

THE 14th CHESAPEAKE SAILING YACHT SYMPOSIUM

Developments in the IMS VPP Formulations

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ABSTRACT

The paper describes the improvements made to the aerodynamic and hydrodynamic force models of the Offshore Racing Council (ORC) International Measurement System (IMS) sailing yacht velocity prediction program (VPP) since 1990. The paper explains the mechanisms of the force modeling used in the IMS VPP to provide a framework within which the modifications and revisions to the VPP are described. The major revisions fall into three categories.

1) The hydrodynamic model, where a revised formulation for residuary resistance and characteristic length has been introduced, which includes modifications to both the residuary and viscous resistance components. Revisions to the drag due to heel and induced drag formulations are described that more accurately reflect the behavior observed from towing tank tests.

2) The added resistance in waves module was introduced to assist with the equitable handicapping of diverse hull types and construction methods, which affect the behavior of sailing yachts in waves. The mechanism by which the sea state is characterised and the added resistance calculated is described.

3) The aerodynamic force model, which derives complete rig lift and drag coefficients from standard sail types is described. The behavior of the VPP force model is compared with wind tunnel test results, and the recent additions of coefficient sets for a range of different sail types is described. Finally the components of a more detailed model of hull and rig windage are outlined.

NOTATION

Δ ----- Displacement
 ρ ----- Fluid density
 ϕ ----- Heel angle
 ∇ ----- Volume of displacement of canoe body
 ζ_a ----- Wave amplitude
 β_T ----- Apparent wind angle
 β_T ----- True wind Angle

A ----- Area
 A_{REF} ----- Reference area
 A_{WP} ----- Waterplane area
B ----- IMS beam
BAS ----- Boom height above sheer line
 B_i ----- Sail blanketing function of individual sail
BTR ----- Beam to draft ratio (B/T_C)
c ----- Chord length
 C_d ----- Drag coefficient
 C_{d_i} ----- Induced drag coefficient
 C_{d_p} ----- Parasitic drag coefficient
 C_f ----- Viscous drag coefficient
 C_l ----- Lift coefficient
 C_{l_x} ----- Maximum lift coefficient
 C_p ----- Prismatic Coefficient
 C_v ----- Δ/L^3
EDMC - Corrected effective mast diameter
EHM --- Effective mast height
 $f(a,b)$ --- Function of parameters a and b
FBAV -- Average freeboard
 F_H ----- Heeling Force (Normal to mast)
flat ----- Sail Flat Parameter
 F_n ----- Froude Number
 F_s ----- Sideforce (in the plane of the water surface)
g ----- acceleration due to gravity
GYR --- Radius of gyration in pitch/LSMH
HBI ----- Height of base of I above water plane
 H_E ----- Effective rig height
I ----- Fore sail hoist
IMS D - IMS Effective draft
L ----- IMS length
LCB ----- LCB position referred to mid LWL
LCF ----- Longitudinal centre of flotation, referred to mid LWL
LSM1 -- Length, second moment, for the yacht in Sailing Trim floating upright
LSM2 -- Length, second moment, for the yacht in Sailing Trim floating with 2° heel
LSM4 -- Length, second moment, for the yacht in a deep condition sunk 0.025*LSM1 forward and 0.0375*LSM1 aft, floating upright
LSMH - Average canoe body length

LWL --- Waterline length
 Mvblcrew Moveable crew weight
 P -----Mainsail hoist
 q-----Dynamic head ($0.5\rho V^2$)
 R_{AW}-----Added resistance in waves
 reef -----Sail Reef parameter
 R_H-----Resistance due to heel
 R_I -----Induced resistance
 R_R-----Residuary resistance
 R_R(ϕ) ---Residuary resistance at heel angle ϕ
 R_{TOT} ----Total resistance
 R_U-----Upright resistance
 s-----Element of section area attenuated for depth
 S_z(ω) ---Wave spectral ordinate
 t-----Thickness
 T_C-----Canoe body draft
 T_{EFF}-----Effective draft
 T_R-----Reduced draft
 V-----Velocity
 V_s-----Ship speed
 V_T-----True wind velocity
 x-----Length in the fore and aft direction
 Z_{CE}-----Vertical centre of effort position above water plane

INTRODUCTION

The purpose of this paper is to describe the improvements made to the aerodynamic and hydrodynamic force models of the Offshore Racing Council (ORC) International Measurement System (IMS) sailing yacht velocity prediction program (VPP) since 1990. The paper is not intended as a complete description of the IMS VPP. This is now beyond the scope of a single paper thanks to the plethora of modifications, adjustments and type forming features that have been introduced through the years. The IMS VPP, whilst containing some well developed algorithms for force calculation, is primarily a handicapping system, and the paper is offered as part of the dialogue between rule makers and users that helps the IMS system progress. The author has served on the International Technical Committee of the ORC since 1993, and the choice of the particular aspects of the VPP discussed is his. The views expressed about the reasons for particular changes and the effects they promote are also the author's, and are not to be taken as reflecting those of the ITC or ORC as a whole.

In the early 1970's the H. Irving Pratt project funded researchers at the Massachusetts Institute of Technology to produce a methodology that would predict the speed of a sailing yacht, given knowledge of its hull, rig and sailplan geometry. The aim of the project was to improve yacht race handicapping and it covered a huge amount of new ground, including:

- A hydrodynamic force model based on towing tank tests.

- An aerodynamic model for the sail forces at all apparent wind angles.
- Development of an iterative optimisation scheme, which produced equilibrium sailing condition solutions.
- Derivation of new methods of race scoring to utilise the seconds/mile handicaps that the VPP predicted for each point of sailing.
- Development of a hull offset measuring machine and associated Lines Processing Program (LPP) to pre-process hull shapes prior to introduction into the VPP.

The final MIT report (Kerwin 1978) describes the force models developed by the project, and provides the best description of the starting point for today's IMS VPP. In 1976 the Offshore Committee of U.S. Sailing adopted the MIT VPP computer program as the basis of the Measurement Handicapping System (MHS) to facilitate the equitable handicapping of diverse boat types. In November 1985 the Offshore Racing Council voted to adopt this system as a second rule alongside the International Offshore Rule (IOR). Finally the International Measurement System (IMS) became the only internationally administered handicap rule.

International Measurement System (IMS)

The prime function of the IMS is as a handicapping system. At its inception it was hoped that by producing the "best" VPP the problems of handicapping diverse yacht types in all sorts of races would be resolved. This has not yet happened, nevertheless the IMS offers handicaps for all types of races from the Sunday morning no spinnaker club race right up to International Grand Prix events such as the Kenwood Cup.

The designers of pure racing yachts treat the IMS as a pseudo measurement rule and attempt to exploit perceived handicapping-performance mismatches in the VPP algorithms. At the other end of the spectrum factors such as the Dynamic Allowance have been introduced which offer some relief to the **genuine** cruiser/racer sailor who would otherwise find himself outgunned against a professionally prepared and crewed race boat. Demands for simple, low cost measurement for recreational sailors have resulted in the development of ORC Club. This uses the existing database of measured hulls and owner declared dimensions to produce an entry-level certificate which is non the less compatible with the full panoply of IMS proper.

This goal of providing a universal handicap rule for all levels of offshore racing, based on a rational VPP, is a major undertaking, and no other handicapping system attempts to span such a wide constituency. The formulations used in the VPP are developed and managed by the International Technical

Committee whose proposals for rule “improvements” must be ratified by the Council at their annual meeting in November. This paper is concerned solely with developments to the IMS VPP force models. Despite its value in handicapping terms no consideration will be given to features such as the dynamic allowance. Details of all aspects of the IMS may be found in the ORC publications.

The rule formulations are devised almost entirely in the public domain through the work of the ITC and the minutes of the Offshore Racing Council, and therefore the IMS formulations are shaped by inputs from a wide variety of designers and researchers. Because of its accessibility the IMS formulations are frequently used by designers, and researchers as the first port of call when looking for an analytical solution to a design problem.

An exposition on all the formulations used in the IMS is beyond the scope of this single paper. However it is several years since a paper on the IMS has been published in the technical literature, and the author hopes that this type of discussion paper will promote the mechanisms by which the ORC draws new information into its deliberations on the IMS VPP.

Scope

The current IMS handicap system comprises 3 separate elements:

- 1) A **measurement procedure** whereby the physical shape of the hull and appendages are defined, along with dimensions of mast, sails, etc.
- 2) A **performance prediction procedure** based on (1) via a lines processing procedure which determines the parametric inputs used by the VPP.
- 3) A **race management system** whereby the results of (2) are applied to offer condition specific race handicapping.

This paper will discuss only the performance prediction aspects of the IMS.

VPP METHODOLOGY

The VPP has a two-part structure comprised of the **boat model** and the **solution algorithm**. The boat model is often thought of as a black box into which boat speed, heel angle, reef and flat are input. The output is simply two numbers; the aerodynamic driving force and hydrodynamic drag. It is then the job of the solution algorithm to find a driving force–drag equilibrium, i.e. balance the seesaw in Figure 1 (Milgram 1993), and to optimise the sail controls (reef and flat) to produce the maximum speed at each true wind angle.

The boat model is divided into 2 parts;

- **Aerodynamic part**
For a given wind and boat model variable set (V_T , β_T , V_s , ϕ , reef, flat), determine the apparent wind angle and speed that the sails ‘see’ and predict the

aerodynamic lift and drag they produce for a given reef and flat. The aerodynamic forces are resolved into a driving force and heeling force.

- **Hydrodynamic part**
Predict the resistance (drag) and righting moment the hull produces for the assumed speed and heel angle, given that hydrodynamic sideforce will equal the known aerodynamic sideforce.

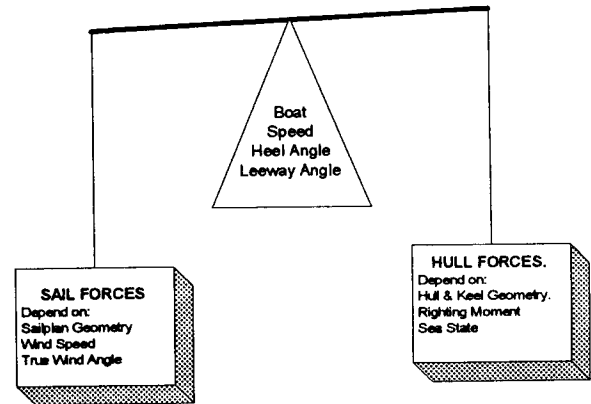


Fig. 1 VPP Force balance.

