VPP VS PPP:
CHALLENGES IN THE TIME-DOMAIN PREDICTION
OF SAILING YACHT PERFORMANCE

Sandy Day [1], sandy.day@na-me.ac.uk
Luca Letizia [2], l.letizia@safety-at-sea.co.uk
Allan Stuart[3], a.stuart@ safety-at-sea.co.uk

Abstract. In this paper we describe some preliminary work in the development of a tool for time-domain simulation of yacht performance in waves. This tool (termed Performance Prediction Program, or PPP) was created to properly consider all aspects of yacht dynamics at design stage, rather than restricting design optimisation to the maximisation of boat speed in idealised conditions. This PPP has been developed in parallel with a six-degree of-freedom Velocity Prediction Program (VPP) in order to perform comparative studies.

The approach used to predict yacht motion in the time-domain is described in this paper, along with the challenges posed by the incorporation of conventional aero- and hydrodynamics models commonly associated with VPPs in a new and unconventional design tool. Some of the solutions adopted to meet these challenges are outlined, whilst the difficulties peculiar to this type of analysis and not normally faced in the development of conventional VPPs are highlighted.

Some of the results obtained using the developed PPP are briefly presented and compared with those of the complementary six-degree-of-freedom VPP and other obtained using a commercial VPP. Some details of a more comprehensive validation exercise are also included. Finally, some considerations on the practical use of PPPs in racing yacht design conclude the paper.

1. INTRODUCTION

Since their introduction over twenty years ago, velocity prediction programs, or VPPs have been developed to a point at which they can provide designers with a mature and reasonably reliable tool for predicting sailing yacht speed in steady-state conditions.

Researchers continue to fine-tune the simplified models, both physical and statistical, typically utilised within VPPs to predict aero- and hydrodynamic performance; simultaneously, software designers strive to improve the user interfaces to maximise the opportunities for their successful application in design. However, the fundamental goal of VPPs has remained relatively stable: to predict the steady-state velocity and attitude of the yacht in a desired set of environment conditions.

Even now, many VPPs balance only three degrees of freedom of the yacht: the (space-fixed) longitudinal and transverse forces and the heeling/righting moment. Whilst Archimedes can be assumed to take care of the space-fixed vertical forces, the neglect of the effect of yawing and trimming moments can lead to unrealistic predictions of speed, and in the worst cases, the design of yachts which cannot be sailed to their full speed potential due to control difficulties even in flat water.

Whilst the more sophisticated VPPs currently available include yaw and trimming moment balance in addition to heeling moment and horizontal-plane force balance – and

thus calculate the equilibrium of the yacht in six rather than three degrees of freedom – they still offer little help for designers in predicting the actual performance of yachts in a realistic seaway, and, in particular, the effects of sea-keeping and course-keeping ability on speed.

Whilst these effects are important to a greater or lesser extent for all designs, they are of paramount importance for designs intended to be capable of being sailed at high speeds for extended periods under autopilot, such as Open 50s and 60s. The ideas behind the current study were initially developed during a design project undertaken in 1999 by one of the authors aiming to optimise the course keeping capabilities of Ellen MacArthur's Open 60 *Kingfisher*, designed to race the 2000 Vendee Globe, (in which she finished second to Michel Desjoyeaux).

The intention of the current study is to develop a six-degree of freedom time-domain simulation tool which can be used for examining the performance of yachts (and autopilots) in a realistic wave environment, including the effects of vessel motions on the controllability of the vessel: hence stepping forward from Velocity Prediction Programs (VPPs) to Performance Prediction Programs (PPP).

The research is still at a relatively early stage, and the program developed thus far is still affected by a number of problems that are currently under the investigation. Much of the effort has been expended thus far on

addressing these problems, rather than concentrating on improving the accuracy of the predictions of this PPP. A number of challenging issues have already been identified and some interesting results have been found. Some of these ideas, issues and results are described in the current paper.

2. BACKGROUND

The development of a "complete" fully non-linear time domain solution for the motions and aero-hydrodynamic forces of a yacht under the action of wind and waves would be an enormous undertaking requiring vast computing resource. Consequently, a substantial degree of simplification of the problem is required in order to allow solution of the problem within a reasonable time and with moderate resources. It is also clearly desirable to adopt a modular approach into which improved methods for particular calculations may be easily incorporated.

For the initial phases of the study described here the problem was broken down into four models as follows:

- Generalised non-linear ship motion model
- Quasi-Steady aerodynamic model
- Quasi-Steady hydrodynamic (lifting surfaces and hull resistance) model
- Autopilot model

The ship motion model is based on a hybrid approach employing the evaluation of Froude-Krylov and hydrostatic pressures up to the instantaneous incident wave elevation, coupled with linearised potential flow theory for radiation and diffraction. This model is described in more detail in section 3. The quasi-steady forces are calculated using "standard" VPP-type approaches, described in section 4.

In order to maintain the modular nature of the approach, it was decided that these component models would be implemented as separate stand-alone software executables, running simultaneously on a PC or workstation through a data exchange protocol.
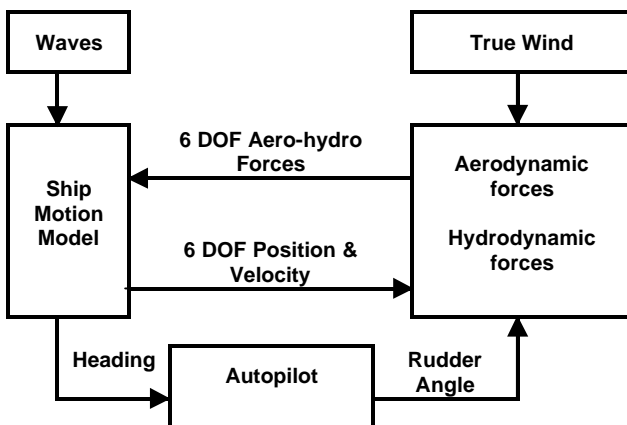
This approach, whilst superficially rather cumbersome, has a number of advantages; existing software may be easily utilised, module substitution can be carried out extremely easily when improved versions become available, whilst software modules incorporating commercially confidential algorithms (such as autopilots) may be easily incorporated if required. The system is illustrated schematically in Figure 1.

3. GENERALISED SHIP MOTION MODEL

3.1 Background

The ship motion model used in the current study (PROTEUS 3.1) was originally developed by Letizia, Jasionowski and Vassalos [1,2] to assess the survivability of damaged ships. PROTEUS 3.1 has been extensively validated during a series of large scale projects funded by the British government and the European Union, and is currently used for commercial work by Safety At Sea Ltd.

