ESTIMATING A YACHT'S HULL-SAILPLAN BALANCE AND SAILING PERFORMANCE USING EXPERIMENTAL RESULTS AND VPP METHODS

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This paper describes an approach to calculate the longitudinal position of the hydrodynamic and aerodynamic force centres on a sailing yacht, and the resulting rudder angle required to hold a steady course across a complete range of sailing conditions. The paper discusses the effect on performance, in terms of boat speed, by means of experimental tank testing to derive the hydrodynamic data; wind tunnel testing to derive the aerodynamic data; and the use of a 4 plus degree of freedom (DOF) velocity prediction program (VPP). It highlights the data required to carry out such analysis and is summarised in a worked example.

The main objective of this paper is to outline a process which is achievable within a design office environment and skill set, whereby a designer can use generic data derived from experimental or CFD and amalgamate it with theoretical and regression models for individual components to ensure that the "balance" question is satisfactorily addressed at a stage in the design and development process where meaningful changes can be made to geometry.

1 INTRODUCTION

As sailing yachts are getting larger, 70 metre plus LOA is unexceptional, the achievement of good hull-sailplan balance across a complete range of sailing speed and heel conditions become more difficult. This is due to design features related to their size and operational constraints. Large sailing vessels often have shallow draft relative to their length, restricted draft and rudder(s) area and high induced drag characteristics leading to large leeway and high hydrodynamic drag angles. All of these effects make coinciding the aerodynamic and hydrodynamic lines of action more difficult, and the normal "fixes" to ameliorate the problem, such as altering mast rake and sail trim, or the sailing trim are not easy to apply on such large vessels. The long established rules of thumb to determine hull-sailplan balance or 'lead' can no longer be relied upon, highlighted in [1] and [2]. This necessitates the use of alternative approaches to understand and determine the elements that contribute towards balancing the hull and sailplan.

The majority of large superyachts have multimasted rigs to meet design and operational restrictions. These sailplans can have vastly different longitudinal centres of effort in comparison to sloop rigs with complex interactions between the cascade of sails and sheeting options. This makes the use of techniques such as wind tunnel testing or CFD invaluable as a means of determining the aerodynamic centre of effort and how it changes with apparent wind angle, sail flattening and easing.

This paper breaks down this balance problem into three main stages:

- The estimation of the hydrodynamic forces including centres of lateral resistance; lift and drag values
- The estimation of the aerodynamic forces including centres of effort; lift and drag properties
- A solution phase, combining the above elements and other parameters including righting moment across a range of sailing conditions to predict steady state rudder angles and sailing performance.

The budget often restricts the quantity of project specific experimental or computational data points that can be gathered. The designer can offset this restriction if he has the skills to use limited datasets, or data from similar vessels and casting these into a more complete summary of the yacht's performance, particularly in relation to helm balance effects. By incorporating other methods and sources of data more depth is added to the global yacht model and allows it to be extended beyond the limits of the original data and results in more complete and robust performance envelopes.

This paper is aimed at the yacht designer, to show an approach that combines the use of different data sources to create a meaningful performance prediction tool that captures balance effects for large sailing yachts. Additionally the techniques described are relevant to the productive management of a 'mixed economy' where data from physical experiments, CFD simulations and parametrically based force models can all be woven into the fabric of the design decision process.

2 TANK TESTING

Sailing yacht tank testing is principally used as a means of estimating a vessel's resistance and sideforce generating properties, with limited attention paid to the impact of rudder use on resistance. This has typically been the case in race boat development where changes of longitudinal centre of lateral resistance (CLR) are reasonably well understood and easily predicted with deep keels and rudders taking large proportions of the lift generation. Large yachts often have comparatively shallow draft appendages which in turn leads to greater lift contributions from the relatively inefficient hull. This lift generation by the hull induces a Munk moment which can have a significant effect upon the centre of resistance. These effects must be incorporated within any analysis if it is to yield meaningful guidance for the designer.

