Technology in the Americas Cup

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Abstract
The most important recent development in yacht design has been the computer prediction of the performance of a yacht before it is built, both for the performance of the design in terms of speed around the course and for the performance of the various components in terms of structural integrity. This paper therefore begins with an outline of the design problem in terms of the force and moment balance for a yacht before discussing the more detailed design of the hull, appendages, mast and sails. Most of what is said applies to any AC syndicate but, where appropriate, examples are given from Team New Zealand (TNZ).

1 Performance Prediction

Equilibrium of forces and moments
Equilibrium for the forces acting in the plane of the water may be written as two equations involving the aerodynamic and hydrodynamic components of lift and drag. A third equation is given by the balance of moments taken about the longitudinal axis of the yacht. In principle these equations can be solved for three unknowns, which allows prediction of the hull speed, its angle of leeway (angle of incidence of the hull) and heel angle for a given hull and sailplan when sailing at a given angle to a wind of known speed. The development of so-called velocity prediction programs (VPP's) is now quite advanced, and allows designers to routinely predict yacht performance at the design stage. However the set of performance equations is not complete until the forces and moments on the hull and sails can be expressed in terms of incident speeds and angles, and so much of the R&D expenditure therefore goes into computational and experimental methods of finding these. More detail on VPP's may be found in Larsson [1990].

TNZ used a commercially available VPP from the Wolfson Unit for Marine Technology and Industrial Aerodynamics at Southampton University - it had the great advantage of running on a PC, so that the designers of different components could readily investigate the effects of their design changes on overall performance.

Design constraints
The design of the boat is subject to the constraints of the IACC rule; this is actually *many* rules, but the most important one is

$$L + 1.25\sqrt[1/2]{S} - 9.8\sqrt[1/3]{V} = 16.3$$

This formula was developed with the aid of VPP's, and is intended to ensure that any well-designed yacht with length, displacement and sail area (L, V, S) within the ranges prescribed should perform equally to any other. It can be shown that this equation does indeed lead to equal speeds for boats running dead downwind in winds light enough that only hull friction drag is important, but when the effects of heel or wave drag are added the rule is no longer sufficiently accurate to ensure equal performance; while it is correct to a first order approximation the performance advantages need only be second order, as even a 0.1% advantage is a clear win of 2 boat lengths.

This means that the 'best' combination of length, displacement and sail area is quite strongly dependent on the expected wind conditions for the course. In the first (1992) series in San Diego the different syndicates had arrived at different combinations for these, and accordingly there was a wide separation in performance, while for the second iteration of designs in 1995 the performance was closer. Now that the venue has changed to a location with quite different wind and waves we can expect to see wide variations in performance once again.

2 Sail Design

Sail coefficients
The needs of the VPP for aerodynamic data are very demanding - a means of predicting the lift, drag and moment coefficients of multiple, interacting sails of any planform at any heel angle in any twisted and sheared incident flow, and all this over a range of angles of attack from 0 to 180 degrees. The method must also account for the changes in sail shape which can be made subsequently by the sailors - while in use a sail may have its camber altered from 5 to 20%, and its geometric twist over the span varied from 15 to 30 degrees. The aerodynamics is further complicated by changes in heel angle and by the variation of incident true wind speed with height which causes the apparent wind to vary in both direction and speed along the span. For downwind sails both the incident shear and twist are dramatically large and their effects must certainly be accounted for in any rational treatment of the aerodynamics.

Computational fluid dynamics
The 3-D vortex lattice is ideally suited to the analysis of upwind sails, although it predicts only lift, heeling moment and induced drag so friction drag has to be found by other means (correlations or boundary-layer methods). Iteration for sail wake position is important, as is proper panelling. Most international sail design companies have access to such programs, and North Sails used its own package (VorFlow) extensively for TNZ.