In the approach adopted in PROTEUS 3.1, the equations used to describe the ship motion behaviour are derived from the conservation of linear and angular momentum, resolved in a body-fixed system of reference located at the centre of gravity of the vessel, as illustrated in Figure 2. This leads to a set of 6 scalar equations describing the rectilinear and angular motions. The equations for angular motions are presented here in vector form in equation (1):

$$I_s \cdot \frac{d}{dt}\vec{w} + \vec{w} \times [I_s \cdot \vec{w}] = \vec{M}_s \qquad (1)$$

The right hand side of the equation, $\vec{M}_s$ (and the corresponding force vector in the set of equations for rectilinear motions), represents the sum of the external forces and moments acting on the vessel. These are expressed in a body-fixed system of reference located at the ship centre of mass. In contrast, the true wind velocity and the wave environment are defined in terms of an earth-fixed co-ordinate system, so that the true
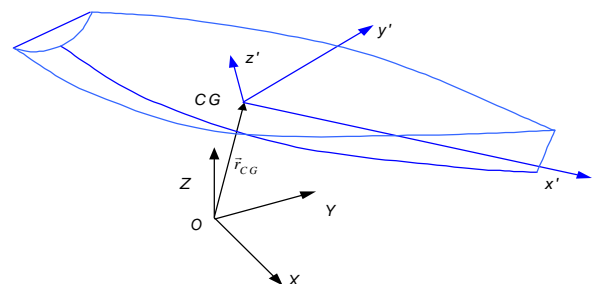

Figure 1. Schematic of software system

Figure 2. Earth-fixed and body-fixed co-ordinate systems

wind and the principal wave direction as well as the desired heading of the yacht can be set at any value.

The forces and moments are decomposed here into two categories; the quasi-steady aero-hydrodynamic forces and moments described in section 4, and the unsteady forces and moments associated with the vessel motions. This second group of forces include Froude-Krylov, radiation, diffraction and hydrostatic pressure forces and moments. The Froude-Krylov and hydrostatic pressure are integrated over the instantaneous wetted area; the radiation and diffraction forces and moments are derived from linear potential flow theory and expressed in the time domain based on convolution and spectral techniques.

In order to reduce computation overheads, hull asymmetries such as that due to the quasi-steady heel under sail are taken into account by adopting a "database" approach, in which the hydrodynamic coefficients are predicted beforehand over an appropriate range of speed and attitude, and then interpolated during the simulation. Viscous effects on roll and yaw of large ships are estimated on the basis of well-established empirical methods whilst the second order drift and current effects are catered for, for these vessels, based on a parametric formulation.

The system of equations is re-arranged into matrix form as a set of twelve first order differential equations. These are solved using a 4th order Runge-Kutta-Feldberg integration scheme, with variable step size, to find the time history of the earth-fixed position in space of the centre of gravity of the yacht as well as the instantaneous heel, trim and yaw angles.

3.2 Challenges in motion prediction of yachts

In relation to non-linear motion damping, it must be noted that the viscous damping methods mentioned above are not applicable to small vessels such as yachts and therefore default to zero in the simulation. There are particular challenges related to the estimation of angular motion damping for small vessels.

A substantial proportion of roll damping for a sailing yacht comes from aerodynamic damping developed by the sails and is therefore included (in some sense) in the aerodynamic model described below. It is interesting to note that the current formulation actually allows us to predict roll fairly accurately without need for additional assumptions or refinements in the model.

Unfortunately, this is not true for pitch. For a small vessel in moderate to heavy seas, most of the damping for this mode of motion is introduced by slamming. This effect has not been appropriately modelled in the present version of the PPP, and consequently the program tends to over-predict pitch motion in such environmental conditions. Whilst a generalised treatment for this

problem will require an in-depth study, a simple model based on the estimation of the instantaneous variation of the vessel added mass during a slam is currently under development and will be introduced soon in the hydrodynamic module of the present PPP.

The prediction of yaw damping is closely related to the prediction of the hydrodynamic yaw moment, and is discussed in section 4.4 below.

4. QUASI-STEADY HYDRODYNAMIC FORCES

4.1 Background

The quasi-steady hydrodynamic forces required relate to the horizontal plane forces acting on the hull of the yacht (i.e. resistance and side force) and the hydrodynamic yawing moment generated by the hull for a given rudder angle. Heeling and trimming restoring moments and buoyancy forces are taken care in the conventional manner in the ship motion model.

4.2 Horizontal plane forces

The horizontal plane forces are calculated using a "standard" VPP-like approach, based on the Delft series regression equations as described in Gerritsma *et.al.* [3] These equations allow the prediction of the resistance of the vessel as a function of the forward speed, the heel angle, and the side force acting on the vessel, and the prediction of the side force as a function of heel and leeway. This formulation is ideal for a VPP in which it is assumed that the aerodynamic and hydrodynamic forces are in equilibrium and the input to the hydrodynamic part of the calculation is based on the aerodynamic forces resolved in an appropriate co-ordinate system.

In the current problem a number of issues must be resolved before these equations may be used. Firstly, the assumption must be made that these equations, derived on the basis of steady speed tests may be used in conjunction with instantaneous speed, heel angle etc. to derive the instantaneous forces – thus the assumption must be made that the forces are "quasi-steady". This is clearly open to some debate; however, no reasonable alternative is available at present.

Secondly, the form of the equations requires some re-arrangement in the current context; here we clearly cannot assume that the vessel is in equilibrium, and we wish to find the hydrodynamic forces based on the knowledge of the instantaneous attitude and velocity. Thus the leeway angle must be found from the velocity vector, and the hydrodynamic side force from the leeway angle.

It should be noted that the version of the Delft series employed in this context is not the latest; at the time of writing the software was being updated to take advantage of the more recent version given in Keuning and

Sonnenberg [4]. This leads to some further difficulties, as these equations do not include an explicit relationship between leeway angle and side force.

Finally, there is a need for great care with co-ordinate systems. As described in section 3, the ship motion module calculates ship motion in a earth-fixed system of reference and the velocity of the yacht in a body-fixed co-ordinate system; however the data for the prediction of the quasi-steady hydrodynamic forces is required in what might be regarded as a hybrid body/earth-fixed system which remains oriented with two axes in the earth-fixed horizontal plane, but rotates around the vertical axis as the yacht's heading changes. Calculation of the transformations required between the three co-ordinate systems is simple; what is perhaps rather less obvious is how precisely the fully six-degree of freedom data obtained from the motion model should best be interpreted as input to the regression equations.