Standard semi captive model sailing yacht testing techniques adopted by the authors are described in [3] and [4]. Following the completion of an upright resistance curve (zero heel, zero yaw), at each test speed and heel test condition a sweep of leeway angles will be tested on both tacks with a rudder set to a plausible helm angle. Some judgement must be exercised here, it is clearly wrong to test at zero rudder because this means every test point has the "wrong" rudder angle. Therefore an angle of say 2 or 3 degrees may be chosen, although this will not be the correct angle it does at least mean that the test data has captured some of the effects of the pressure field around the rudder. A matrix of speed and heel combinations covering the expected vessel sailing range will be carried out. The major benefit of this style of testing is that it allows for good estimation of the different resistance components, robust scaling of the model scale results and provides a direct approach to assimilate the data for into a VPP.

Figure 1 summarises the typical results for one speed/heel condition, on one tack. The labels show the leeway and rudder angle for each data point. The leeway variation sweep was carried out with the set rudder angle of 4°, after which a rudder sweep was carried out at 5° of leeway.

These results here can be used to determine:

- Heel drag (drag at zero sideforce)
- Drag at sailing sideforce
- Effective draft

The effective draft is determined by applying a least square fit to the standard leeway speed data. This is appropriate for most vessels, however the linear assumption does not hold when significant lift is taken by the hull or low aspect ratio appendages operating at high leeway angles as is the case with many large yachts. In such cases a first order polynomial or similar is used to fit the data.

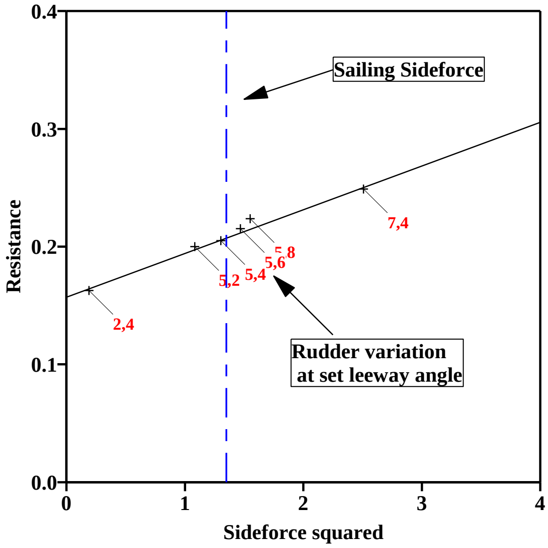

Figure 1: Typical tank testing resistance versus sideforce^2 plot

The rudder effectiveness tests are carried at or close to the leeway setting coinciding with sailing side force (SSF) appropriate to that heeled condition, as can be seen in Figure 1 with the SSF line. Rudder angle changes are made over a range, i.e. 2, 4, 6, 8 degrees. These are then used to determine the relative change in CLR with rudder angle, which can be seen in Figure 2. This can then be undertaken across a range speed/heel conditions with the CLR change being expressed per degree of rudder angle for each condition.

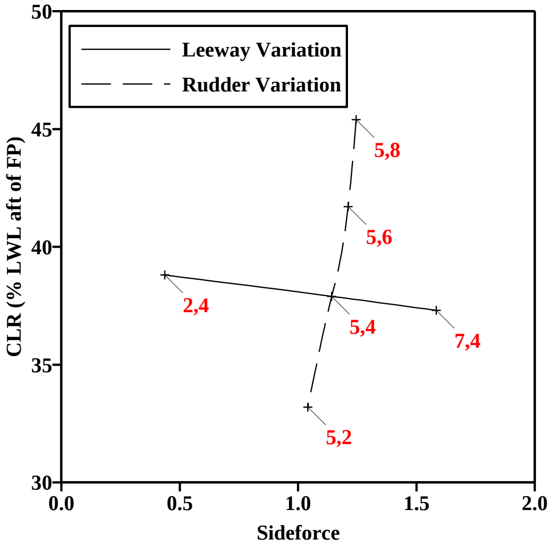

Figure 2: Typical longitudinal centre of lateral resistance (CLR) change with sideforce

The complete set of data will eventually consist of 8-10 data sets like the one shown in Figure 1, and 3-4 rudder variation data sets like the one shown in Figure 2. These data are scaled to the full size and submitted to a fitting process which the VPP can interrogate across the entire range of boat speed, heel and sideforce to yield the following data:

- Resistance as a function of sideforce
- Vertical and Longitudinal centre of lateral resistance at standard rudder setting
- Sideforce versus leeway relationship
- Rudder angle relationship to CLR and resistance