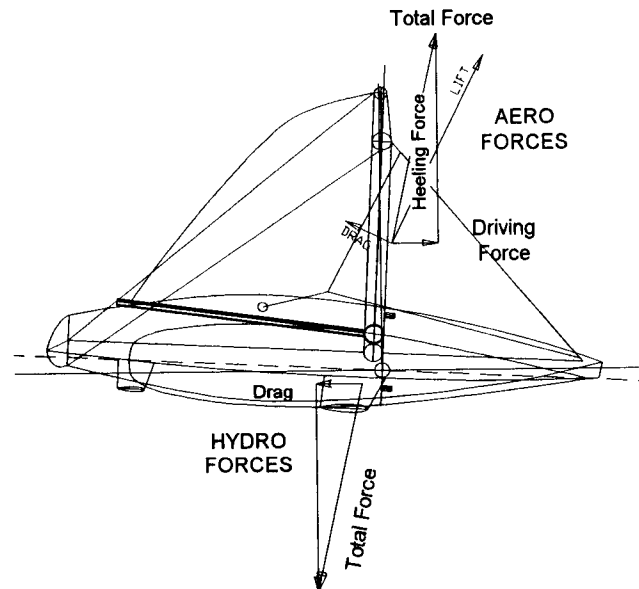


Fig. 2. Force balance in the plane of the water surface.

Figure 2 shows a yacht sailing on starboard tack. In order for the yacht to hold a steady course the magnitude and line of action of the aerodynamic and hydrodynamic forces must be the same. The VPP adopts an iterative procedure at each true wind speed and angle to find “equilibrium” sailing conditions, defined by unique values of V_s , ϕ , reef, flat where;

- 1) the driving force from the sails equals the hydrodynamic drag.

- 2) the heeling moment between the aerodynamic and hydrodynamic forces equals the hull righting moment, as shown in Figure 3.

It should be noted that the IMS VPP, in common with most others, solves only for a balance of force and moment about the track axis. The yaw moment balance is ignored so that sail trimming options, or speed and heel values that produce excessive yaw moments, are not reflected in terms of their influence on speed.

The basic force modeling procedures adopted in the original MHS VPP are still largely used today except for the substantial improvements to the aerodynamic force model set in motion by Hazen's work in 1980. The speed predictions are tolerably accurate and planned refinements will further improve correlation with observed performance. It must be remembered that the raison d'être of the VPP is as a handicap system, although the wide use of its output by designers and handicappers indicates the validity of its predictions.

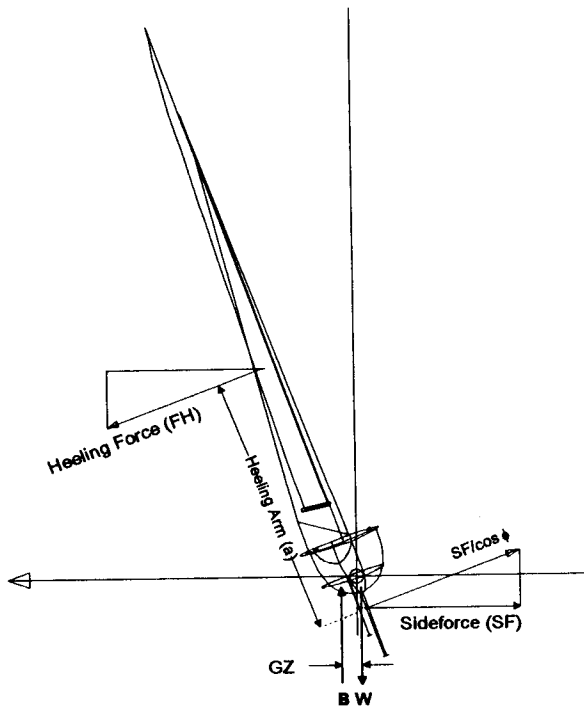


Fig. 3 Roll Moment Equilibrium.

HYDRODYNAMIC FORCE MODEL.

Equation 1 shows a convenient way of viewing the calm water resistance of a sailing yacht. The total

hydrodynamic drag is assumed to be the sum of the following components:

$$R_{TOT} = R_U + R_H + R_I \quad [1]$$

Upright Resistance (R_U) comprising:

Residuary resistance (R_R)

Appendage viscous drag

Canoe body viscous drag

Heel drag (drag due to heel alone) (R_H)

Induced drag (R_I)

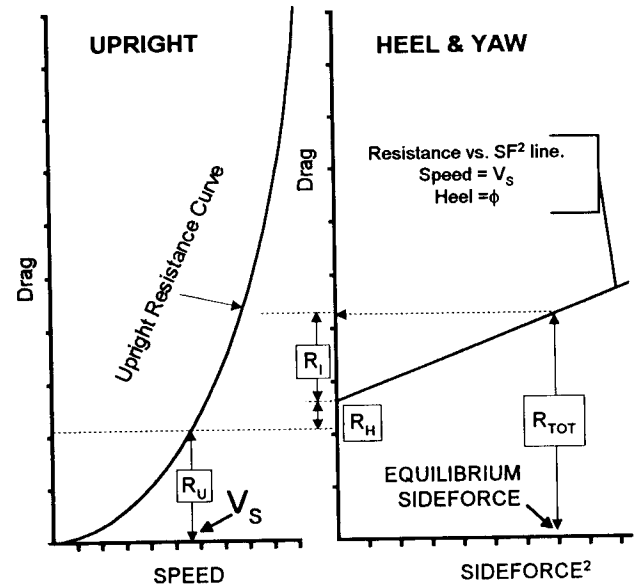


Fig.4 Hydrodynamic resistance breakdown used in the VPP.

The combination of R_U , R_H and R_I is shown graphically in Figure 4. At a given speed V_s the upright resistance is determined from the resistance curve. When the yacht heels and produces sideforce the resistance value can be determined by the intersection of the resistance against sideforce² line with the equilibrium sailing sideforce line. A more complete description of this procedure is given in the course notes for the 1998 WEGEMT School on Sailing Yacht Design held at Southampton University (Claughton et al, 1998). The requirement of the hydrodynamic force model is to determine these three resistance components. The typical proportion of the various components, as a fraction of the total resistance, when sailing upwind in different true wind speeds is shown in Figure 5

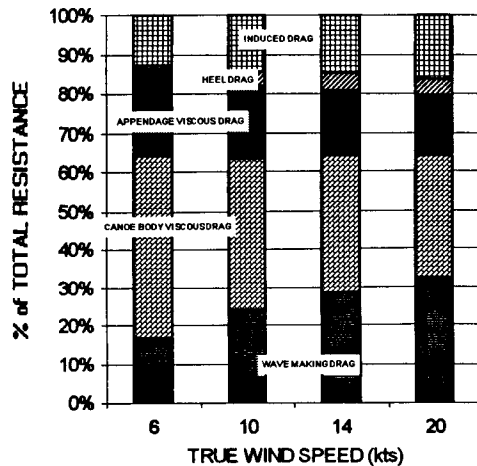


Fig. 5 Proportion of resistance components at different true wind speeds.

Viscous Resistance.

In its original form the viscous resistance of the canoe body and appendages were calculated from the ITTC 1957 model-ship correlation line based on the total wetted area of the hull and appendages, using 0.7LWL as the characteristic length. The current IMS VPP still uses this method to calculate the viscous resistance of the canoe body, but applies a more sophisticated scheme to the keel and rudder.

The currently implemented scheme divides each appendage into 5 segments as shown in Figure 6, and determines the viscous coefficient of resistance of each strip based on the local (strip specific) Reynolds Number and thickness/chord (t/c) ratio.

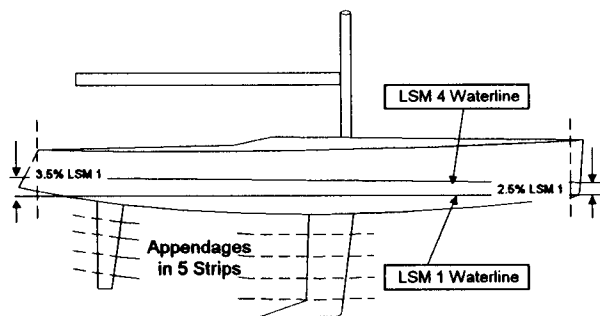


Fig. 6 Strip wise segmentation of appendages.

The viscous resistance of each strip is then calculated from the product of the dynamic head, the local wetted surface area and an appropriate skin friction resistance coefficient. (Cf). The determination of the appropriate Cf is based on data presented in

Fluid Dynamic Drag (Hoerner 1965) and is programmed using a scheme devised by Karl Kirkman, Dave Greeley and Jim Teeters. The calculation is based on 4 Reynolds Number regimes, calculated for a flat plate and t/c ratios of 10 and 20%, as shown in table 1.

Reynolds No.	1000*Cf Flat plate	1000*Cf t/c = 0.1	1000*Cf t/c = 0.2
1.00E+03	44.55	62.2	79.89
3.162E+03	24.85	42.07	59.29
1.00E+04	13.86	28.93	44.00
3.162E+04	7.734	20.20	32.66
1.00E+05	4.945	10.74	16.54
3.162E+05	3.461	4.985	6.51
1.00E+06	3.00	3.62	4.49
2.512E+06	3.00	3.62	4.49
6.310E+06	3.00	3.62	4.49
1.585E+07	2.811	3.39	4.21
5.012E+07	2.38	2.88	3.57
1.995E+08	1.95	2.36	2.93

Table 1 Appendage Cf. values used in the IMS VPP

This approach works well for plain fin keels and rudders, but for keel bulbs which occupy the lowest appendage strip some further calculation must be done to ensure that an appropriate characteristics are derived. The following approach is currently used:

- Use a chord length equal to the average of the top of the bottom strip and the longest fore and aft length occurring in the bottom strip.
- Use a mean thickness equal to the strip volume divided by the mean chord ((a) above) divided by 0.66.
- Use a reference area equal to half the actual wetted area of the bottom strip. This allows for the wetted area of the keel bottom and the tops and bottoms of bulbs and wings.

Residuary Resistance

The determination of the wave making, or residuary resistance, of a sailing yacht hull has proved over the years to be the most taxing aspect of the IMS. It is the area where the assistance/exploitation dichotomy is most exposed, in that alterations in the formulation that are aimed at assisting "older" designs offer scope for exploitation by custom designs, witness the current trend for bumping hulls to achieve aft LCB and high prismatic coefficient.

To date the residuary resistance has been derived by the following method.

- Carry out towing tank tests on a series of scale model yacht hulls with systematically varying parameters.
- Determine the residuary resistance using standard extrapolation procedures.

- 3) Determine a parameter set for a regression analysis (e.g. Length, beam, canoe body draft, displacement), calculated as per the rule requirements.
- 4) Carry out a regression analysis to express the residuary resistance against F_n curve as a function of the parameters chosen in (3).