In particular, it was not particularly obvious to the authors how the body-fixed rectilinear and angular velocity should best be used to calculate the "speed" and "leeway" used in the Delft equations. In fact it was not absolutely clear to us from [3], even in the steady motion case, whether the Delft speed should be interpreted as the component of velocity along a projection of the boat centreline onto the still water surface (i.e. that which might be measured by a yacht's log in otherwise still water), or whether it should be taken as the component of velocity in the direction of motion of the CG (i.e. the carriage velocity in the case of tank tests).

The decision was taken (somewhat arbitrarily) to interpret the body-fixed forward speed as equal to the Delft speed, whilst the leeway angle was calculated based on the horizontal components of velocity in an earth-fixed system with its x-axis aligned on the projection of the yacht centreline onto the still water surface. Further testing of the sensitivity of the results to these assumptions is planned for the near future.

Of course, for the small trim and leeway angles typically obtained from VPP calculations in still water, the differences found between different possible interpretations will be small; however, it should be remembered that in waves, the instantaneous trim and leeway angles may not be all that small.

4.3 Yaw moment

A rather greater difficulty is found in calculating the yawing moment, and in particular the influence of the rudder angle on the yawing moment since the equations given in [3] do not include any means of predicting this, or indeed any data which might be used for this purpose.

In order to address this difficulty, a heuristic method originally suggested for the calculation of side force and heeled resistance in the first Delft Series study [5] was

adapted. In the original approach the hull/keel/rudder was assumed to behave like an isolated lifting surface, which consisted of the actual keel of the yacht extended to the still water level. The lift slope of this lifting surface is assumed to behave according to the equation:

$$\frac{\partial C_L}{\partial a} = \frac{5.7 AR_E}{1.8 + \cos\Lambda\sqrt{\dfrac{AR_E^2}{\cos^4\Lambda} + 4}} \qquad (2)$$

where AR_E is the effective aspect ratio of the keel, and Λ is the sweep angle, whilst the induced resistance is assumed to behave as:

$$C_{Di} = \frac{C_L^2}{p\,AR_E} \qquad (3)$$

In the original paper the effective aspect ratio was expressed as a fraction of the geometric aspect ratios of the extended keel (assuming a rigid free surface), i.e.

$$AR_E = e.2AR_G \qquad (4)$$

The values of e were then tabulated for each of the 22 hulls tested, once for side force prediction, and once for induced resistance prediction. Clearly, the fact that the effective aspect ratios need to be tabulated separately in order to predict closely related phenomena is an indication that the method is far from perfect; however it does provide a starting point for a prediction of the yaw moment as a function of rudder angle.

In order to use the data for the current study, it is assumed that the keel and rudder can be treated as isolated lifting surfaces in this manner. The side force and heeled resistance were calculated (using the equations and coefficients presented) for each yacht of the series presented in [5] over a range of heel angles. The "extended keel" approach was then applied to both the keel and rudder and the assumption made that the efficiency e was the same for the two lifting surfaces. It was further assumed (as recommended in [5]) for the purposes of the data analysis of the yachts studied that the rudder inflow speed was 90% of the inflow speed at the keel, and that the angle of attack at the rudder was 40% of the angle at the keel. For each boat, at each heel angle, the appropriate value of e was then calculated separately for the side force and the heeled resistance.

Finally the values of e obtained for each heel angle were regressed against $\nabla_c^{2/3}/S_c$. This provides a method which can be used to calculate side force, heeled resistance and yaw moment for any rudder angle using the equations (2) and (3) above; alternatively the method may be used only for the calculation of yaw moments, with the side force and heeled resistance obtained from other approaches such as those presented in [3] or [4].

Data for the position of the Centre of Lateral Resistance (CLR) of the yacht with rudder central is presented for two speeds in [5], so the yaw moment calculation using this heuristic approach can be checked. Unfortunately, the approach tends to predict the CLR of the yacht too far aft, so a further correction is required to the yaw moment. In this case, the simplified slender-body method of Nomoto [6] is used to estimate the yaw moment contribution from the fore body of the yacht. A similar "efficiency" was then calculated for the fore body for each yacht at each of the two speeds speed in order that the CLR was predicted correctly according to the experiment results, and a regression equation derived for this efficiency.

With this correction the yaw moment can be calculated using appropriate coefficients for inflow speed and angle in conjunction with the rudder angle to estimate the lifting force on the rudder.

This deals with the components of yawing moment related to side force; however it should not be forgotten that the resistance would lead to some yaw moment when the yacht is heeled. No data has been found to throw any light on this so the resistance force was assumed to act at the CB.

4.4 Further development and future challenges

Some significant further developments to the model described are being implemented at the time of writing. Some components of the Delft series regression model described in [4] are being implemented in order to improve resistance prediction; however, as noted earlier, it is not immediately obvious how the revised model can be used to predict hydrodynamic side force from the instantaneous leeway angle as required in this context. Clearly the current model adopted here is not ideal; and it would be desirable to devise an improved model that will allow the prediction of side force, induced resistance and yaw moment from the instantaneous leeway and rudder angles.

Results suggest that yaw damping is far too low in the current model. Whilst a heuristic model for viscous effects should be incorporated (and, in fact, a limited experimental investigation on this subject has been planned), a more important omission in the current model is related to the assumption that the angles of attack on the equivalent keel and rudder are related only to the leeway angle (and rudder angle) and hence based only on the horizontal components of the earth-fixed velocities. It is felt that the neglect of the influence of the yaw velocity leads to unrealistic values particularly for the yaw moment generated by the rudder.

Some problems have been found in the start-up phase of the simulation when the yacht starts from rest. In these conditions in reality the lifting surfaces are likely to be operating at large angles of attack, and therefore to be at least partially stalled; however the regression models relating leeway angle, side force and induced resistance are only intended to represent fully attached flows. In these conditions it will be necessary to resolve very carefully between lift/drag and side force/resistance co-ordinate systems; this issue is closely related to those discussed in section 4.1.

5. QUASI-STEADY AERODYNAMIC FORCES

5.1 Background

As with the quasi-steady hydrodynamic forces, a first approximation to some of the corresponding aerodynamic forces can be calculated using methods adapted from VPPs.

In particular the aerodynamic drive, side force and heeling moment can be obtained reasonably straightforwardly, once the appropriate wind speed and direction have been obtained. In the current model, the original IMS method described in Poor [7] is adopted; however the more recent version, as described in Claughton [8] is being implemented at the time of writing. These models allow the prediction of the drive, side force and heeling moment based on the apparent wind velocity at the (body-fixed) height of the centre of effort (CE).

