Aerodynamic and Hydrodynamic Aspects of America's Cup Yacht Design

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INTRODUCTION

Wind engineering treats the interaction of the wind and built-structures. Coincidentally, winning the America's Cup is very much about this same interaction. In simplest terms, success in this preeminent sailing event requires the development of a built structure whose interaction with the wind produces more aerodynamic thrust and less hydrodynamic drag than the competition. Almost without fail, the competitor who actually does this will indeed take home the Auld Mug. This assumes structural integrity, qualified sailors, and there are of course a few rules, which guide and constrain the development of the built-structure, hereafter referred to as a yacht, just as there are some rules and conditions for the contest itself.

The conditions for the America's Cup racing are usually arrived at through mutual consent by a challenging club and the defending club, and so can vary from one America's Cup to the next. The America's Cup event these days involve match racing between yachts that conform to the International America's Cup Class (IACC) Rule. Match racing, in contrast to fleet racing, involves two yachts whose predominant concern is their position relative to the other yacht, rather than their absolute time or speed around the course, which will be a windward-leeward format, three times around for a total of 18.5 nautical miles.

The forthcoming America's Cup competition in Auckland, New Zealand involves a number of challenging yacht clubs, which will compete with each other over a four-month period starting in October 1999. This Challenger Series will result in the selection of the sole Challenger for the actual America's Cup Match in February 2000, in which he or she will meet the defending yacht club, the Royal New Zealand Yacht Squadron.

Removed from the Royal Yacht Squadron in England through the efforts of the schooner *America* in 1851 the America's Cup was retained by the New York Yacht Club for a lengthy period. In 1983, in races in the Atlantic Ocean off Newport, Rhode Island, the America's Cup was won by the Royal Perth Yacht Club. In the subsequent event in 1987 in the waters of the Indian Ocean off Fremantle, Western Australia, it was won by the San Diego Yacht Club. They retained the Cup in the 1992 Match in the Pacific Ocean waters off San Diego but were defeated in 1995 by the Royal New Zealand Yacht Squadron, who acquired the America's Cup and brought it to Auckland.

Remarkably, in the recent history of America's Cup there have been only three locations where the event has been raced, and now Auckland's Hauraki Gulf will make the fourth. This means that there have been a rather small number of design wind specifications and characterizations. Nevertheless, the success of an America's Cup yacht depends very much on developing a reasonably correct design wind specification.

The Rule

The IACC rule was developed in first draft during the latter part of 1988 in an effort to pick up the pieces after that year's America's Cup contest between the 90-foot waterline "Big Boat" and the 55-foot waterline catamaran. Up until then, and since 1958 -- the so-called modern era of America's Cup racing -- the yachts were "12-Metres", subscribing to the International Metre Rule.

The IACC rule contains an interesting preamble, and whereas it does not actually form part of the class rule, it does note that the International America's Cup Class is intended:

(a) to produce wholesome day sailing monohulls of similar performance while fostering design developments that will flow through to the mainstream of yachting; and

(b) for yachts that are raced 'around the buoys" with tenders present, as opposed to offshore in high wind and rough sea conditions with or without tenders.

[This is the only mention of wind in the document, with the exception of rule 33.5(b) which specifically prohibits sails which are multiple-surfaced, whether inflated by the action of the wind or otherwise.]

As stated in the "Notice of Race" rather than the Class Rules, the Race Committee may postpone a race when the "wind is too variable, or too light, or too strong, or the seas too rough to reasonably conduct a race to test the relative speed of the two yachts." To some extent the fact that there are time limits on the Match races (e.g. 4 hrs 15 min) helps determine if the winds are too light. However, the Race Committee determines whether the winds are too strong, and there is not a specific limit, nor any guidelines.