The model test data for the IMS has been provided almost entirely by the Delft Systematic Yacht Hull Series (DSYHS). The most recent description of their work was presented at the 1998 HISWA Symposium. (Keuning & Sonnenberg 1998). The Ship Hydromechanics Laboratory at the Delft University of Technology have to date tested over 50 models spanning 4 series of hull types which have mirrored the changing character of sailing yacht hulls over the last 25 years. The parent models of 3 of the series are shown in Figure 7. This remarkable body of work has been the mainstay of sailing yacht research in the public domain for two decades. The technical community owes much to the enthusiasm and dedication of the project's instigator Professor Gerritsma and his protege Dr Keuning who has, along with his staff, continued the work at the Delft Laboratory.

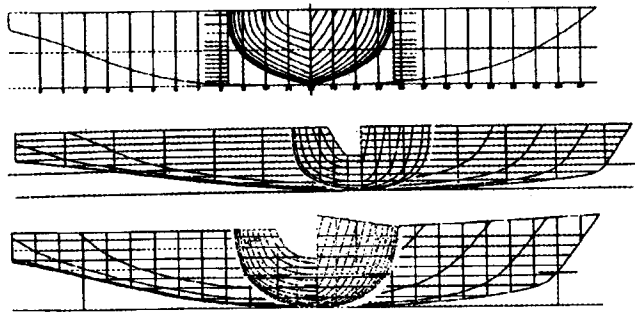


Fig.7 Delft Systematic Yacht Hull Series parent models.

MHS Residuary Resistance Formulation

The residuary resistance formulation was originally based on the first few models of the DSYHS and the first MHS VPP formulation, equation 2, had only three coefficients (a_1 – a_3) defined at eight values of Froude Number from 0.12 to 0.54.

$$F_n = \frac{V}{\sqrt{gL}} \quad [2]$$

$$\frac{R_r}{\Delta} = a_1 \times \left(\frac{B}{Tc}\right)^{a_2} \frac{C_v}{\sqrt{C_v^2 + a_3}}$$

Figure 8 shows the residuary resistance against speed for a typical yacht with an IMS L of 14m (46 ft.) and a displacement of 8 tonnes (17600 lbs). Also shown are two variations, one with a 50% displacement reduction, based on the same waterline,

and the other retaining the same displacement/length ratio but extending the waterline by 20%.

Figure 8 demonstrates that residuary resistance is primarily determined by the length of the yacht's waterline, and its displacement. Making the yacht lighter produces a bodily downward shift of the residuary resistance curve, whilst an increase of length, at constant displacement/length ratio, stretches the resistance curve to the right. These are the two major mechanisms that control residuary resistance. The next most important parameter is the canoe body beam/draft ratio (BTR), and these 3 parameters were the only ones included in the first residuary resistance formulation. Contributing to the apparent simplicity of this early formulation was the fact that the characteristic length used in the derivation of F_n was determined from the second moment of area (LSM) of the sectional area curve of the immersed part of the hull, as shown in equation 3.

$$LSM = 4.26 \sqrt{\left(\frac{\int x^2 \sqrt{s} dx}{\int \sqrt{s} dx}\right) - \left(\frac{\int x \sqrt{s} dx}{\int \sqrt{s} dx}\right)^2} \quad [3]$$

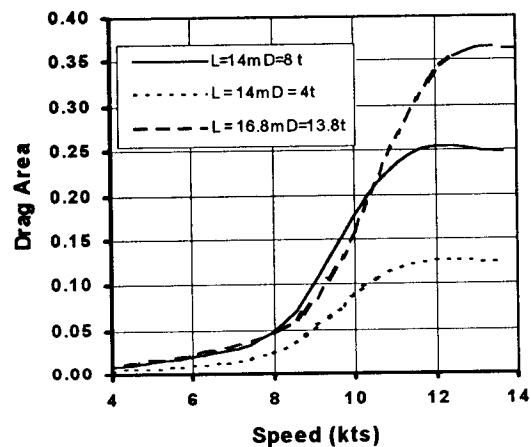


Fig. 8 Residuary resistance against speed for different Length and displacement values.

The length used in the determination of Froude number is in fact an average of 3 LSM's each one related to a different flotation condition, equation 4.

$$L = 0.3194 \times (LSM1 + LSM2 + LSM4) \quad [4]$$

The use of a 2° heel condition, LSM2, is intended to prevent exploitation by lines distortion, and the sunken condition, LSM4, shown in Figure 6 is intended to reflect the yacht's overhangs that would be immersed when sailing fast. This approach is still used today in the IMS to avoid the distorting effects of point

measurements. The residuary resistance formulation, equation 2, tackled only the effect of length/volume ratio and beam/draft ratio. The effect of nuances of volume distribution within the canoe body being handled by the LSM. It is an elegant and satisfactory approach to avoiding the distortions sometimes produced by "point" measurement rules.

1998 Residuary Resistance Formulation

By the early 1990's however there was pressure on the rule makers to become more sophisticated in their treatment of diverse hull types. Also the database of residuary resistance curves generated by the Delft towing tank and the careful analysis work of Axel Mohnhaupt had grown to cover a wide parameter space with the testing of the series 2 and 3 models. Also at this time 5 IOR maxi models tested by Bruce Farr and Associates at the Wolfson Unit MTIA were included in the regression family. These models were the displacement/length variation part of a systematic series carried out in support of the design of yachts for the Whitbread Round the World Race, won by Steinlager 2. At this time therefore a more complex equation was formulated to regress the residuary resistance database. The formulation used in the IMS went through a number of revisions, each one accompanied by very audible howls of protest from half the fleet, and silent smirking from the remainder as the handicaps fluctuated under each new interpretation of the physics of residuary resistance.

The current 1998 formulation is shown in equation 5 and as well as the obvious terms such as beam to draft ratio, prismatic coefficient and longitudinal center of buoyancy there is also a waterplane area term which is important as the high speed regime is approached.

$$1000Rr/\Delta = a_0 + a_1Cp + a_2 \frac{B}{T_c} + a_3L_{VR} + a_4 \frac{A_{WP}}{\nabla^{2/3}} + a_5 \frac{L_{CB}}{L_{VR}} + a_6 \frac{L_{CB}^2}{L_{VR}^2} + a_7L_{VR}^2 \quad [5]$$

$$L_{VR} = L/\nabla^{1/3}$$

The coefficients are evaluated from Fn of 0.125 to 0.6 in steps of 0.025 and the VPP determines the residuary resistance at a particular speed from a cubic spline fit to the 20 R_R data points yielded by the regression equation. The parametric limits for the multipliers of each coefficient in the above equation are shown in Table 2. The form of the current residuary resistance formulation contains a quadratic LCB term but only a linear prismatic coefficient (Cp) term.

Figure 9, taken from tests on a systematic variation of prismatic coefficient on 3 models is

presented as a ratio plot, where the drag of the high and low prismatic coefficient hulls is expressed as a ratio to the baseline, hull. Figure 9 shows two features. Firstly the difference in resistance for changes in Cp is only a few per cent and may be regarded as second order compared to those accruing from changes in length, displacement and BTR, and secondly it indicates that at each speed there is an optimum prismatic coefficient. The current residuary resistance model does not model this effect because when a quadratic Cp term is included the regression analysis produces a less satisfactory fit to the database. Possible remedies to this situation are discussed in the section about future work.

Coefficient	Lower Limit	Upper Limit
a_1	0.5297	0.5928
a_2	2.4212	13.714
a_3	4.279	9.034
a_4	3.8	12.217
a_5	-0.1251	0.827
a_6	0.002	2.828
a_7	18.31	81.614

Table 2 1998 Residuary resistance formulation parametric limits.

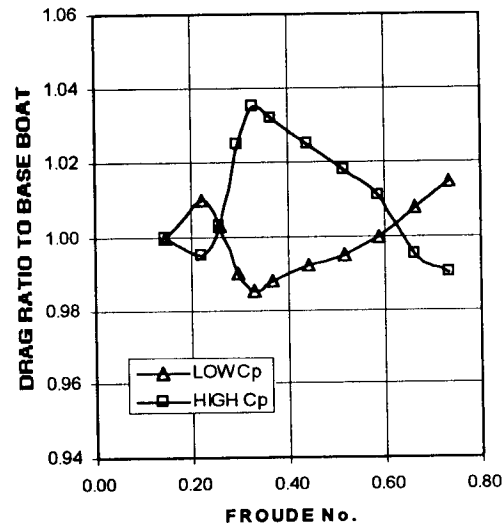


Fig.9 Effect of prismatic coefficient on resistance.

Other changes have accrued in the wake of this change to a more "sensitive" residuary resistance formulation.

Length Determination

The determination of length has been modified, the composite L is still retained, i.e. it is calculated from the 3 LSM values, but the formula has been altered to that shown in equation 6.

$$LSM = 3.932 \sqrt[4]{\left(\frac{\int x^2 \sqrt{s} dx}{\int \sqrt{s} dx} \right) - \left(\frac{\int x \sqrt{s} dx}{\int \sqrt{s} dx} \right)^2} \quad [6]$$

The use of a fourth root, as opposed to a square root de-sensetises the effect of volume in the ends of the canoe body as shown in Figure 10 which shows the calculated LSM for two boats, "A" with a low prismatic coefficient and "B" with a high prismatic coefficient.

The 1990 and current calculation of LSM are shown as horizontal bars, and it can be seen that the original calculation offers the greater LSM differential between the two volume distributions. This de-sensetising of the volume effect was necessary to avoid the effects of volume distribution being carried in two places, the LSM calculation and the R_R equation, once the R_R equation carried volume distribution terms.

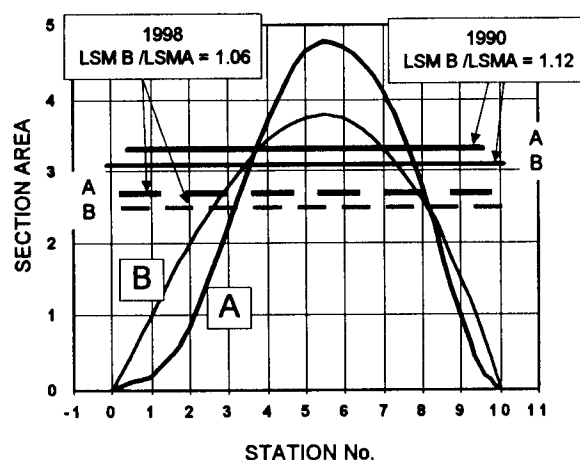


Fig. 10 Determination of LSM 1990 and 1998.