5.2 3D Centre of Effort Prediction

In the current application there is a need for a more complete description of the aerodynamics; firstly because the yaw and trim moments are also required, and secondly because the component of the apparent wind velocity related to the rotational velocity of the yacht is sensitive to the 3D position of the CE, as opposed simply to the height of the CE.

The corollary to both of these requirements is that a 3D (body-fixed) position of the CE is required for all the rig combinations. In the current study, this has been obtained by assuming that the chord-wise position of the CE of each sail is in line with the geometric centroid of the sail plan-form. This is used in conjunction with specified values of 'CE sheeting angles' (and in the case of spinnakers, with pole angles) varying with apparent wind direction, which form part of the input to the program.

With this data known, the true wind velocity and the rectilinear and rotational components of the yacht velocity can be calculated at the CE in a body-fixed system and used to predict the aerodynamic forces and moments.

5.3 Further development and future challenges

There are a number of problems with the rather heuristic approach described above. The methods used for predicting the aerodynamic forces and moments based on apparent wind angle assume that the sails are optimally trimmed for that angle (as well as flattened / reefed /

twisted where desirable). In the current application the apparent wind angle will vary over one roll cycle, but of course in practice, the sail trim will not. Furthermore, the variation in the apparent wind angle will be much greater at the head of the sail than the foot.

A more satisfactory solution would be to calculate a "moving average" apparent wind angle over a number of wave cycles and to then estimate the effect of the instantaneous over- or under-sheeting of the sails on the aerodynamic forces and moments. Additionally, better estimates of the CE position and the resulting aerodynamic moments are required; it is possible that some progress may be made in this area through the use of first-principles calculations such as those of [9].

A related issue is the inclusion or omission of the "reef" and "flat" type variables commonly adopted in VPPs. At present no attempt has been made to incorporate these variables in the model; calculation of values based on maximising VMG (as typically carried out in VPPs) would be a far more challenging task in the context of a PPP, requiring the calculation of VMG averaged over a reasonable number of wave cycles as an objective function. This would take substantial computer resources in the context of optimisation. A relatively straightforward item not included in the current model is the hull/crew aerodynamic forces and moments. These are currently being implemented at the time of writing.

6. STEERING ALGORITHM

As described in section 3.1, PROTEUS 3.1 integrates the equations of motion according to the vector of forces and moments provided internally by the wave excitation routines and externally by the yacht aero- and hydrodynamic modules described in sections 4 and 5. The integration is performed for all degrees of freedom, thus allowing the explicit estimation of all of the yacht's motion.

The heave, pitch and roll motions are all bounded by the compounded action of gravity and buoyancy; however, this is not the case for any of the planar motions. In a complete 3D model such as PROTEUS 3.1 it is therefore essential to introduce a feedback mechanism that would bind yaw thus stabilising heading and controlling the vessel displacement in the horizontal plane.

In order to achieve the above, a simple linear PID autopilot was introduced, which varies the rudder angle according to yaw and yaw rate of change, in order to steer the boat to keep a given value of heading. The coefficients of proportionality necessary to obtain course-stability were tuned appropriately for the boat used in this development and, in this respect, it is to be noted that the autopilot described here was introduced only to obtain a stable solution rather than to ascertain the manoeuvring characteristics of this vessel or to optimise its steering. These important design capabilities are nevertheless retained by the developed PPP since

they are inherent in the modular structure of the code that allows us to substitute the relatively simple "default" autopilot just described, with any other commercial system capable of digital communication using standard protocols.

In this version of the software, it is possible to vary the desired heading during the course of the simulation. This feature was introduced in order to study the effect of course variations on the stability of the code and on the behaviour of the yacht as predicted by the PPP. This feature is important, for instance, when one wishes to verify the loss of speed during a tack and its overall duration. In relation to the observations made above on the inappropriateness of the current estimation of yaw damping for large angles of attack, the ability to change the desired heading during the course of a simulation occasionally gave rise to spectacular – and obviously non-physical – course instabilities.

7. SAMPLE RESULTS

In order to guide the development of the PPP a large number of simulations were run. In this section some of the results obtained will be presented, to illustrate both the problems encountered and the positively rewarding surprises that this PPP has proven itself capable of. Some of the results of full-scale trials performed during a racing event (Bangor Week 2001) are also presented, as they have been used to validate the code. The yacht employed in this series of results is a Sparkman & Stephens 34 called *Ailish*. Main dimensions, lines and sail plan are given below.

Table 1: Principal particulars

L_{BP}	7.360 m
L_{OA}	10.100 m
B	3.190 m
T_{max}	1.897 m
KG	1.951 m
D	5.261 tonnes
Sail Area (max upwind)	64.500 m^2

The tests described here are summarised in Table 2. All tests were run in upwind conditions for a variety of values of the main environmental parameters (true wind speed and significant wave height). The effect of the crew (quite significant for a keel boat of this size) was included only through an increase of displacement and a static shift of the centre of gravity.

Test 1: Figure 5 shows a screenshot of Parallax (PROTEUS 3.1 post-processing software). The left-hand-side window shows the trace in the horizontal plane of the large transient drift at the start of simulations. Note that the dot grid size in this window is one metre and that wave and wind directions are both in line with the earth-fixed x-axis (marked with a ^ sign in the boat track graph).
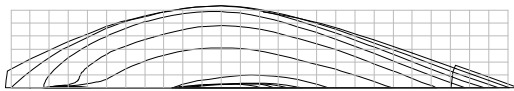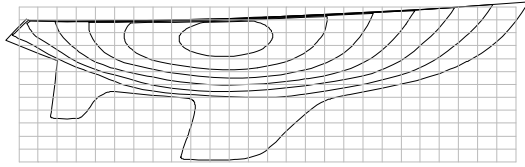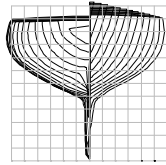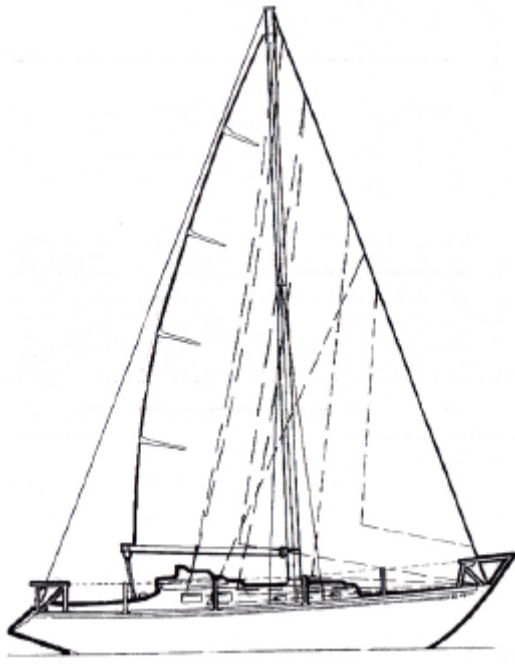
Figure 3. *Ailish* **lines plan**

