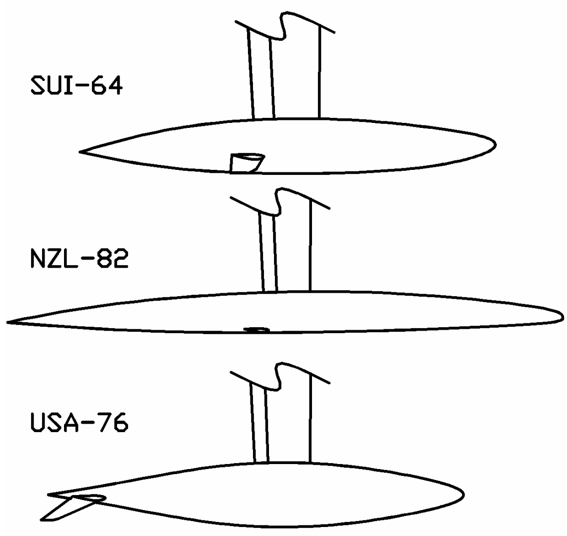

Figure 9: Approximate profile shape of the bulbs adopted on SUI 64, USA 76 and NZL 82.

5.2 LATERAL FIN AREA

The lateral area of the keel fin has gradually diminished over the last 2 Cup events. This has been the result of more effective trim tabs, which are now operated at appreciably higher angles.

Some designers have cut it very fine in this regard, choosing areas which are perhaps a little too small. SUI 64's good upwind ability has in part been attributed to its keel fin being greater than those of its competitors.

5.3 WINGLETS AND WINGLET POSITION

The position of the winglets on the bulb is still being debated amongst experts. Of the 3 fastest boats in the last Cup, SUI 64 and NZL 82 adopted positions corresponding to the trailing edge of the keel fin, while USA 76 chose the more traditional location at the trailing edge on the bulb.

Model tests indicate that, generally, at moderate speeds and moderate levels of side force, the position at the trailing edge of the bulb is to be preferred while, at higher speeds and higher levels of the side force, the location at the trailing edge of the keel fin is to be preferred.

When the winglets are situated aft on the bulb, there is the additional benefit of generating some thrust associated with the pitching motion of the yacht in waves. The further the winglets are positioned away from the centre of the pitching motion (usually considered to be the centre of gravity) the greater the possibility becomes to generate this thrust force. This effect has been overrated however because the increase in viscous drag (associated with the loss in laminar flow on the winglets at greater angles of incidence of the flow) will negate some, if not all, of this thrust.

5.4 RUDDERS

Rudder area has now also decreased to an absolute minimum level. Geometric aspect ratio’s have increased to values never used before on sailing yachts, with the associated danger of stall at moderate rudder angles.

6. ARE FURTHER DESIGN INNOVATIONS POSSIBLE?

While research is still required to perfect the design of the typical 2003 ACC yacht, particularly in many detailed areas, it is the author’s belief that, within the present configuration, the 2003 ACC yacht will be difficult to significantly improve upon. For the present style of yacht, with its T-keel and winglets, the areas that can probably be improved are those associated with the following:

- Fillet geometry, to reduce the drag resulting from the interference of boundary layers (at the junction of canoe body and the keel fin for example);
- The optimum taper ratio of the keel fin in connection with obtaining the best lift-carry over from keel fin to canoe body and vice versa;
- Optimum bulb size and shape, notwithstanding the progress that has been made in the last few years;
- Ways to diminish the wave drag associated with the appendages;
- Winglet position and winglet size and shape, again, notwithstanding the significant amount of work done in this area already.

For all of these topics very significant research efforts are required.

It is the author’s belief that for further design innovation to be successful, it is necessary to explore other appendage configurations. The positioning of the major appendage in the middle of the boat leads to a significant increase in wave and viscous drag. It is in this region that the flow speed around the hull is highest and the distance (of the bulb for example) to the water surface is least. There are some promising alternative options yet to be fully researched. One of these is the twin-keeled yacht such as our design for SUI 59. The wave resistance of this boat was considerably lower than that of the present crop of boats, at the expense of additional viscous drag (and a lack of manoeuvrability).

However, teams that are likely to adopt an innovative design approach are possibly not to meet with success. The America’s Cup design strategy nowadays is that every aspect of the (conventional) design needs to be covered in a more thorough way than the competitors are likely to cover these aspects. Only teams that lack resources (budget and manpower) are likely to adopt an innovative approach because of the realization that a more middle-of-the-road approach is not possible. Having been involved in a number of such campaigns, the author is aware of all the pitfalls associated with such a campaign, nearly always resulting in the failure to “get it right” in some crucial area.

7. CONCLUSIONS AND FINAL REMARKS

In this paper some of the aspects involved in designing America’s Cup yachts are discussed. The subjects covered are by no means complete. Many more details are also part of the design process. The whole process is complex, requiring efficient management, besides relatively large budgets and high-level expertise. In fact, it the author’s experience that the success of a particular design effort is as much associated with the management thereof than it is with the dedication, experience and insight of the technical design staff. Lack of a rigorous discipline and insight in all aspects of the design work, on the part of the design team manager, in most cases results in "chaos", with design team members applying themselves as they want to, with little regard to the "total picture", and the need for the whole team to share in the responsibility of the work being carried out.

At present, the "conventional" ACC yacht, with its U-shaped sections, awkward-looking bow, small fin keel with effective trim tab, large bulb with winglets, and high aspect ratio rudder, is nearing its optimum and final shape. This fact makes it easier for new-comers to the America's Cup to develop a design that is reasonably competitive and, at the same time, makes it harder for those seasoned competitors seriously committed to win the Cup, to develop a design with an edge in speed. Significant budgets and man-power are required to research those remaining elements of this design in which unattained speed-potential is still left.

The possibility of developing a new, innovative design concept with superior speed potential is still possible within the present ACC Rule (assuming that the new version of the Rule does not further limit the characteristics of the canoe body and the appendages). For that to happen, however, it will be necessary to explore other appendage configurations. The positioning of the major appendage in the middle of the boat leads to a significant increase in wave and viscous drag. There are some promising alternative options yet to be fully researched. It remains to be seen, however, to what extent capable and well-funded teams are willing to dedicate budget and man-power to such alternative concepts. Since 1958, only the successful defence of the America's Cup by the USA in 1967, and the win by Australia in 1983 (see reference 8) can be attributed to a "break-through" design concept. All other successful campaigns can be attributed to smaller design improvements and, particularly, to better sailors.

8. LIST OF REFERENCES

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