Residuary Resistance of Appendages

The original Delft Series models had all been tested with a standard keel and rudder and consequently the original MHS approach was to include the appendages as part of the total displacement for the purposes of calculating residuary resistance. On yachts with hull forms where the appendage/canoe body interface was less than well defined this worked satisfactorily. Over time however a more sophisticated treatment was sought, and now all of the DSYHS models have been tested as bare canoe bodies. Also Delft have examined closely the effect on wave making resistance of a fin keel and the paper presented at the CSYS (Keuning 1997) describes this effect in more detail.

An initial attempt at calculating the residuary resistance based on a formula derived from preliminary analysis of the Delft tests with and without appendages led to an over generous allowance for this effect. The racing fraternity promptly exposed the

crudeness of the approach by setting sail with foam filled bulb keels. The determination of these interaction effects is complex and time consuming to do using the towing tank, but some appropriately sensitive solution had to be found that would allow equitable handicapping to be carried out.

Joe Laiosa of Northrop Grumman and Jim Teeters carried out a research program funded by Charles Poor and USSA to develop a new prediction method. The interesting aspect of this program was the use of America's Cup technology and data. The group studied tank test results of 12 Meter and IACC keel designs. To calculate wave drag, Laiosa ran the SPLASH code, a computational fluid dynamics program developed by Bruce Rosen. Initial calculations compared very favorably with the tank results, so Laiosa went on to evaluate many other canoe body and keel configurations. Jim Teeters then went on to express these results in an algorithm that is sensitive to both keel volume and depth. The residuary resistance of an element of keel or bulb is based on 2 baseline curves shown in Figure 11. These show the resistance per unit volume, normalised against F_n^2 for an element of keel fin or bulb at the standard depth, 0.1L and 0.2L respectively.

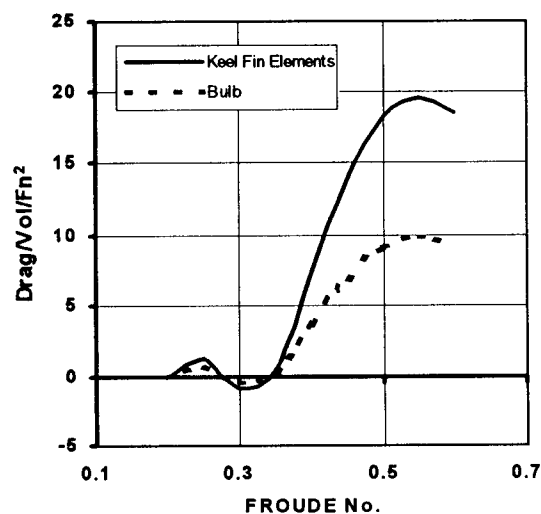


Fig. 11 Appendage residuary resistance per unit volume at standard depth.

As described in the section on viscous resistance the VPP divides the keel into 5 fore and aft strips, stacked on top of each other. The volume and average depth of each strip is calculated. The major factors that influence the wave-making drag of an appendage "strip" are:

- 1) Appendage strip volume.
- 2) Appendage strip depth below the free surface.
- 3) Boat speed.

4) Whether or not that piece of volume is a bulb or part of the vertical foil.

Bulbs are more three dimensional in nature, apparently cause less disturbance to the water flow, and have less drag per unit volume. The drag of bulbs per unit volume is approximately half that of keel strips. The attenuation of drag with depth is approximately linear for both keel strips and bulbs.

Currently, the VPP looks for bulbs only in the deepest strip of a keel. The test criterion is the ratio of the chord length of that deepest strip to the chord length of the strip above it. If that chord ratio is ≥ 1.5 , then the deepest strip is considered to be a bulb. If the ratio ≤ 1.0 , the strip is a keel strip. If the ratio is between 1.0 and 1.5, the drag is found by linear interpolation over chord ratio of the two drags found by treating the strip as a bulb and as a keel.

For traditional style hulls where the keel chord exceeds 50% of LSM1 then the keel volume is added to the canoe body volume for the purposes of calculating the residuary resistance.

Future Residuary Resistance Research

The task facing the ITC at the present time is to develop a robust and equitable formulation for residuary resistance. In the absence of any other considerations the formulation could be improved year on year as more data are gathered from the tank testing and other research programs. However the IMS is not a research program, but a handicapping rule that must maintain, indeed expand, its market share if it is to survive in a competitive market place. Piecemeal modifications of the formulations year on year have attracted criticism when changes made to improve the physical model have produced shuffling of the handicap pack that is not in line with performance observed on the race course. Consequently and justifiably the ORC have become reluctant to change the residuary resistance formulation just because the ITC says the results are "better". Thus it has become hard to justify a change to the residuary resistance formulation unless it both improves the physical model and corrects observed anomalies in the current handicap landscape.

At present the development of better formulations has been approached in three ways. Firstly by the investigation of different parameters in the regression equation (e.g. equation 5). Secondly by the addition of new models to the database, and more recently by the exclusion of some of the Delft series 1 and 3 models that were considered to have unusually proportioned hulls that made them non representative of current practice. This manipulation of formulation and database has resulted in some potentially "better" residuary resistance predictions, but as yet not sufficiently so to warrant changing the rule. One of the factors that governs this approach is the use of a

pure regression technique that exerts no familial control on the coefficients variation with Froude No. Consequently, even though observed performances on the race course suggest a particular rate of performance change with LCB or C_p , this cannot easily be translated into modified regression equation coefficients.

An alternative proposal that would allow the rate of rating credit and debit for non optimum C_p and LCB values to be more accurately controlled has been proposed and is under review by the ITC. This method uses a "base boat" approach where variations in residuary resistance are expressed in terms of variation from the base boat's parameters. Once again LCB C_p and WPA, normalised with respect to length/volume ratio, are the main drivers, used in slightly different combinations to the current IMS formulation. An advantage of this proposal is that it offers the ability to introduce into the residuary resistance formulation data from sources other than the DSYHS, or similarly sized models. This is of particular importance as US Sailing have begun a program of large scale model tests on contemporary IMS hull forms at NRC Canada. Without some alteration in the analysis of the residuary resistance database it is difficult to see how these results can be brought to bear on the formulations. The new "base boat" proposal has, as yet, failed to find universal acceptance in the ITC, despite being the subject of regular submissions from the United States and other Member National Authorities. In due course I am sure some accommodation will be reached between the "regression" and "engineering" camps. In fact the recent approach of weighting modern models in the DSYHS more heavily than older hull types might be seen as a move towards controlled manipulation of the residuary resistance expression.

Another factor that has long proved problematical is the rational determination of length. The current scheme works tolerably well, although detractors might say the rule is type forming, which by definition means some hull shapes are disadvantaged. The effects of volume distribution in the ends of the boat, and the shape of the overhangs themselves are hard to predict, as described by the author. (Claughton 1989). In attempt to explore this area in more detail a Computational Fluid Dynamics (CFD) research program has been proposed, in the interests of deriving data for the handicapping formulations more quickly. It is hoped that this will begin with a validation exercise using the "SPLASH" code early next year.

Drag due to Heel

Drag due to heel arises from three sources:

- 1) A modification of the viscous resistance of the heeled hull, this arises from changes to the wetted surface area with heel angle, and also a modification the pressure form drag due to the

change in hull surface curvature experienced by the water flowing past.

- 2) A modification to the residuary resistance due to a change in immersed length of the hull.
- 3) A change to the residuary resistance of the hull due to the asymmetry of the heeled shape.

Items 1 and 2 in the above list may add or subtract from the hulls resistance, and whilst 3 is normally additive, its magnitude is strongly dependant on hull shape.

The original IMS formulation presumed that the heeled asymmetric hull would have a residuary resistance identical to that of an upright symmetrical hull that matched the heeled yacht's parameters of beam, draft, and length etc. This method under predicted heeled resistance, especially for wide shallow hull forms.

For the 1994 rule a revised formulation was proposed and adopted. It is interesting to quote from the original 1993 submission; "A heel drag formulation is proposed for use in the 1994 IMS VPP. It is a simple formulation developed in the three weeks available, and is intended as a reasonable, but temporary, measure while this area receives further attention and research in the forthcoming year". In fact the formulation shown in equation 7 has worked satisfactorily for 5 years. The original premise that changes to viscous resistance should be related to the wetted surface area at each heel angle was retained. For the residuary resistance effects an expression was developed that provided a proper order of magnitude and form for the heel drag which is based on the assumption that "drag due to heel" is approximately proportional to upright residuary drag. Additionally it uses, in part, the form of the original MHS heel drag formulation. The formulation also matches, as far as is possible with a simple expression, the experimental data available.

$$R_R(\phi) = \left[1 + K_h(\phi) \times (\phi/25)^2 \right] \times R_R(\text{Upright})$$

$$K_h(\phi) = \left\{ \left(1.25 + 2 \left[0.985 - \frac{L_\phi}{L_0} \right] e^{-0.5 F_n^2} \right) - 1 \right\} f_{LDR}$$

$$L_\phi = LSM1 \text{ at heel angle } \phi. \quad L_0 = LSM1 \text{ upright.} \quad [7]$$

$$f_{LDR} = 0.3077 \left(\frac{L}{\nabla^{1/3}} \right) - 0.7692$$

$$4.5 \leq \frac{L}{\nabla^{1/3}} \leq 8.5$$

The principal terms in the expression are as follows:

- the 1.25 term is the constant which forms the basis value of the function around which variations in other parameters cause a variation of heel drag. In

the limit at zero Froude No. heel drag at 25 degrees of heel is approximately 25% of the upright residuary resistance.

- The ratio of upright to heeled LSM's corrects for the change of heel with length, and is the term primarily sensitive to variations in beam/draft ratio.
- The exponential term is the speed correction, which accounts for the fact that heel drag at lower speeds is a greater proportion of upright residuary drag than the proportion at higher speeds.
- f_{LDR} is constrained to a minimum of 0.615 and a maximum of 1.846, corresponding to the calculated values at the limits of LDR.

Over the next year the drag due to heel is almost certain to see its long promised revision when an anomaly in the dynamic righting moment (RMV) which affects high beam/draft yachts is addressed.

Induced Drag

Induced drag is the component of resistance that arises when the hull keel and rudder are producing a heeling force. The predominant source of this drag component is the energy lost to the vortex at the keel tip produced by the equalisation of the pressure and suction forces on opposite sides of the lifting foil.

In the early formulations the drag due to heel and the induced drag were combined in a single expression. This is a sensible approach as induced drag is the drag due to the production of heeling force, which is the force that heels the yacht. However in the current IMS VPP a clearer separation has been used.