Figure 4. *Ailish* **sail plan**

Table 2: Test matrix

Test Nᵒ	Hs	V$_{true}$	Comments
1	0.57m	10kts	Large drift at start
2	0.57m	10kts	Overshooting tack
3	0.50m	10kts	Heavy pitch in moderate sea
4	0.00m	10kts	Speed reduction during tack
5	0.57m	12kts	Condition 1 – small waves
6	0.00m	12kts	Condition 2 – calm water

About 35 seconds of simulations are shown in this figure. The other windows show the attitude of the boat and the time histories of roll/heel (top) and pitch/trim (bottom).
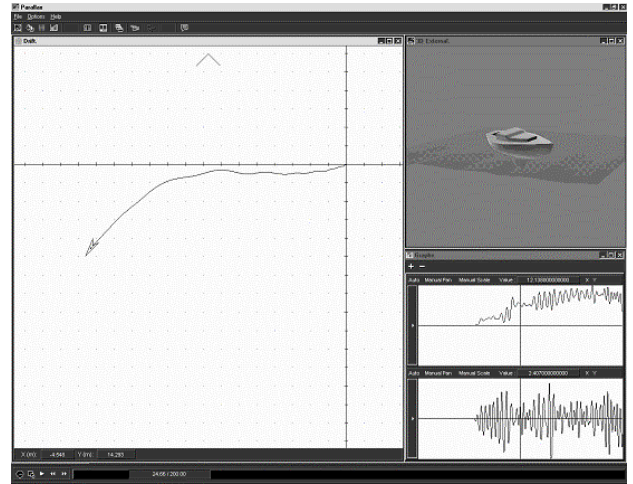
Figure 5. Large transient drift

The drift shown in Figure 5 is not only excessive (about 0.5 m/sec) but also unnatural, as its main component is almost perpendicular to the wind and wave direction. It is believed that this phenomenon is due to the inadequate modelling of hydrodynamic forces and moments at low forward speed when the angle of attack may be large, and when the lifting surfaces may be partly stalled, as described in section 4.4. It must be noted that although the initial transient is not terribly important in the context of long simulations at constant mean heading, the inadequacy of modelling of hydrodynamic forces (mainly viscous) at low speeds and/or large angles of attack will also affect the ability to predict manoeuvring performance.

Test 2: The best illustration of the importance of low-speed and/or large-angle-of-attack viscous forces and moments are in manoeuvring is showed in Figure 6.
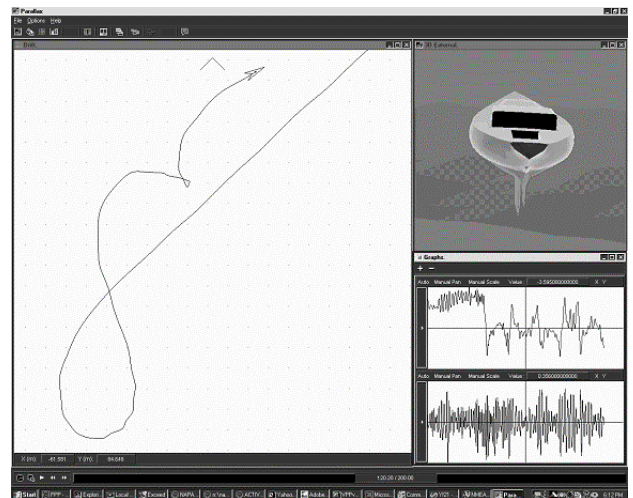

Figure 6. Overshoot after tack

Here Parallax displays the trace in the horizontal plane of the overshoot after a tack, followed by the ship going into a spiral and eventually off course. In this case the poor modelling of viscous forces at low speed couples with the inability of the linear autopilot to keep up with large ship motion.

Test 3: A different kind of problem associated with motion damping is illustrated in Figure 7. In this figure, traces of the pitch motion for the same significant wave height (Hs = 0.569 m) are shown both as predicted by the PPP (top) and as measured during the full-scale trials (bottom) for a head sea. Values of standard deviation for this motion are 1.921 degrees and 0.878 degrees, respectively.
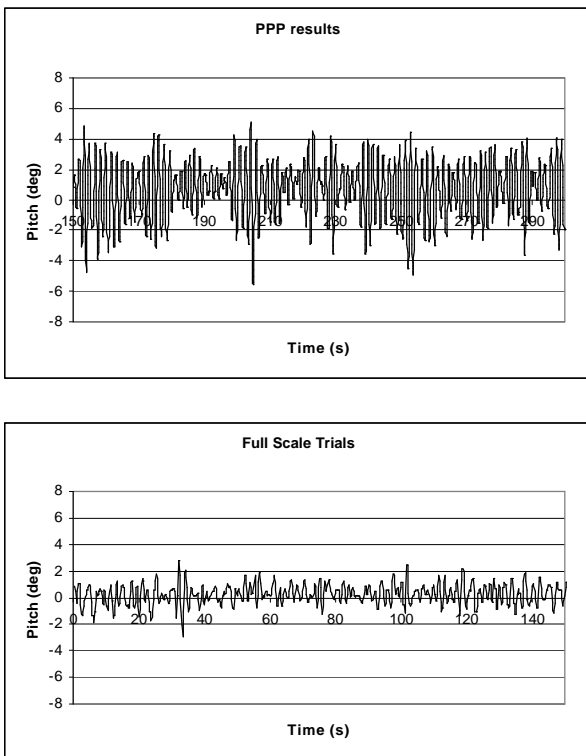
Figure 7. Measured versus calculated pitch motion

As discussed in section 3.2, pitch is over-estimated in moderate head seas (in terms of relative size compared to the boat dimensions) since in these conditions bow slamming, not modelled here, is a major source of non-linear damping.

Although the shortcomings deriving from the severely simplified models adopted for the aero- and hydro-dynamic yacht excitation are well evident from the above, it is important to underline the benefits deriving from PPP simulations. These are illustrated in the following.