The central IACC formula involves length, sail area and displacement:

$$\frac{L_r + 1.25 \times \sqrt{S_r} - 9.8 \times \sqrt[3]{DSP}}{0.679} <= 24.000 \text{ metres}$$

The rated length L_r is the sum of the length between girths LBG, and the forward and after girth corrections (FGC and AGC). The LBG is measured 200 mm above the measurement waterline MWL – the flotation plane of the yacht. The forward and after girth measurements are taken at the forward and after end of LBG , but FGC and AGC are always evaluated at least to be 0.3 m. and 1.6 m. respectively. This controls the look of the class. For example, a wide, shallow "scow" whose forward girth would measure well over 0.3 m, would be hugely penalized.

The rated sail area is derived from the measured sail area Sm -- the sum of the actual mainsail area and the foretriangle area.

In addition to this and other basic rating formulae, there are some important limits specified, either as absolute constraints or as lines beyond which prohibitive penalties are incurred. The most important of these are:

- Measurement condition weight between 16000 and 25000 kg without penalty
- Maximum draft without penalty is 4.000 m.
- Minimum freeboards without penalty ranging from 1.5 to 1.2 m depending on location.
- Maximum beam without penalty is 5.5 m.
- Mainsail hoist (P) from lower band (BAD) to upper band limited to 32 m.
- Height of headsail (I) limited to 80% of P + BAD
- Spinnaker are limited to 1.5 x Sm
- Spinnaker pole limits to 1.35 of foretriangle foot (J) dimension
- Maximum footlength of genoa or staysail limited to J + 3.0 m

Other qualitative limitations include:

- The yacht shall be sloop rigged with one mast only
- No hollows in the hull except in association with appendage, legitimate fitting, etc.
- Total number of moveable surfaces shall not exceed two, with limits of axis of rotation
- Retractable appendages are not permitted

Construction section of the class rule defines minimum shell/skin thicknesses and weights per unit area, criteria applied to building processes, and some other requirements.

A few other items, which impose limits on the more creative hydrodyamicists and aerodynamicists, include:

- The mast shall not have slots, slats or similar devices or contrivances to enhance the aerodynamic performance
- No fairings are permitted between the mast and mainsail
- Sails cannot be artificially thickened (e.g. foamed sails) or be multiple surface (e.g. inflated)
- Spinnakers – intentional openings in the sail are prohibited
- No coating or substance (including riblets, LEBUs, polymers, compliant surface structures and detergents) may be applied to the outside of th ehull or appendage except for polyurethane, epoxy paint or commonly available paint
- Holes or devices in or on the surface of the hull or appendages whose puroses is to bleed off or alter the water flow of the boundary layer are prohibited

After racing in 1992 and 1995, the IACC yachts are beginning to group towards the upper limits of length and displacement. The rated length Lr used in the central formula is actually the measured length (Lm) multiplied by the quantity 1 + .01 (Lm-21.2) [8] so that one can only get so long before unacceptable amounts of sail area must be shed.

IACC Design Problem

Like most design problems, performance yacht design involves trade-off and compromise. Tritely stated, there is no free lunch. The IACC rule outlines the central tradeoffs at the outset – length, displacement, and sail area. But even for a given combination of these three parameters, there are several handfuls of crucial tradeoffs, such as those related to beam (wavemaking+viscous drag vs. stability), or flatness of ballast bulb (viscous drag vs. stability), and so on.

For a given concept, the principal dimensions and shapes are arrived at through cycles of geometry development, performance modeling, scale-model and full size experiments and testing. One of the first tasks however is to improve our understanding of the specific design problem, and for this purpose as well as providing the comparative performance measures between the yachts the principal tool is the Velocity Prediction Program (VPP).

The VPP attempts to simulate the balance of forces and moments that determines the sailing speeds of an individual yacht. The most widely used steady-state VPP's solve two equations which express the balance of longitudinal forces and rolling moments for the two state variables of speed and heel angle.

Typically, changes in environment including sea conditions but in particular the wind strength will drive the sizing and shaping of the yacht. The VPP initially provides insight into the hydrodynamic and aerodynamic design criteria. For example, the distribution of boat speeds or heel angles for an IACC yacht will vary with race venue and yacht size, and Figure 1 shows a typical distribution of boatspeed. In contrast to this plot, the distribution of speeds and heel angles for the Volvo Ocean Race (formerly Whitbread Round the World Race) is a little more interesting.