Upwind sails operate close to maximum lift, and downwind sails have large regions of separated flow - in both cases Reynolds number effects may be expected to be significant, and fully 3-D viscous codes have also been used for sails. Figure 1 shows the results of some preliminary work on spinnakers done at the Yacht Research Unit (Auckland University) by Hedges (1993).

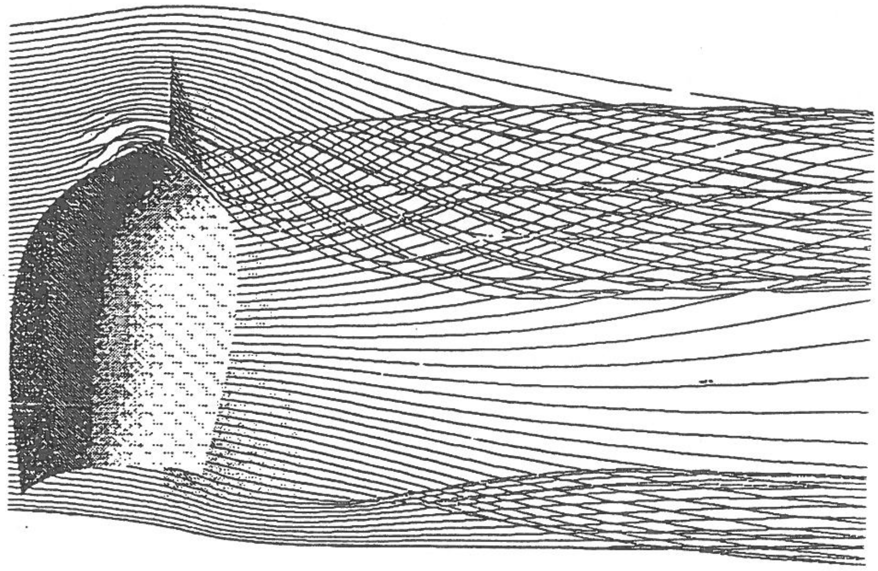

Figure 1. Calculated streamlines for flow over a mainsail and spinnaker combination

Wind-tunnel testing for sails
Flay and Jackson (1992) discuss the requirements for proper similitude and conclude that the most serious problems are those of matching Reynolds number and incident twist. Force coefficients often show an unexpected sensitivity to wind speed due to the difficulty of constructing models which can maintain their shape as the speed increases (small movements in the sail supports lead to relatively large charges in the sail shapes). Reynolds number effects on lift are unknown, but must be significant for sails operating near their maximum lift.

The problems of modelling trim have been largely overcome by Kerwin (1978) who proposed that trim could be accounted for by new two variables - reef and flat. The Kerwin model has been widely adopted in commercial VPP's, and seems to work remarkably well. While the variation with angle of attack of the maximum lift of the sailplan has to be supplied, this formulation cleverly avoids associating the sail forces with explicit features of sail trim, and instead uses the reef and flat concepts to complete the system of equations for the force and moment balance. One of the most interesting aspects of the model is that it works far better than it should, as a little thought shows a number of defects. The reason for its success is discussed by Jackson (1996), who also introduces a new 'twist' factor.

Team New Zealand made a major step forward in commissioning the University of Auckland for a unique wind tunnel which incorporated incident twist in wind direction. This 3m x 6m tunnel was designed by Dr Richard Flay and constructed very cheaply and in a remarkably short time. The tunnel proved especially helpful in developing downwind sails where the flying shape of the sails was observed to be far more realistic than that obtained in conventional tunnels. TNZ subsequently tested some 300 different downwind sails in the tunnel (at 1:15 scale) and estimated that about 1/2 of the considerable design gains were made there, including a 15% increase in driving force in some cases!