Test 4: Figure 8 shows a comparison of speed reduction as estimated by the PPP with that measured during the Bangor Week, for the same conditions (calm sea, fast tack). Although the prediction is not perfect (the PPP

over-estimates the speed reduction peak by approximately 0.5 knots) the agreement is impressive, especially considering that the shape of this curve and the time to recover speed are predicted correctly. This type of result is important as it indicates that the possibility of a realistic simulation of the global performance of a boat during a typical race is well within reach.
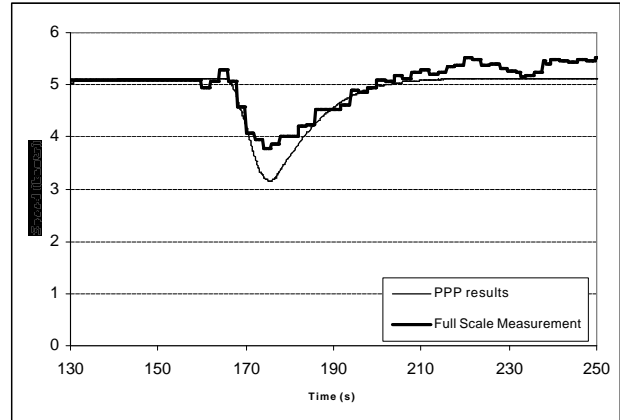

Figure 8. Speed reduction during tacking

Test 5: A comparison of boat speed as estimated by the PPP against that measured during the full-scale trials and using both the complementary VPP and a commercial code is given in Figure 12. The second polar plot from the top refers to Test 5 conditions and is sufficient to illustrate the capacity of the PPP to estimate boat speed at least as well as traditional VPPs can. Furthermore, a comparison of estimated versus measured roll motion for the same test shows that unlike pitch, roll is satisfactorily estimated by the PPP, with most of the damping provided directly by the simple aerodynamic model adopted in the current version of the program. In terms of standard deviation from a mean heel angle of approximately 20 degrees, the roll motion estimated by the PPP is 2.9 degrees, whilst the measured value is 3.5 degrees.
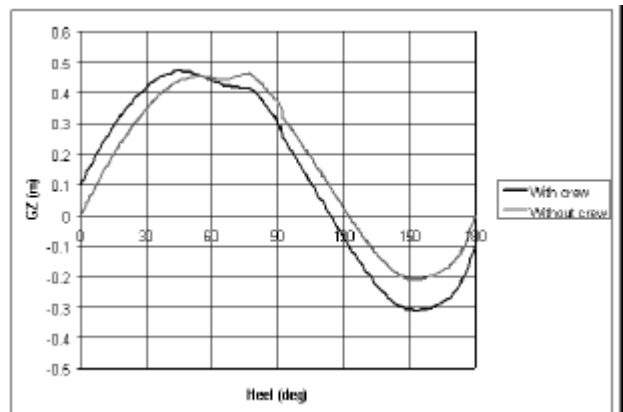

Figure 9. *Ailish* Righting lever curves

Test 6: Figure 10 shows boat speed as estimated by the PPP in calm water for the same wind speed and angle of attack of Test 5, compared with that estimated by the same program in waves and by the complementary VPP.

From this polar plot it is not only clear that the PPP is consistent with its steady-state counterpart (as it would be expected since the yacht aero- and hydrodynamic modules are the same for both codes, apart from the estimation of added resistance that is neglected in the complementary VPP) but also that the PPP is capable of predicting added resistance due to head waves without recurring to additional artificial assumptions.
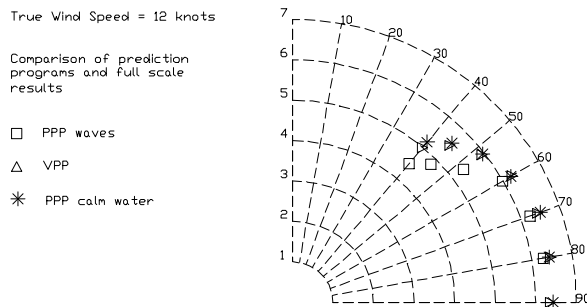

Figure 10. Comparison between calm water and waves

8. FULL-SCALE TRIALS RESULTS AND VALIDATION

Performance measurements of *Ailish* in a racing environment were carried out from 9th to 13th July 2001 during Bangor Week in Belfast Lough, Northern Ireland. A summary of the races is given in Table 3 with an indication of the average environmental conditions. The purpose of these measurements was to acquire data under realistic racing conditions for use in the validation and calibration stages of the development of the PPP.

Table 3: Summary of racing conditions (averages)

Day	Race	Wind (kn)	Hs (m)
Mon1	Triangular	11.768	1.019
Mon2	Windward/leeward	11.247	1.019
Tue	Belfast Lough Race	14.578	0.569
Wed1	Figure 4	19.839	0.929
Wed2	Windward/leeward	21.063	1.135
Thu1	Trapezoid	16.677	1.105
Thu2	Trapezoid	16.988	1.105
Fri	Windward/leeward	11.880	0.656

These measurements were carried out on a relatively low budget, using the yacht's own instrumentation (GPS, Log and wind instruments), an MRU (Motion Reference Unit), a laptop computer, a wave-rider buoy and in-house data acquisition software *NMEA Data Studio*. In the following, an account of the preliminary analysis of these results is given.

8.1 Polar Plots

In Figure 12, polar plots relative to Tuesday race are presented for wind speeds ranging from 10 to 16 knots. It must be noted that in this context only upwind

performance has been taken into consideration, although similar analysis is currently undergoing for downwind sailing. It must also be noted that there is good correlation between wind speed and wave height for this race, as shown in Figure 11. In addition, it was observed during the tests that wave and wind direction would normally roughly coincide; an occurrence that is to be expected for restricted waters such as Belfast Lough.
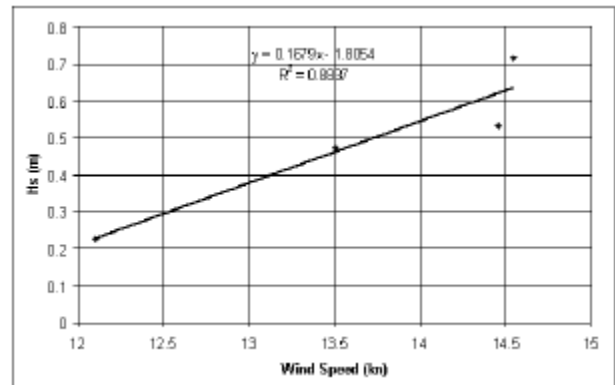

Figure 11. Wave/wind correlation for Tue race

In the polar plots presented, it is possible to detect two main trends. Firstly, the predictions of the PPP tend to underestimate boat speed for close beating and this discrepancy gets worse with increasing wind speed. Secondly, although the six degrees of freedom complementary VPP also under-predicts boat speed for close beating, the disagreement with experimental data seems to be much smaller, whilst the commercial VPP overestimate boat performance consistently. It is also worth noting that all codes provide similar results for close reach.