Equation 8 is based on simple aerodynamic theory for the induced drag of a lifting surface of finite span. It is interesting to note that induced drag depends only on keel effective draft, the keel aspect ratio per-se does not affect induced drag. Keel lateral area affects the sailing leeway angle and the local keel lift coefficient, but does not affect induced drag.

$$D_I = \frac{F_H^2}{\pi \rho V^2 T_{EFF}^2} \quad [8]$$

$$T_{EFF} = 0.92 T_R = \text{IMS D}$$

The value of the effective draft (T_{EFF}) is determined by the LPP using the original expression for a "reduced draft" (T_R) which is calculated based on the local section maximum draft and hull cross sectional area. This expression which treats the hull and keel as one half of a slender axisymmetric body, calculates the effect of streamline contraction around the canoe body. In this way the influence of a deep hull on effective draft is accounted for.

If the yacht sailed in a homogeneous fluid then Equation 8 would be a satisfactory description of the induced drag behavior of the yacht. However in reality both speed and heel angle affect the value of effective draft. As the yacht sails faster the mid-ship wave trough deepens, and as the yacht heels the root of the keel and rudder move closer to the free surface. Both of these effects allow the pressures on the keel to produce surface waves, or in the worst case ventilation, particularly at the rudder root. These effects mean that the water surface acts less and less as a reflection plane as speed and heel angle increase. The variation of effective draft for a sailing yacht at different speeds and heel angles, derived from towing tank tests, is shown in the upper part of figure 12.

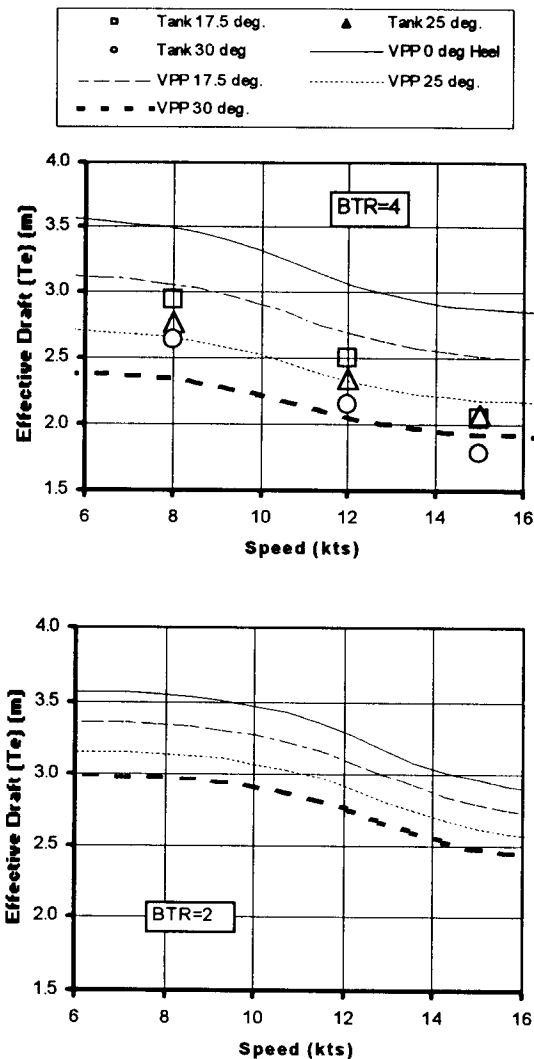


Fig. 12 Variation of effective draft with speed and heel angle.
Upper BTR = 4. Lower BTR = 2

In order to account for these effects a speed and heel angle correction to the upright, zero speed effective draft was proposed by Jim Teeters and

adopted by the IMS in 1994. The form of the correction for the tested model (BTR=4) and a lower beam to draft ratio is shown in Figure 12. The figure shows how the deleterious effects of speed and heel angle on induced drag are reduced as beam to draft ratio is reduced. Once again, like the heel drag factor it is a plausible and appropriately sensitive representation of a complex physical phenomenon.

A final modification to the effective draft formula was subsequently adopted to address a trend towards deeper and deeper keels on out and out racing yachts. This trend arose because of the nature of fleet racing in yachts of similar performance. It was found that extra draft, even though the VPP predicted higher speeds, was beneficial in being able to achieve and maintain a place in the front rank of the race to the windward mark. Also on windward leeward races which, by definition, involve a lot of tacking the deep draft keel proved to be more competitive in the "down speed" condition coming out of tacks. Equation 8 shows that if heel angle, and therefore heeling force, are constant the induced drag is inversely proportional to speed². Thus the effect of keel draft is handicapped only for the induced drag at "full speed", whilst in a race with a lot of tacking some note should be taken of the extra induced drag occurring when sailing at lower speed.

This effect is taken into account by the use of an "unsteady factor" (FUNSTEADY). Initially this was a multiplier on effective draft of 0.95, thus increasing the proportion of induced drag above the "full speed" value, thus providing an extra weighting to induced drag. This measure has not wholly quelled the drive to deeper draft in the racing fleet, and therefore for 1999 the "unsteady factor" will be based on a mean IMSD/length ratio of 0.19, at shallower draft than this FUNSTEADY is reduced, at deeper draft FUNSTEADY is increased. This is purely a type forming modification to the VPP. The final equation for induced drag is shown in Equation 9. The function in speed and heel angle $f(\phi V_s)$ is that shown in figure 12.

$$D_I = \left\{ \frac{F_H^2}{T_{EFF}^2 \pi \rho V^2} \right\} + \left(FUNSTEADY^2 \times [f(\phi V_s)]^2 \right) [9]$$

$$FUNSTEADY = 0.95 + (T_R/L - 0.19)$$

To date the contribution of the rudder to the induced drag behavior of the yacht is ignored, hence the trend to deeper rudders which offer a route to unhandicapped induced drag reduction. This aspect of performance is scheduled for investigation by the ITC during 1999.

ADDED RESISTANCE IN WAVES.

The addition of an added resistance in waves (R_{AW}) module to the VPP was made in the early 1990's, and was brought about by the fact that cruising

yachts, with outfitted interiors, were disadvantaged relative to their “stripped out” rivals. This is not surprising, since all anecdotal evidence indicates that reducing the yacht’s moment of inertia by concentrating weight close to the centre of gravity will yield a performance gain when sailing in waves. The US Sailing funded project to introduce this feature into the VPP had three aims which tackled the fundamentals of predicting R_{AW} :

- 1) Define a sea spectrum (wave energy density function) appropriate to the sailing venue.
- 2) Devise a plausible and appropriately sensitive physical model of how parametric changes to the yacht affect R_{AW} when sailing in the sea state defined in 1.
- 3) Devise a method by which a yacht’s pitch inertia could be determined directly by a physical test, in the same way that stability is measured by an inclining test.

Determination of wave climate

As part of the research prior to introducing the R_{AW} module US Sailing funded the deployment of a wave height measuring buoy at several popular sailing venues. The buoy was deployed during typical races and the water surface elevations were recorded together with the wind speed. On the basis of these measurements a single definition of wave climate was derived in the form of a wave energy spectrum normalised for a true wind speed of one knot. This approach has the merit that it is relatively easy to apply, because, whilst the significant height becomes a function of wind speed the modal period remains fixed at 5 seconds.

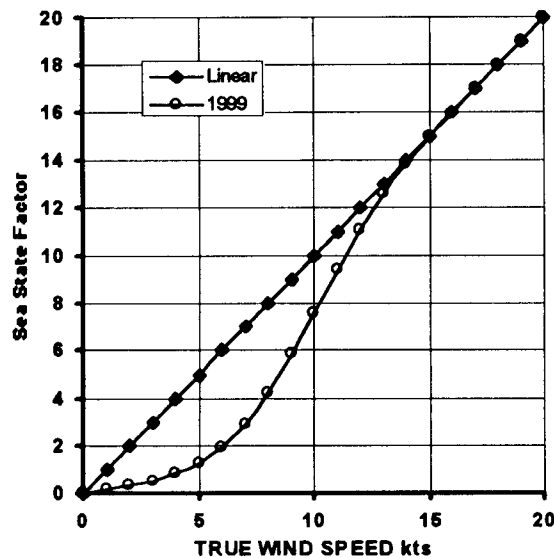


Fig. 13 Wave energy as a function of True Wind Velocity.

When this experimentally derived linear variation of wave energy with wind speed was implemented it was found that the magnitudes of R_{AW} were too high. Added resistance effects were seen to be dominating handicaps in 6 to 8 knots of wind when the sailors could see that no waves were present on the race course. In order to correct this a “bubble”, or more correctly a dimple, was put in the curve that defined the wave energy as a function of wind speed.

Figure 13 shows the original linear sea-state factor together with the further reduction in the light wind wave energy agreed at the 1998 annual meeting. The 1999 IMS formulation is shown in equation 10.

$$f(Vt) = Vt \left\{ 1 - 0.8375 \left[1.175^{(-0.00248 \cdot Vt^{3.5})} \right] \right\} \quad [10]$$

Determination of added resistance response.

The burden of producing a plausible physical model of added resistance behavior in the form of an added resistance Response Amplitude Operator (RAO) fell to Jim Teeters and Dr. Paul Sclavounos. Equation 11 shows how the added resistance is calculated from the product of the wave energy spectrum and the R_{AW} RAO. The wave spectrum in each wind speed is defined by a constant times $f(V_T)$. The task facing the researchers was to produce RAO values for parametric variations of sailing yacht hull forms.

$$\overline{R_{AW}} = 2 \cdot \int_0^\infty R_{AW} / \zeta_a^2 \cdot S_\zeta(\omega) d\omega \quad [11]$$

The method adopted to do this was as follows:

- 1) Define a “base boat” for the parametric series
- 2) Use the “SWAN” computational fluid dynamics (CFD) code to calculate added resistance at 3 Fn.’s and across a range of wave headings.
- 3) Computing time was not available to carry the same calculations for the whole 21 boat parametric test fleet, whose limits are shown in Table 3. Consequently each yacht was evaluated in head seas at Fn.’s of 0.200, 0.265 and 0.325.
- 4) Use the results of (3) to determine the variation of added resistance with each parameter of the test fleet.
- 5) Create a formulation for R_{AW} based on calculating parametric “deltas” relative to the base boat. Equation 12 shows the 1999 formulation and the baseline parametric values are shown in Table 3

PARAMETER	SERIES RANGE	BASE VALUE
<i>GYR</i>	0.2-0.32	0.25
<i>L/B</i>	2.77-4.16	3.327
<i>L³/V</i>	103-156	125
<i>LCB</i>	0.50-0.56	0.53
<i>LCF</i>	0.54-0.60	0.57
<i>B/T_C</i>	--	4.443
<i>LCB-F</i>	--	-0.03
<i>Fn</i>	--	0.325

Table 3 R_{AW} test fleet parametric limits and base values.

$$R_{AW} = 2\rho g L f_s f(Vt) \cdot 0.55 \cdot f(\beta_T) \times f(L_{40}) \times \left\{ 0.00146 + f(Fn) + f(K_{rr}) + f\left(\frac{L}{B}\right) + f\left(\frac{B}{T}\right) + f(LCB - F) \right\} \quad [12]$$

$$f(Fn) = 0.00191 (Fn - 0.325)$$

$$f(k_{rr}) = 0.01575 (GYR - 0.25)$$

$$f(L/B) = [(5.23^{-L/B}) - (5.23^{-3.327})] / 8.494$$

$$f(B/T) = (0.000166 * (B/T_C - 4.443))$$

$$f(LCB-F) = 0.01150 * [(LCB-LCF) - (-0.03)] + 0.05780 * [(LCB-LCF)^2 - (-0.03)^2]$$

$$f(L_{40}) = 0.5059 \times \log(L/40) + 1$$

$$f(\beta_T) = \cos(\beta_T) / \cos(40)$$

In equation 12 the f_s factor provides a means to adjust the added resistance values and perhaps can be thought of as a sea energy or strength coefficient. A value of 0.8 is used.