Sail structure
Finite element analysis has been in routine use by sail designers since around 1987, leading quickly to sail panel layouts which aligned cloth fibres with the direction of principal stresses and so to sails which were both lighter and able to hold shape through a wider wind range. However as sail fibres have become stiffer so the sail shape and construction have become less accommodating to trim, and it has become increasingly important to design the sail structure of the sail so that the membrane stresses are equilibrium with the wind pressures at the intended flying shape. With the aid of their in-house FE program MemBrain, North Sails NZ were able to design stable mainsails with considerably more roach than before (more sail high up). They were also able to incorporate carbon fibre yarns which were twice as stiff as the kevlar used previously.

The North Sails 3DL process was also an important step forward for TNZ. This process uses a full-scale deformable mould over which is laid a laminate of load-bearing fibres between two sheets of mylar. It produces sails which are lighter and perfectly smooth on both sides - the TNZ sails were 20% lighter and 17% stronger than those used in the previous campaign.

3 Hull and Appendage Design

Naval Architecture
The design process is considerably speeded by the use of a hull design package capable of automatic calculation of hydrostatics and hull shape parameters. TNZ used MacSurf extensively (an Australian product).

Force Coefficients
Dimensional analysis shows that the force coefficients for a hull of length L moving at speed U depend both the Reynolds number and the Froude number ;

$$Re = \frac{UL}{\nu} \ , \quad Fr = \frac{U}{\sqrt{gL}}$$

In principle the coefficients depend upon both numbers, but fortunately the assumption that interactions may be ignored (Froude's Hypothesis) seems to work well - this allows the drag to be broken into components due to friction, lift and wave-making, and then to be estimated separately. The breakdown of drag components for a typical IACC yacht is shown in Figure 2.

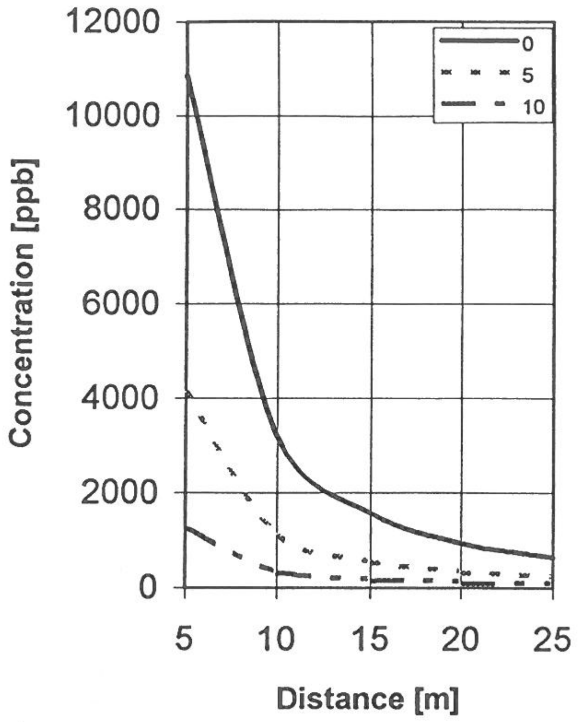

Fig. 1. Predicted H_2S concentrations using AUSPLUME and METSAMP Measured 64 ppb at (13.6m, 1.3m)