8.2 Motion Data

Ship motion in six degrees of freedom was recorded using an MRU. Of these only roll, pitch and heave have been analysed for the purposes of this paper. Figure 13 shows graphs of mean values (heel and trim) and standard deviations (heave, roll and pitch) of these signals as measured during racing and as predicted by the PPP. The data is plotted against wind speed and trend-lines are added for ease of interpretation.

The reason why motion data is plotted against wind speed is that this way a comparison between polar plots and yacht motion is straightforward. Furthermore, it must be noted that this choice is not only a natural one for the angle of heel, but it also makes sense for the other motions, given the strong correlation between significant wave height and wind speed observed from the experimental data. In this respect, it is worth mentioning the fact that despite this correlation, the PPP results shown were produced for a constant Hs = 0.569 m (corresponding to a wind speed of approximately 14 knots) and varying wind speeds.
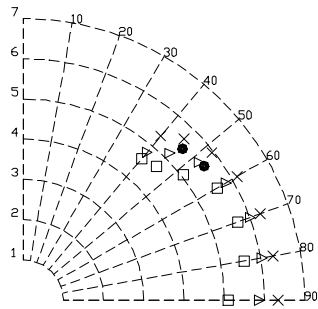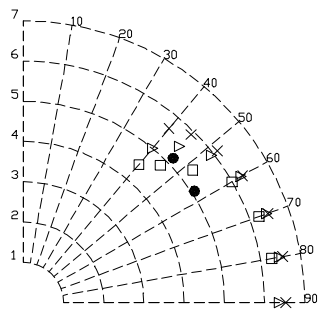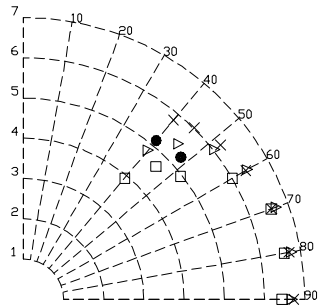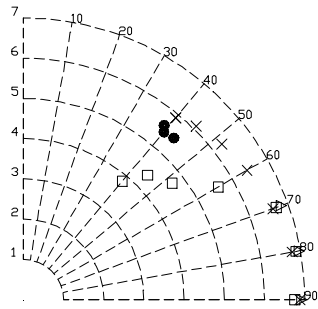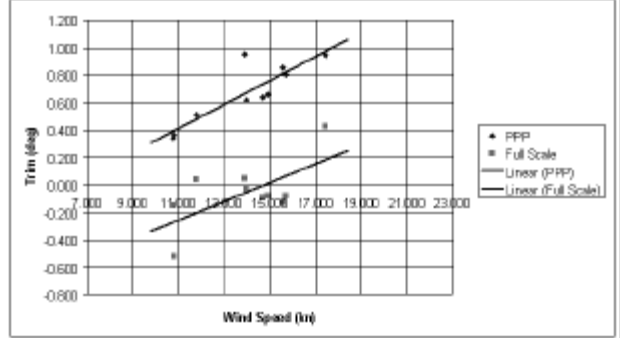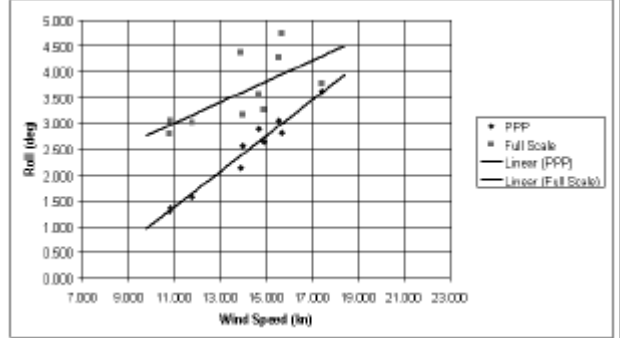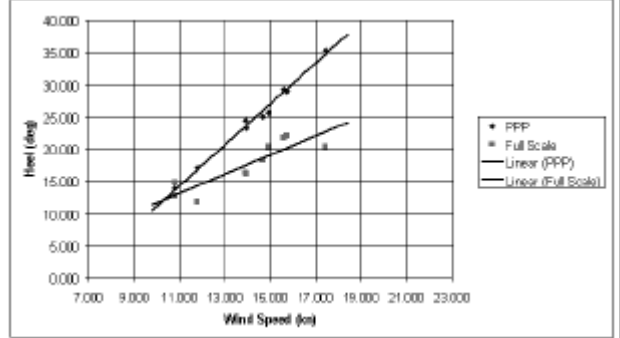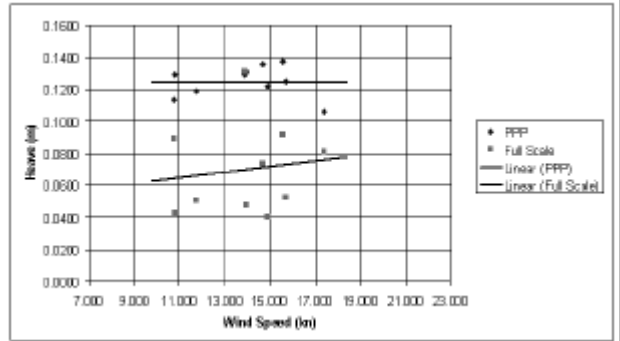
Figure 12. Polar plots for Tuesday race
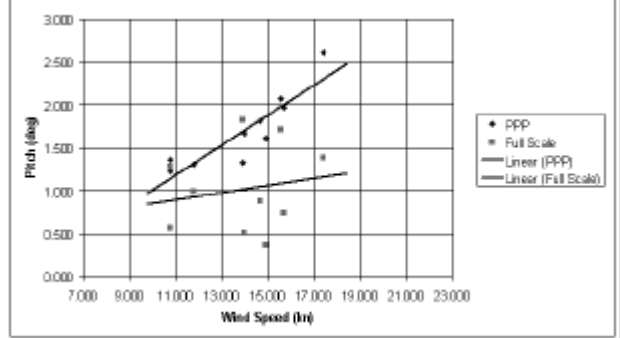
Figure 13. Motion data for Tuesday race