The $f(Vt)$ function is shown in equation 10 and figure 13.

The 0.55 factor represents the wave direction function, necessary because the R_{AW} calculations for the series were done in head seas, but yachts sail at approximately 45 degrees to the prevailing wind and sea direction.

The $f(\beta_T)$ function makes the added resistance a cosine function of heading with 40 degrees true wind (wave) heading as the basis.

The remaining functions in equation 12 take the difference between the boat and the base boat and then evaluate the increase or decrease in R_{AW} . The calculation of R_{AW} is done using the physical parameters (L , B , T_C) appropriate to the sailing heel angle. Whilst the absolute values of the calculated

R_{AW} are entirely plausible there has always been a lively debate in the ITC about the correct magnitude of the rate of change of R_{AW} with respect to B/T_C , L/B etc. There is a considerable database of model test results, together with a range of CFD tools, e.g. the SWAN code used in the initial development of the formulations, the SPLASH code, and the SEAWAY code developed at Delft University. The HISWA paper (Keuning et al 1998) offers an alternative evaluation of added resistance based on a well developed regression analysis based on model tests and computer calculations.

Determination of Pitch Radius of Gyration K_{YY}

The third element of the added resistance calculation is the determination of the pitch inertia of the yacht's hull and rigging. At the outset it was hoped that a physical in water test could be devised to measure the yacht's pitch inertia. This proved to be impractical and the IMS was forced to introduce an empirical way of assessing inertia so that the R_{AW} module could be introduced into the VPP. Since its introduction the R_{AW} module has been asked to carry ever increasing handicap burdens, thanks to its sensitivity to radius of gyration, which can be linked to different yacht characteristics. For example, rudder construction, mast weight, degree of outfit, hull construction material are all used as surrogate measures of inertia. It has become a universal catchall for all manner of perceived effects that defy rational physical analysis, apart from "if you do this the boat does better".

A yacht's base gyradius is calculated from the equation 13, and then other declared features of the yacht's construction and rig accrue adjustments ($Gyradius_inc$) to this base gyradius, as described in section 726 of the rule book. For example carbon fibre hull construction attracts a $gyradius_inc$ of -0.010.

$$K_{rr} = 0.222 \times (LOA + LSMH) / 2$$

$$LSMH = 0.3194 \times (2 \cdot LSM1 + LSM4) \quad [13]$$

$$GYR = K_{rr} / LSMH - 0.03 + Gyradius_inc$$

Overall Effect

Table 4 shows the magnitude of R_{AW} for a 40 ft sailing yacht at the base gyradius (GYR) of 0.25, and at values of 0.23 and 0.27. The added resistance is expressed as a percentage of the calm water upright resistance. It is this resistance difference that carries all the "inertia" effects.

True Wind	Significant wave ht (m)	GYR		
kts	m	0.23	0.25	0.27
% Upright drag				
6	0.25	4.0	5.1	6.2
12	0.59	14.1	18.0	21.8
20	0.79	21.2	27.0	32.8

Table 4 Summary of pitch gyradius effects on R_{AW} .

AERODYNAMIC FORCE MODEL.

The treatment of the aerodynamic part of the IMS VPP force model has not been fundamentally changed since the shift from the Bay Bea "complete sailplan" approach to that described by George Hazen in 1980. Consequently the descriptions in references by Poor & Sironi reflect current practice. However the scope of the IMS has been widened over the years, first to offer handicap credit to yachts with simplified rigging and more recently to accommodate asymmetric off wind sails. Consequently, in the interests of completeness it is worthwhile at this stage to outline the basic principles of the IMS sail force model.

Individual Sail Force Coefficients.

The fundamental components of the aerodynamic model are the individual sails, characterised by the following parameters, which are shown diagrammatically in Figure 14:

- Sail area
- Centre of effort height above the sail's datum
- Cl_x and Cd_p versus β_{AW} envelope. (Maximum lift coefficient and parasitic (viscous) drag coefficient versus apparent wind angle.)

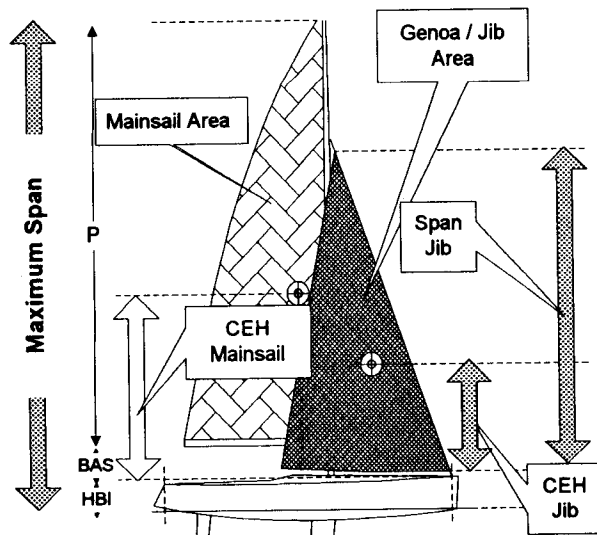


Fig. 14 Definition of sail geometry.

These values vary with the type of sail, for example mainsail, jib, and spinnaker. The VPP also requires knowledge of how to treat these sails when set together so that calculations of blanketing effects and calculations of combined effective span are correctly carried out.

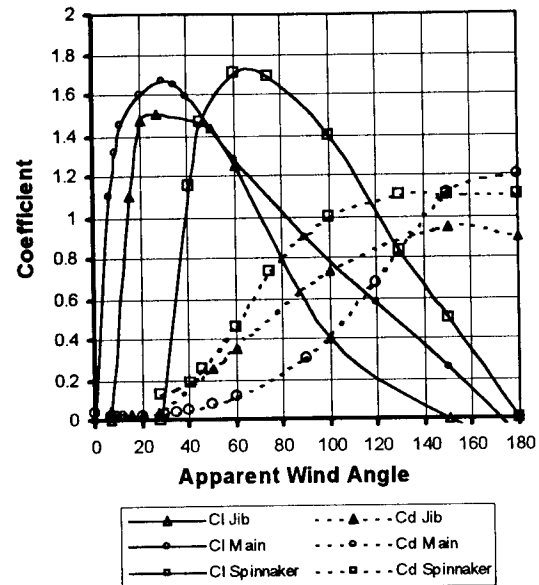


Fig. 15 Individual sail lift and drag coefficients taken from IMS VPP.

Figure 15 shows the individual two-dimensional coefficients for the 3 sail types originally supported by the IMS. The characteristics of the mainsail and jib and spinnaker were derived empirically when the sail force model was introduced. The coefficient values, which are based on cloth area, show typical effects:

- As apparent wind angle increases a rapid rise in lift to a peak value prior to the onset of separation and stall.
- The sails 'fill' at different apparent wind angles, reflecting the different sheeting arrangements and shapes of the sails.
- At an apparent wind angle of 180°, approximating to an angle of attack of 90°, the lift has declined to zero and the drag coefficient increased to 1.0

Force Coefficients for sail combinations.

The force model for a combination of sails is developed from an aggregate of its component sails.

Lift and drag and Centre of Effort height

Aggregate maximum lift and linear parasite drag coefficients are the sum of each sail component's contribution normalised by the reference area:

$$Cl_x = \sum Cl_{xi} B_i A_i / A_{REF}$$

$$Cd_p = \sum Cd_{pi} B_i A_i / A_{REF} \quad [14]$$

$$A_{REF} = \sum A_i$$

The subscript "i" refers to individual sails and the function B_i is a 'blanketing' function that may be used to introduce sail interaction effects. For upwind sailing it is equal to 1.0, meaning no blanketing effect. The centre of effort height is evaluated by weighting each sail's individual centre of effort height by its area and partial force coefficient (comprised of lift and linear component of parasite drag). The quadratic parasitic drag coefficient K_q is the sum of the individual sails' contributions:

Effective span and induced drag

The induced drag coefficient is calculated from knowledge of the effective rig height.

$$Cd_i = \frac{Cl^2 \cdot A_{REF}}{\pi H_E^2} \quad [15]$$

The effective rig height is taken as the highest point of the rig, usually (P+BAS+HBI) multiplied by a rig height factor, which is 1.1 for apparent wind angles up to 30 degrees and then declines to a value of 1.0 at an apparent wind angle of 90 degrees. If the jib area is less than the fore triangle area then the rig height factor is reduced, but cannot fall below 1.

Total lift and drag

The total sail lift and drag coefficients are given in equation 16, in which the reef parameter represents a linear reduction in span or chord, but is squared in these equations. Thus reef = .9 means sail area is reduced to 81% of the reference area. The *flat* parameter characterises a change in sail sheeting, coupled to a reduction in sail camber, such that the lift is proportionally reduced from the maximum lift available. Thus flat = 0.9 means 90% of the maximum available lift is being used.

$$Cl_{TOTAL} = flat \times reef^2 \times Cl_x$$

$$Cd = \text{parasite drag}$$

$$+ \text{quadratic profile drag}$$

$$+ \text{induced drag} \quad [16]$$

$$Cd_{TOTAL} = reef^2 Cd_p$$

$$+ K_q (reef \times flat \times Cl_x)^2$$

$$+ \frac{A_{REF} \times (reef \times flat \times Cl_x)^2}{(\pi / H_E^2)}$$

The apparent wind angle is relative to the yacht's track and the heeled mast plane. It is evaluated at the calculated height of the centre of effort, as is the dynamic pressure q .