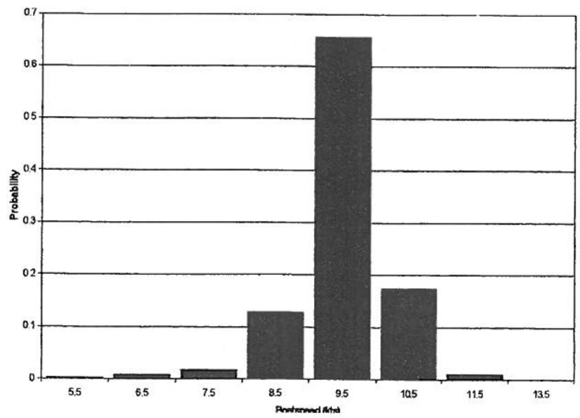

Figure 1. Example of typical distribution of boatspeeds for IACC yacht on windward-leeward course.

Perhaps the remarkable thing about IACC yacht design for a windward-leeward course is the very limited range of speeds and heel angles of interest. A displacement yacht with plenty of sail area will often find itself quickly running right up to speeds at which the wave make drag begins to increase dramatically, near a 0.35 value of Froude number $Fn = v/(Lg)^{1/2}$. The IACC yachts are just such a boat.

It is also instructive to look at the "drag budget" for the candidate design and evaluate the relative magnitude of the various components that contribute to the overall drag of the yacht. The relative magnitudes of these components often dictate the amount of resources invested into research to reduce a particular type of drag. In Figure 2 below, the hydrodynamic drag budget is shown for an IACC yacht upwind sailing for a range of wind speeds. Taking the right most stack, for the highest wind speed, the components from bottom to top are wave drag, canoe body viscous drag, appendage drag, heel drag, and induced drag. In very approximate terms, one can think about