Observations worthy of note are as follows:

- Whilst measurements indicate an increase in heave motion with wind speed (wave height) the PPP does not show the same trend. This is in fact a sign of consistency from the part of the code given the constant Hs value just mentioned.
- The PPP slightly overestimate heave amplitudes.
- The PPP also over-predicts heel for higher wind speeds. This effect is a result of not including de-powering of the mainsail in the aerodynamic module and also affects the PPP and the complementary VPP speed predictions.
- Over-prediction of heel also influence roll motion, which increases as wind speed increases even for a constant Hs value. The reason for this can be found in the softening shape of *Ailish* GZ curve (Figure 9).
- Notwithstanding the abovementioned effect of large heel, roll amplitudes are predicted satisfactorily (indeed the PPP tends to under-predict roll motion for upwind sailing). Nevertheless, in other sailing conditions large roll angles were observed. It is possible that the introduction of improved modelling of hydrodynamic damping due to lift and viscosity effects might improve this prediction further.
- Trim by bow increases with wind speed as a result of heel and this trend is well predicted by the PPP, even if the actual average trim angle is not correct because the effect of crew on LCG was not included in the PPP simulations.
- Pitch motion is instead clearly over-predicted by the PPP. Although it is not completely clear why this is the case, it is thought that the absence of slamming damping and the effect of sail de-powering on encounter frequency might be to blame.

8.3 Discussion

The results shown above are only a small part of the data collected during the full-scale trials. Even from the preliminary analysis of this small sample, the usefulness of the information collected as a means to validate and calibrate the new PPP is undeniable.

From the polar plots it is clear that added resistance in waves is captured by the PPP. Nevertheless, this effect is a function of the pitch motion and the latter is not yet well captured by the PPP. As a result, the accuracy of the added resistance predicted is still not acceptable. In this respect, it must be noted that the underestimation of boat speed in the polar plots is not only due to predicting excessive added resistance in waves but rather by a combination of this and the inadequacy of the aerodynamic module in terms of sail de-powering. It is conceivable that an improvement in this module might lead to considerably better results as it shifts the prediction of the complementary VPP closer to those of its commercial counterpart and the PPP forecasts closer to the experimental data.

Sail de-powering also affects vessel motion to some extent, although it is also known to the authors that a number of other effects need to be improved in the current modelling of yacht aero- and hydrodynamic, for the PPP motion prediction to improve further. Nevertheless, it is important to note that this model is sufficiently realistic to capture aerodynamic roll damping in close upwind sailing.

Notwithstanding the above, it is believed by the authors that the experimental evidence presented is sufficient to illustrate the capacity of the developed PPP to predict purely dynamic effects such as added resistance in waves.

9. USE OF A PPP IN YACHT DESIGN

With further refinement, it is hoped that the system developed will be of benefit to yacht designers, racing teams and autopilot developers. Obviously, given the amount of detailed information required to run a PPP and, in turn, the level of detailed information that a tool of this kind can provide, the PPP concept is not intended to replace that of VPPs as a preliminary design tool. By the same token, although the level of accuracy and detail in the modelling required for a PPP will have to improve substantially for this tool to be realistically useful, it is believed by the authors that the unique capacity of PPPs to bring together and simultaneously evaluate the influence on the overall yacht performance of a vast number of design and operational parameters, will make of this type of numerical methods an invaluable analysis tool for detailed design optimisation.

The PPP requires a complete 3D model of the yacht geometry, which is not likely to be available at an early design stage; furthermore the calculation of a full set of speed polar plots in even a single wave environment is very substantially more demanding on computer resource than the equivalent calculation using a VPP (this is because the PPP is a simulation of performance in the time domain; to obtain a polar plot a series of runs must be performed and singularly analysed by statistical means). Although the possible use of PPPs in preliminary design cannot be discounted a priori (see for instance the capability of PPPs to assess the influence of aft body shape on the planing characteristics, course-keeping performance and resistance to capsize of a yacht) reasons such as those given above lead us to believe that a PPP is probably not the most appropriate tool for preliminary yacht design, when many competing configurations must be assessed and time is of the essence.

During the detailed design phase, though, it is necessary to optimise variables such as keel profile, bulb sections, rudder area, position of all appendages, rig size and configuration, ballasting arrangements etc. In doing this, it is important not only to ascertain what influence each of these parameters has on boat speed directly, but also – and often more importantly – how they influence other

aspects of yacht behaviour and, in doing so, its overall performance. An example of this can be easily given for ocean-going racing boats such as the Open 60. In fact, it is not difficult to imagine what disastrous consequences would have a keel/ballast optimisation that brings the pitch natural frequency of a vessel close to the spectral peak frequency of the wave that the yacht is most likely to encounter over its route. Perhaps even more evident is the effect of inadequate rudder and autopilots on the course-keeping performance and safety of ocean-going racing boats in heavy seas, as more than a few Vendee Globe and Mini-Transat skippers have had occasion to verify directly during racing.

Conceivably, these examples can also illustrate the possible use of PPP in race preparation, whenever parameters relevant to boat performance (see, for instance, the influence of ballasting sequence and arrangement on boat performance in large and short waves) can be altered at this stage. In this phase, the usefulness of a PPP would rather be a result of the ease with which parameter values can be altered and performance comparison made excluding the effect of all other parameters. This makes possible an objective exploration of the effect of a vast number of parameter combinations that can be used to optimise sea trials testing.

This version of the PPP is still at a very preliminary stage and a lot of effort is being made to introduce better aero- and hydrodynamic models that would allow the evaluation of such subtle design changes as those listed above. In this respect, it must be noted that the capability of PROTEUS 3.1 to utilise database interpolation can be used proficiently to integrate the results of simple CFD analysis in the simulation. Perhaps more importantly, efforts are also being made to improve and simplify significantly the interaction between user and software, by developing a dedicated GUI that would improve interfacing, pre- and post-processing.

10. CONCLUSIONS

A new numerical tool developed for the analysis of yacht behaviour in a realistic environment has been presented in this paper. This Performance Prediction Program (PPP) is capable of simulating yacht motion when under sail in a seaway, also including some manoeuvring and course-keeping capabilities. Various issues encountered in the development of this PPP have been illustrated together with an explanation of the solutions adopted or proposed to obviate to their limitations. A series of results have been presented and briefly compared to full-scale trials data. Finally, a case has been made for the use of this type of analysis both in detailed design optimisation and race preparation. Although the development of this PPP is still at its infancy, it is believed by the authors that this type of numerical analysis represents a highly promising design tool for future generations of ocean-going racing yachts.

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