Comparison with wind tunnel results.

In 1995 US Sailing and North Sails, represented by Peter Reichelsdorfer, funded a series of wind tunnel tests carried out by the Wolfson Unit at the University of Southampton. These tests were conducted on a generic IMS type yacht and offered a good opportunity to assess the veracity of the IMS force model. The test methods and analysis techniques are well documented in references by Campbell and Claughton 1995-1998 and papers presented by Ranzenbach et al at the 1999 CSYS.

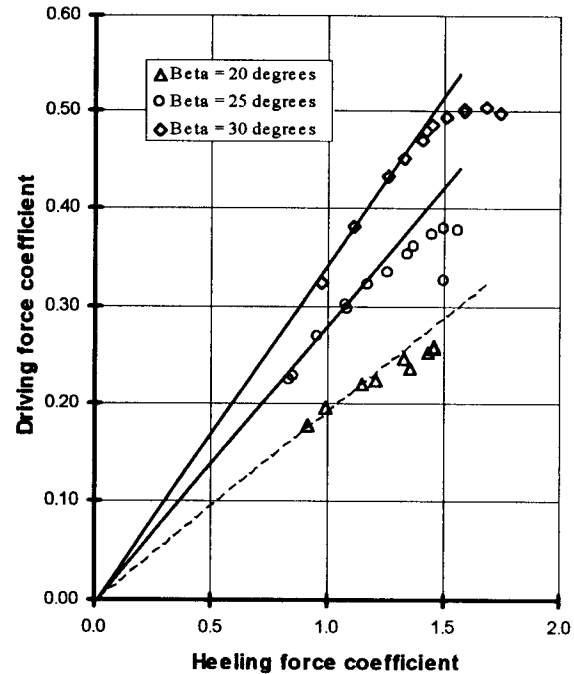


Fig. 16 Typical driving force against heeling force data from wind tunnel tests.

Driving Force and Heeling Force.

Figure 16, taken from Campbell 1997, shows how sails are trimmed in the wind tunnel, and in the authors view, in real life. The results are plotted as driving force against heeling force coefficient for sails trimmed at 3 discrete apparent wind angles. Each data point was obtained from a different sail setting. The maximum drive point was sought by adjusting the main and jib trim to achieve the highest driving force. The reduced heeling force points were achieved by progressively easing the main sail down the traveler, and setting the sails with more open leeches to reduce the heel force. This is generally the way that sailors

cope with reducing heeling force as the wind speed increases.

These are typical results characterised by:

- Discernible maximum driving force.
- A reduction in driving force as the sheets are eased, to a point where the sails are close to flogging.
- An increase in the available driving force as apparent wind angle increases.
- Bad sail sets characterised by low driving force.
- Evidence of “over sheeting” at maximum drive condition characterised by reducing driving force with increasing heeling force. This is less apparent at close apparent wind angles where its hard to over trim
- A maximum driving/heeling force ratio which occurs at less than the maximum driving force.

Lift and Drag Coefficients.

Figure 17 shows the data from Figure 16 shifted into the wind axis system and expressed as lift and drag coefficients plotted as C_d against C_l^2 for each test point.

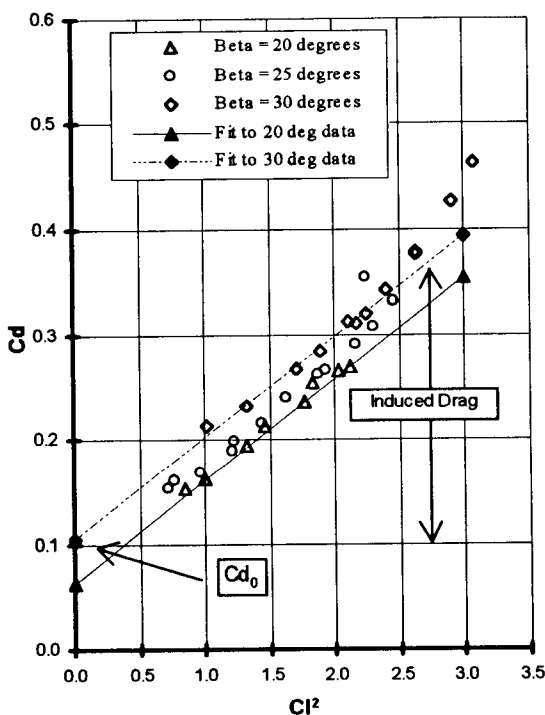


Fig. 17 Drag against Lift² from wind tunnel tests.

This presentation shows that the description of the induced drag as a function of the effective rig height (equation 15) which determines the slope of the C_d vs. C_l^2 line is indeed an accurate description of the wind tunnel results, and a good estimate of drag at any C_l can be made if H_E and C_{d0} are known.

The IMS model constrains sails to flatten along a straight C_d vs. C_l^2 line, but figure 17 shows that the

highest lift coefficients are associated with some increased separation drag, not included in the current sail model. This is to some extent compensated for by the IMS using an effective rig height which is 5-10 % less than that determined from the wind tunnel tests. A more detailed discussion of these results is given in Campbell's 1997 CSYS paper.

Centre of Effort Height.

Another factor associated with easing the sails to reduce heeling force is the vertical position of the centre of effort.

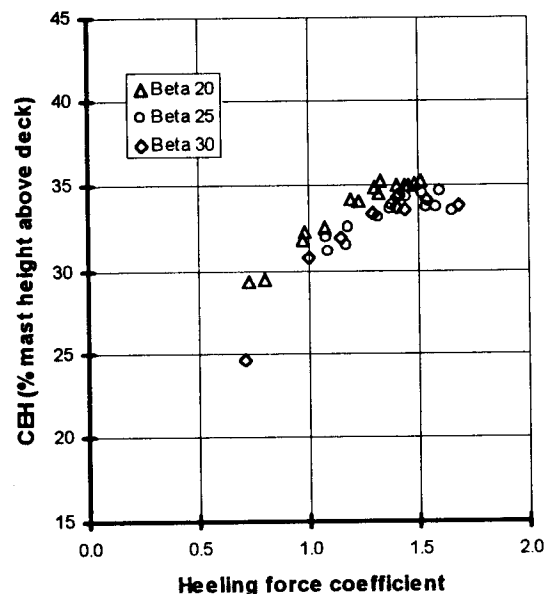


Fig.18 Centre of Effort height vs. Heeling force from wind tunnel tests on a Fractional Rig.

In the IMS VPP the centre of effort position remains at the same vertical height until the sails begin to reef, whereas figure 18 shows that as heeling force is reduced by flattening and twisting the sails the Centre of effort height (CE_H) moves lower. This “twist” effect, whereby a lowering of CE_H is linked to the FLAT term was proposed for inclusion in the 1999 VPP to address a perceived over valuation of righting moment.

Results for different sail types.

The IMS VPP now contains force coefficients for several variations on the 3 basic sail types. Figure 19 shows the force coefficients for the standard mainsail and the “simple” main sail for yachts without checkstays. The coefficients for the mainsail without checkstays, that control mast bend, are characterised by reduced lift coefficients and increased drag coefficients.

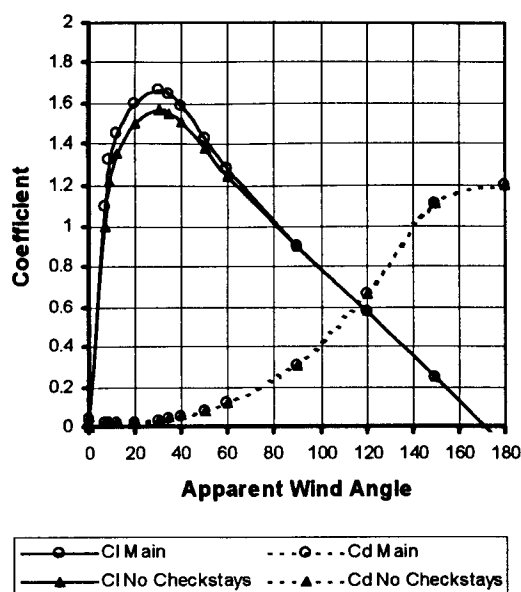


Fig. 19 Mainsail lift and drag coefficients in the IMS VPP

The restrictions on mainsail girths have also been removed and the area calculation is now based on the physical cloth area. The calculation of centre of effort height, and a modification to the effective rig height reflect the perceived physical effects of varying mainsail roach profile.

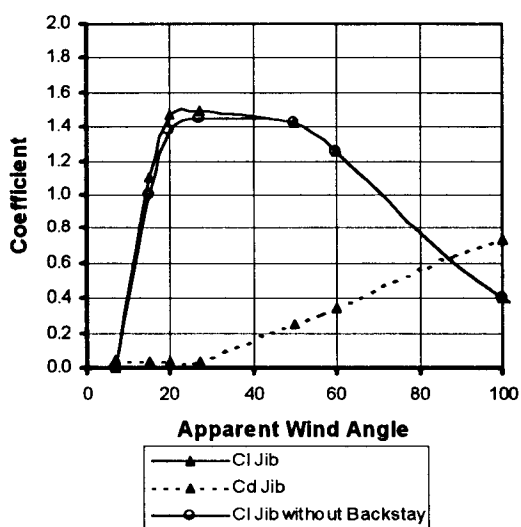


Fig. 20 Jib lift and drag coefficients in the IMS VPP

Figure 20 shows the force coefficients for the standard genoa and the "simple" genoa, for yachts without a means of adjusting head stay tension. The reduced lift coefficient for the genoa without an adjustable backstay to adjust headstay tension reflects

the fact that the headstay cannot be loosened to increase sail camber in light winds.

Figure 21 shows the force coefficients for the symmetric and asymmetric spinnakers set on a conventional spinnaker pole and for the asymmetric spinnaker set on a centerline strut. At close apparent wind angles, up to about 80 degrees the asymmetric sail set on a pole and set on a centreline sprit are the same, and are characterised by lower C_d 's and higher C_l 's than the standard spinnaker. The extent of their performance superiority in this wind angle regime is somewhat more than is discernable from the wind tunnel tests, but bundled into the coefficients is the fact that the asymmetric sails generally have centers of effort that are further forward than the symmetrical sails.