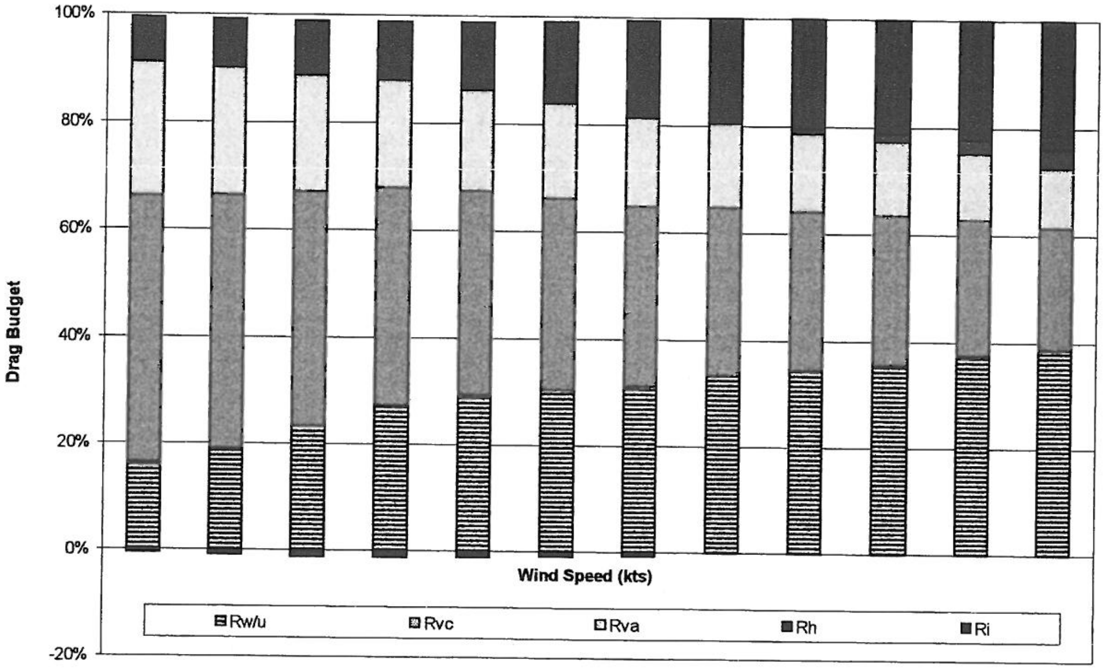

Figure 2. Typical hydrodynamic drag budget for upwind sailing in an IACC yacht

wave drag being about 33%, viscous drag of appendages and canoe body another 45%, induced drag another 20%. So-called heel drag is how all these other components vary from upright to heeled condition, and it can be negative in some cases. Even though viscous drag of the canoe body and appendages are a large proportion of the overall drag, it is difficult to do much about it. This drag is for the most part proportional to wetted surface.

The aerodynamic drag budget is interesting. For typical upwind sailing on an IACC yacht, the parasite drag of the sails is about 13%, the induced drag is about 65%, and the parasite drag of the rigging and hull (so-called windage) is 22%. Once again, even though induced drag is about 65%, there seems to be little one can do about it. The very large roach profiles on various mainsails over the years represent efforts to change the spanwise lift distribution in a favorable way and reduce this huge component of aerodynamic drag by a small amount.

Because the relative performance of IACC yachts depends strongly on the true wind velocity, it is clearly important to have an accurate determination of the design wind conditions. The first estimator is of course the average wind speed. In Newport the average wind was less than 12 knots. In Fremantle, the average wind was in excess of 16 knots. In San Diego the average wind is 8-9 knots. And in Auckland, the skipper of Whitbread 60 *EF Language* after his stopover in the City of Sails earlier this year indicated, he believed the average wind speed to be 19 knots, because it was 38 knots at the finish of the Sydney-Auckland leg, and virtually calm when they departed Auckland for the long leg to Brazil.

Secondly the variation of wind over the "racing afternoon" from about 1300 until 1700 is important to consider, and the sequence of wind from day to day. All four venues have had some degree of thermally induced local breeze, often called the sea breeze. However the sea breeze in Fremantle which would come in strong and long seems to bear little resemblance to the weak sea breeze of San Diego which would occasionally come up and blow itself out before a race was over. In Auckland, there is a wide variation in wind speeds from month to month and for the same month is different years. Figure 3 shows an example of daily afternoon averages for one February near the America's Cup race course.

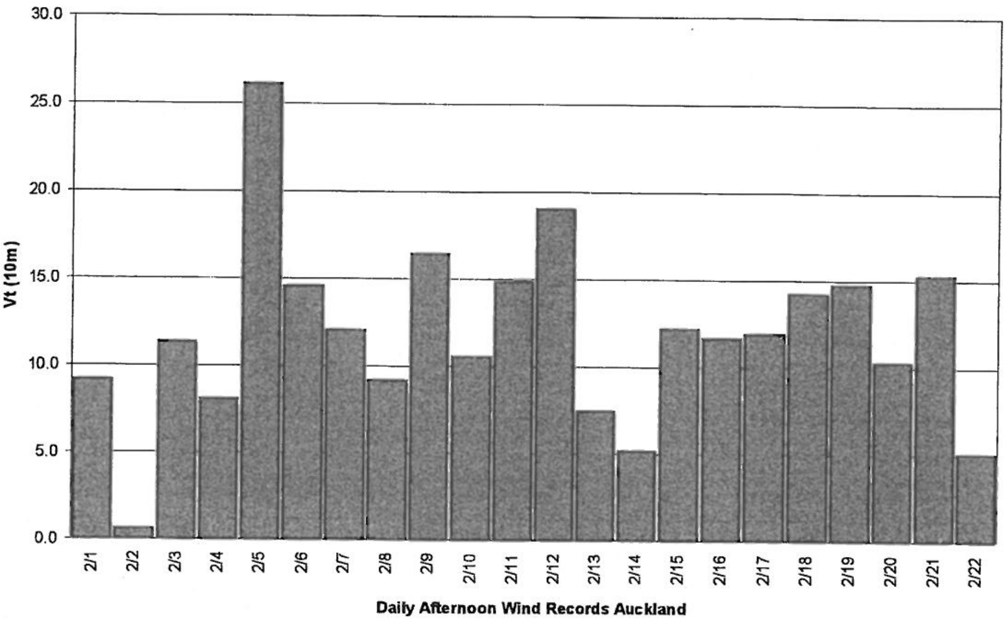

Figure 3. Example of daily afternoon wind records (Auckland)

Records and understanding of the direction of the wind are important with respect to generation of a seaway. As part of race simulation models, knowledge about character of wind shifts (in direction) is also important.