For direct input into a VPP this is summarised to a table input of:

- Boat speed
- Heel angle
- Leeway angle
- Rudder angle
- Resistance (Force along the vessel track)
- Sideforce (Force normal to the vessel track)
- Roll moment (Mx)
- Yaw moment (Mz)

3 SAIL AERODYNAMICS

Large superyachts often have multi-masted sailplans due to mast height restrictions, ranging from ketches to 3 masted or more schooners. At the design stage, a number of questions are often being asked, such as what is the overall sail performance in terms of driving force, sideforce and achievable apparent wind angles. Are the masts in best location and are the separations suitable? Do the sails interact favourably? Do sheeting locations impact on the deck arrangement? The wind tunnel offers a perfect environment in which to address these questions. It often provokes a stimulating discussion between the stylists, sailmakers, Naval Architects, and designers.

3.1 WIND TUNNEL TESTING

There are a number of practitioners of scale model experimental sail aerodynamics. Historically, these have focussed on driving force, sideforce and roll moment parameters [5], but in more recent times the importance of yaw measurement upon absolute yacht performance has received greater attention [6] and [7].

Sail testing techniques are discussed in a number of other sources. The authors adopt the following processes which enable robust analysis and scaling of the results to full scale and facilitates complete datasets for direct inclusion into VPPs. Bare hull and mast windage tests are carried out to assist in the understanding of the breakdown of forces.

Whilst maintaining constant wind pressure, each sail combination at each tested apparent wind angle is optimised by sheeting all the sails to produce the maximum driving force. Having achieved this, other combinations of sheeting are used appropriate to de-powered modes, i.e. maximum drive force (Df) at a specified limit of heeling moment (Hm) (optimising Df/Hm ratio). At this stage, the change of longitudinal centre of effort (CEA) with depowering and sheeting can be observed. This process indicates the range of potential movement of centre of effort.

The data is analysed to apply the blockage corrections, and calculate the sail force and moment coefficients which are then used at full scale. The authors use an in-house software 'WindCorrect' to carry out this analysis and create aerodynamic data fit files for each tested sail set that can be read directly by the VPP.

Figures 3,4,5 show typical results for one sail configuration and three apparent wind angles, Drag coefficient (C_D) versus Lift coefficient (C_L), non-dimensional Driving force (Df) versus Heeling moment (Hm) and Centres of efforts versus Heeling force (Hf), respectively.

The objective of the tests is to produce a set of data for each sailset (e.g. full sail, offwind and reefed configurations) that encompasses a range of apparent wind angles for input into a VPP. This uses an approach similar to that of the ORC [8] to model sail easing and flattening.

In Figure 3, the line fit through the C_D versus C_L^2 data for the apparent wind angle (β_a) of 30˚ corresponds to the effective rig height and is used to derive the drag associated to the eased/flattened sail settings. This figure shows typical sail trimming effects, at 30˚apparent wind angle the C_D versus C_L^2 line is sensibly linear, the maximum C_L^2 of 2.5 ($\sqrt{2.5}=1.58\ C_L$) is achieved by over-trimming the sail so that a little extra drag is incurred, then as the sail are eased the lift coefficient can be reduced to 1.0 before sail efficiency is lost. At the wider apparent wind angles it becomes increasingly difficult to efficiently de-power the sail.

This is carried out on as many of the proposed sail plan options as is possible, covering upwind, reaching and downwind configurations as well as reefed settings.

Figure 4 shows the VPP input file fit applied to the 30˚ β_a and the maximum Df values appropriate to each apparent wind angle.

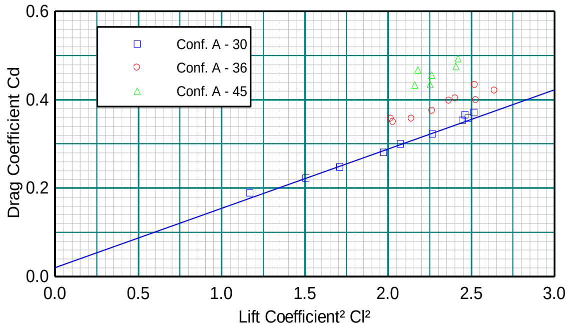

Figure 3: Typical wind tunnel C_D versus C_L^2 plot

Figure 5 shows forward and lower shift in centre of effort as the sailplan is eased. As with a majority of rig types, the most significant and efficient easing strategies result to sheeting out the aft most sail, with lesser easing moving forward through the sailplan.