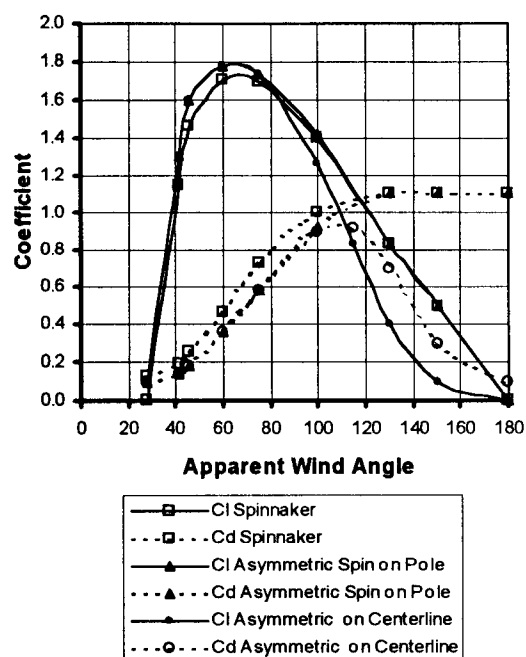


Fig. 21 Spinnaker lift and drag coefficients in the IMS VPP

On off wind courses, at apparent wind angles greater than 90 degrees the coefficients for the symmetric and asymmetric sails merge together, whilst the drag coefficient for the sail set on a centreline sprit reduces sharply to reflect the fact that the spinnaker pole cannot be squared aft.

The handicapping of spinnaker pole length is somewhat more difficult and at present the IMS treats long poles by adding a fraction of the excess of the spinnaker pole length over spinnaker width divided by 1.8 to the rated spinnaker width. Asymmetric sails are further handicapped because the luff length used in calculating sail area is 60% of the luff plus 40% of the leech length.

Figure 22 shows the IMS VPP derived lift and drag coefficients, excluding windage effects, for the mainsail and genoa with rig dimensions that mirror those used in the US Sailing wind tunnel program.

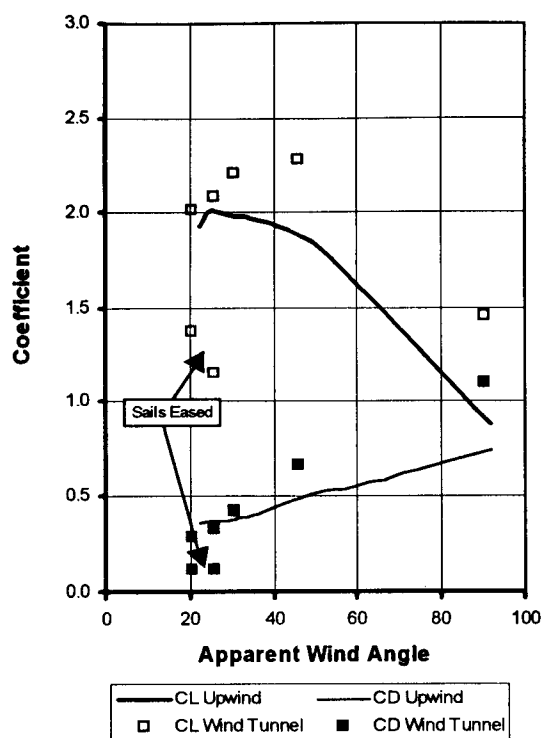


Fig. 22 Sail force coefficient for upwind rig, excluding hull windage

Also shown on figure are some of the typical individual test points derived from the wind tunnel tests. Both maximum driving force and some eased settings are shown. The wind tunnel test points only appear at the apparent wind angles which were tested, whilst of course the IMS VPP furnishes a complete curve. In general the behavior of complete rig coefficients agree well with the wind tunnel test results

Figure 23 shows the IMS VPP derived lift and drag coefficients, excluding windage effects, for the mainsail and spinnaker and the mainsail and asymmetric spinnaker set on a centreline sprit. Once again the corresponding points from the wind tunnel tests are shown.

In general the behavior of the complete rig coefficients agree well with the wind tunnel test results in terms of behavior at different apparent wind angles. For the off wind sails the IMS VPP appears to understate, by 15-20%, the force available. This should be viewed in the context of the fact that the wind tunnel results were obtained in the absence of an atmospheric boundary layer, and the fact that the current coefficients do a satisfactory job for the IMS as

a handicap rule. In real life there are many occasions when the theoretical maximum sail forces cannot be employed due to the fact that the yacht cannot be controlled. Another feature not well modeled in the VPP is the degree to which the off wind sails continue to produce significant amounts of lift at wide apparent wind angles, which will inevitably lead to an underestimation of the drag coefficient.

The aerodynamic modifications to give assistance to simple rigs are not rooted in any detailed scientific analysis. However, as in other areas of the rule, they offer a plausible and appropriately sensitive force model, which gives some benefit to the simply rigged cruising yacht and allows modern racing yachts with non overlapping jibs and no runners to compete in the racing fleets. The next item on the development agenda is to look at the force coefficients at close apparent wind angles, to bring the VPP predictions of the angles at which spinnakers can be set more in line with observed performance. A rational treatment of this is however hampered by the lack of a yaw moment balance in the VPP. The VPP therefore ignores the difficulty of steering a yacht which is hard pressed under spinnaker and the advantages in terms of a more forward centre of effort accruing of an asymmetric spinnaker.

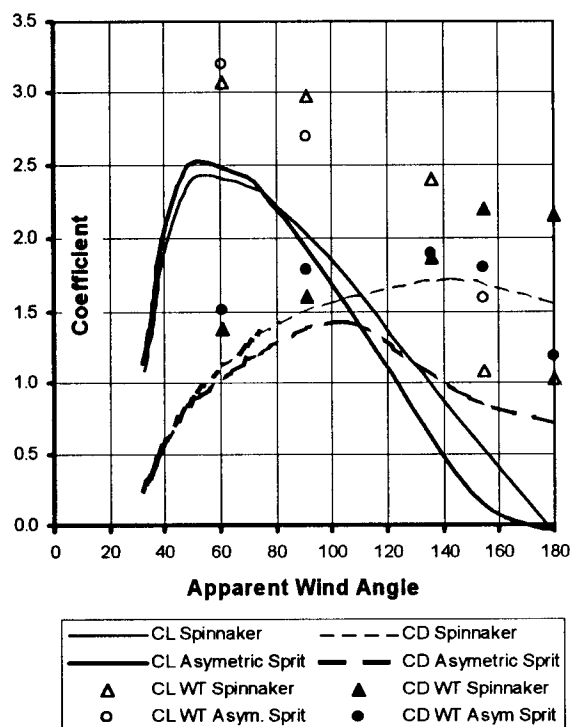


Fig. 23 Sail force coefficients for downwind rig, excluding hull windage

In the interests of further broadening the types of yacht able to race under IMS there is now no linkage

between foretriangle dimensions and maximum allowable spinnaker dimensions. Consequently over length spinnaker poles and mast head spinnakers on fractional rigged yachts are more equitably handicapped.

Windage

For the 1998 rule a wholesale revision of the aerodynamic windage drag force model was undertaken. This was precipitated by an increasing trend towards large mast dimensions which were exploiting a loophole in the rather crude expression for windage inherited from the original MHS VPP.

WINDAGE ELEMENT	Apparent. Wind Angle 0°		
	Z _{CE}	C _D	A _{REF}
	1997 Formulation		
HULL	0.4EHM+HBI	1.13	FBAV*B
MAST	0.4EHM+HBI	1.13	EHM*EDMC
WINDAGE ELEMENT	1998 Formulation		
	Z _{CE}	C _D	A _{REF}
	1997 Formulation		
HULL	0.66(FBAV +Bsinφ)	0.68	FBAV*B
MAST-Sail	HBI+EHM*reef/2	0.4 ^a	Front Area
MAST-Bare	HBI+EHM*(1-reef/2)	0.8 ^a	Front Area
RIGGING	HBI+I/2	1.0 ^b	I*/f(Default. Rigging wt.)
CREW	HBI+0.5+B/2sinφ	0.9	0.25
WINDAGE ELEMENT	Apparent. Wind Angle 90°		
	Z _{CE}	C _D	A _{REF}
	1997 Formulation		
HULL	0.4EHM+HBI	1.13	FBAV*B
MAST	0.4EHM+HBI	1.13	EHM*EDMC
WINDAGE ELEMENT	1998 Formulation		
	Z _{CE}	C _D	A _{REF}
	1997 Formulation		
HULL	0.66(FBAV +Bsinφ)	0.68	f(FBAV*L,φ)
MAST-Sail	HBI+EHM*reef/2	0.6 ^a	Side Area
MAST-Bare	HBI+EHM*(1-reef/2)	0.8 ^a	Side Area
RIGGING	HBI+I/2	1.0 ^b	I*/f(Default. Rigging wt.)
CREW	HBI+0.5+B/2sinφ	0.9	0.5* Mvblcrew
<i>a modified by EDM factor for non standard mast section aspect ratio.</i>			
<i>b plus spreader factor = 0.2</i>			

Table 5. Comparison of MHS and current windage force model.

The windage drag is incorporated into the force balance by adding to the aerodynamic drag a windage drag determined from equation 17. Each windage element is ascribed its own dynamic head (q_n) based on an apparent wind velocity appropriate to its centre of effort height (Z_{CE}), reference area (A) and drag coefficient (C_d).

$$D_{WINDAGE} = \sum q_n \cdot A_n \cdot C_{d_n} \quad [17]$$

The extent of the changes is summarised in table 5 which shows the original MHS formulation and that used in the 1998 IMS VPP. The original IMS VPP used the dynamic head at the sailplan Centre of effort for all calculations of q, whilst the new formulation adopts a dynamic head appropriate to the vertical height of each windage element. Once again the revised model is not striving for perfection, it attempts to be plausible and appropriately sensitive to features that affect windage drag. As well as curtailing a drive to artificially large mast sections the adoption of a higher windage drag for the bare mast delayed the onset of reefing to a higher wind speed, more accurately reflecting real life behavior.

Conclusions

The modifications to the IMS VPP described in this paper have by and large been aimed at improving the mathematical modeling of complex physical phenomena. However its is clear that many of the implementations of these "improvements" have been made with the aim of preventing exploitation as well as improving the provision of time allowances. This is exactly as it should be. The IMS is a handicap system first, a VPP second. Many of its formulations are to a greater or lesser extent type forming, and bundled into the performance prediction are elements which purists would regard as subjective. Nevertheless the IMS VPP does a good job of providing handicaps for the widest possible range of yachts. What the IMS VPP most certainly is not is an analytical tool, its modus operandi and its purpose mitigate against that. Therefore, whilst the paper has been aimed at exploring some of the factors that affect yacht performance I would urge readers interested in the pure science of performance prediction for sailing yachts to consult the many references by the following authors; Kerwin, Milgram, van Oossanen, Larsson, Oliver, Schwenn, Keuning.

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