A major element of the IACC design problem is that there are crossovers in performance related to wind speed. Consider two boats, identical in most respects except that one boat has 5% larger beam than the other. This translates into extra stability, more viscous drag and more wave drag. This means the beamier boat will be faster upwind above a certain "crossover" true wind speed, and slower downwind in all wind speeds. On a day when the wind speed is greater than the crossover true wind speed, the beamier boat will have a high probability of being first to reach the first windward mark, and this upwind speed usually translates into success. If the wind speed is less than the crossover, the beamier boat will look very ordinary. Most skippers will value the upwind performance much more than downwind performance. This crossover characteristic of IACC yacht design in conjunction with the variation of wind from day to day as shown in Figure 3, is one of the critical aspects of America's Cup "wind engineering."

Tools

A variety of computational and experimental tools are employed in an America's Cup design project. For the present Team New Zealand project, some of the types of programs used are shown in Table 1 and test facilities are shown in Table 2. Not shown in Table 1 are a variety of programs used for the analysis of test data, including expansion of test results from model-scale to full scale, and analysis of full scale testing and meteorological information. In terms of decision making, performance prediction tools and model testing are the relied on.

Computational Fluid Dynamics
The wide range of tools and methods included under the heading of computational fluid dynamics (CFD) are of little value for yacht drag prediction, although they are nevertheless useful and informative in several ways for hull and appendage design.

Particularly useful are pressure and velocity distribution maps, on-body and off-body streamlines. Additionally, computation of lift curves (lift vs. angle of attack), as well as trends in longitudinal and vertical centres of pressure, are valuable products of CFD, most of which can be carried out with potential flow methods.

Table 1. Some of the computational tools used by Team New Zealand

Category	Area	Program	Remarks
Geometry	Hull Surface	FASTSHIP MACSURF	*Hull Surface Definition (NURBS)*
	Appendages	MULTISURF	*Complex geometries definition*
Performance	Velocity Predicition	WINDESIGN	*Decision making and improve understanding*
	Race/Strategy Models	Various	*YRI, U.Auckland*
	Tacking/Maneuvering	Various	*YRI, U.NSW*
	Seakeeping	MIT5DOF	*Linear, strip-theory, frequency domain with winglet thrust*
CFD General	Potential Flow (3D)	PMARC (V10)	*Understanding of complex flows around appendages and sails*
	RANS	FLUENT	*Understanding of complex flows around appendages and sails*
	Airfoil (2D)	XFOIL	*Fin,rudder foil sections*
Structures	Finite Element (General)	NASTRAN/ PATRAN	*Used for general understanding of hull structure and mast structure*
	Mast/Rig System	AES Rig Program	*Special, non-linear for mast/rigging*
Sails	Aerodynamic	VORFLOW	*North Sails -Vortex-Lattice Method*
	Structural	MEMBRANE	*North Sails*
CAD	Drawing/Drafting	MICROSTATION	
	Solid Modeling	UNIGRAPHICS	

Reynolds-averaged Navier-Stokes (RANS) codes are helpful in providing information about the character of the flow – laminar, transition, turbulent, separation, boundary layer thickness, etc. Free-surface codes, whether linear or non-linear, potential flow or hybrid, can be useful in weaving together a coherent set of resistance formulations based on a set of systematic tank data. In general it seems that boats with flat, shallow overhangs like most modern racing boats, or boats with high-speed transom sterns like Whitbread 60s pose a number of particularly difficult problems for free-surface programs.