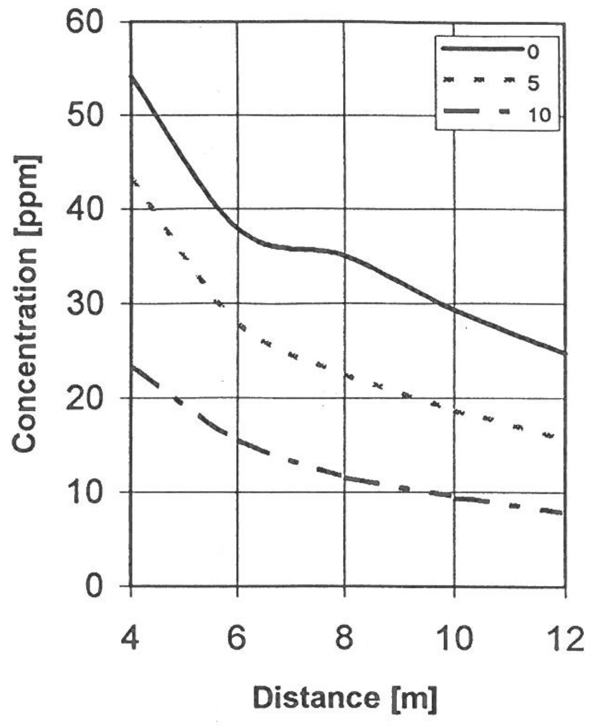

Fig. 2. Predicted NH_3 concentrations using AUSPLUME and METSAMP Measured 10 ppm at (6.5m, 0.3m)

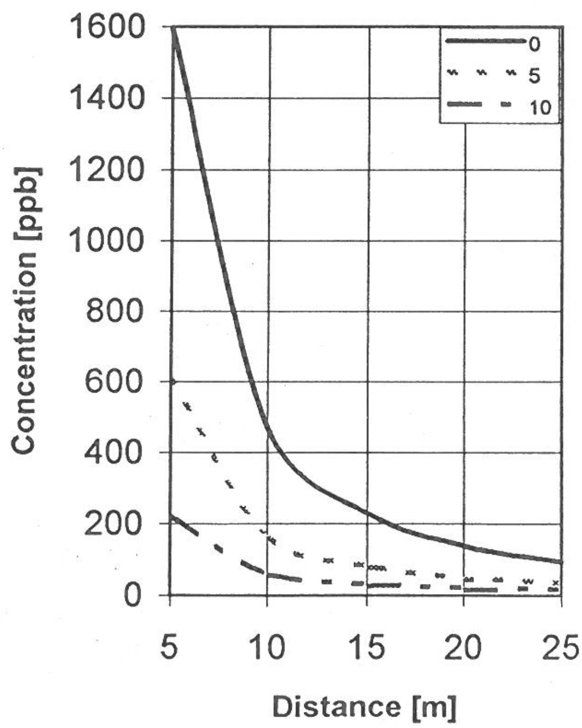

Fig. 3. Predicted H_2S concentrations using AUSPLUME and METH2S Measured 64 ppb at (13.6m, 1.3m)

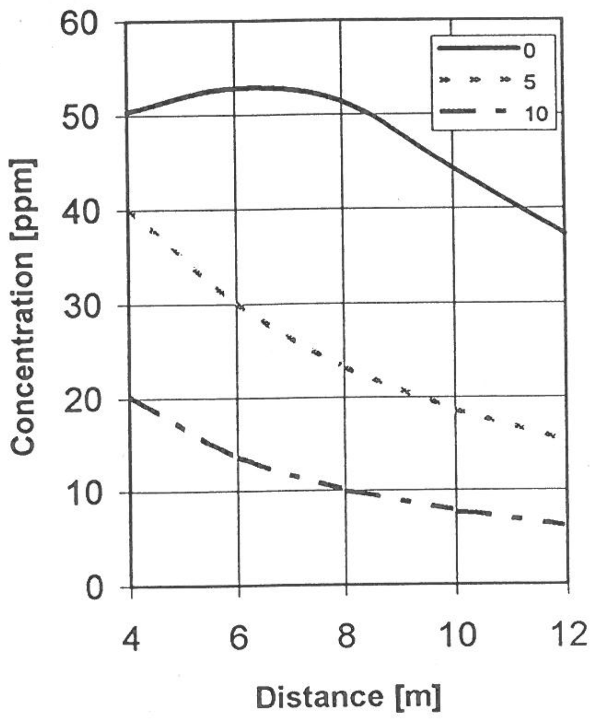

Fig. 4. Predicted NH_3 concentrations using AUSPLUME and METNH3 Measured 10 ppm at (6.5m, 0.3m)