From CFD, one might reasonably expect the error in *drag* calculations to range from 2–3% or more, when great care is taken in the modeling and assumptions. This estimate is based on the author's experience in developing and using potential-flow tools and RANS codes, as well as analysing and attempting to use results from a variety of computational fluid dynamists for a number of projects over many years.

Table 2. Experimental Facilities

Category	Area	Type of Facility	Remarks
Tank	¼ Scale Appended Hull Models	Smooth Water & Reg. Waves	*DERA, Gosport, England*
Wind Tunnels	Sails & Windage	Twisted Flow	*U.Auckland,North Sails*
	Rigging/Sail 2d	Open-Jet	*U. Auckland*
	Appendage Drag	Large, Med Speeds	*U. Southampton*

Model Testing

Model testing is an established means to

- explore concepts
- help make comparative design decisions
- provide a data to develop hydrodynamic force formulations for the VPP.

Although expensive to carry out, scale-model experimentation is low-risk in terms of expenditure of resources for a reliable result. Variation in accuracy in tank testing is due to a number of causes which will not be discussed here, but one might reasonably expect the standard deviation of error to be ± ½ percent from data provided by an experienced facility and personnel, with quarter to third model scales.

VPP Regression Formulations

Formulations in VPP's that estimate wave resistance or heel and induced drag vary widely in their accuracy. In general, one can expect a good set of wave resistance formulations will be accurate within ±½ to 1 percent over a prescribed range of parameters – beam-to-draft B/T, displacement-length ratio DLR, etc. Heel drag and induced drag formulations may be in the range of ± ¾ to 1½ percent.

Design Aspects

Given all the tools above, and some understanding of the design problem, the design of an IACC yacht includes:

- Concept selection - in which the variants usually have to do with appendage arrangements
- Sizing – determination of length and displacement and beam for given wind conditions
- Hull Lines – creation of the shape that integrates various physical characteristics, sectional area curve, style of section shapes, forward and aft profile, and so on
- Appendage Sizing & Design – minimizing drag but meeting minimum lift requirements, and trading off stability for parasite drag, control and directional stability

- Structural Design – Within IACC rule constraints, reliable and light, and stiff. Weight saved goes into the bulb where it does great things.
- Deck Layout – Integration of structural efficiency and operational efficiency

The design of the rig and sails are done in parallel with the hull design. IACC rigged masts must not weigh less than 820 kgs nor have the centre of gravity lower than 12.250 m. above the mast datum band.

Sail design is an art and science, but very much builds on practical experience and success of previously tested sails. Sails are highly loaded structures, and the problem is one of obtaining and keeping the target flying shape that is known to have worked well. Competitive IACC mainsails and headsails are built using so-called 3DL technology, which involves laying up a composite of cloth and film over a full size mold which has been deformed into the specified shape provided by the sail designer.

There are a large number of issues and questions in the area of yacht hydro and aerodynamics for which no satisfactory answer has been developed (or at least published). Some examples are:

Wave resistance – for an arbitrary, non-lifting (or lifting) hull form wave resistance cannot be predicted analytically or computationally. This is mostly why we have to test tank models.

Viscous drag of 3D Bodies – for arbitrary bulb geometry, viscous drag cannot by predicted analytically or computationally. This is one reason we have wind tunnel tests of appendages.

Character of Flow on Full Scale Appendages - the extent of laminar flow on bulbs and foils is not known with any confidence. Various campaigns have carried out limited attempts to ascertain this, and there remains insufficient information.

2D lift and drag polar for real sails shapes - as a function of camber, location of maximum depth, etc. this is not known, and would be important to developing an improved sail force model

3D Models of Upwind sails a twisted, sheared flow – interaction of two sails in non-uniform flow is clearly difficult yet progress in this area would probably contribute much to improvements in yacht performance.

Final Remarks

America's Cup yacht design incorporates a wide variety of disciplines, many of which were not mentioned in this brief note. To be competitive in the America's Cup requires attention to each of these disciplines. Whilst a rational approach exists for the design of the yacht, there remain countless areas where reliance must be placed on experience, judgement and ultimately the talent of the sailors.