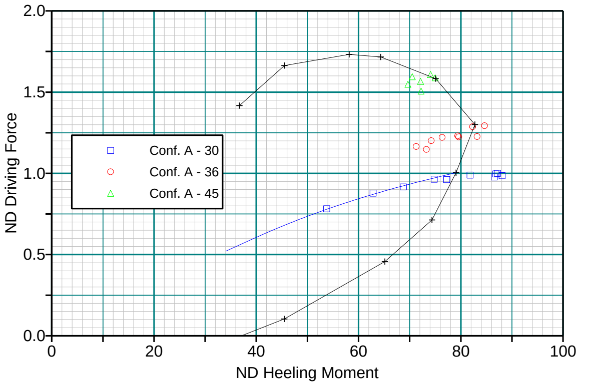

Figure 4: Typical wind tunnel driving force versus heeling moment plot

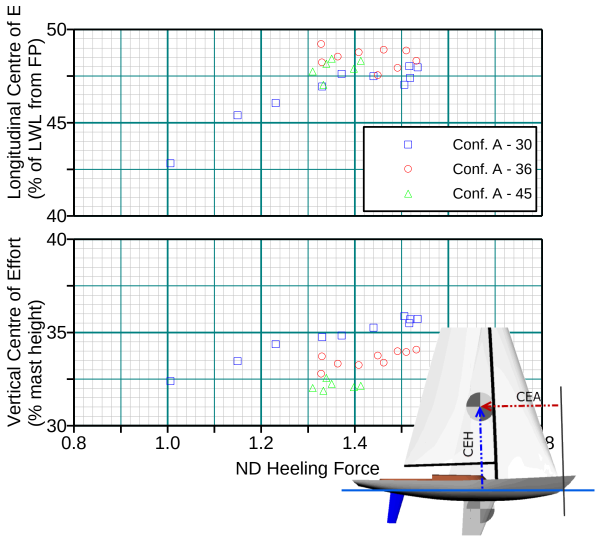

Figure 5: Typical wind tunnel CEH and CEA versus non dimensional heeling force plot

It is important to maintain similar CEA characteristics as a sailplan is reefed to prevent large changes in rudder angle. This is the stage were alternative strategies can be tested to ensure this is the case and highlight reefed configurations that are not.

3.2 FITTING PROCESS

From analysis of the scaled test data, the following data are determined for the range of apparent wind angles tested, this includes:

- C_L
- C_D
- CEH at maximum Df
- CEA at maximum Df
- Effective Rig Height (He)
- Function of change of CEH and CEA with C_L

This data set is then augmented by interpolating and extrapolating for other apparent angles that were not tested, to create a continuous set of data that can be used by the VPP. As with the hydrodynamic data fits the aerodynamic data are not simply faired surfaces through the test data points, they are derived by interpolating and extrapolating the effective rig height and the maximum lift coefficient with its associated drag coefficient across the apparent wind angle range. By adopting this physics based approach valid data can be derived for the full range of wind angles from a relatively sparse set of test data.

All this data has been corrected to the upright condition, as the VPP will apply the appropriate heel manipulation.

This is a highly appropriate solution in the creation of a consistent and robust data set for direct inclusion into a VPP environment. Other test methods will answer specific questions, i.e. most appropriate sail settings for a specific wind condition, vessel stability and wind angle but will be of limited overall value in creating a systematic or complete dataset for inclusion in a mathematical fitting process such as a VPP. This analogous to the situation experienced in tank testing, where “sailing dynamometer” systems that generated data only at conditions where the roll moment equilibrium of the full scale boat was matched at each heel angle. This system gave instant gratification by capturing stability effects without the need for further analysis, but it generated data sets that lacked the heeling force degree of freedom, and in so doing provided data that was much less easily applied in the general case.

4 SOLUTION PHASE

The velocity performance prediction program (VPP) has the ability to integrate the complete range of hydrodynamic and aerodynamic elements.

4.1 HYDRODYNAMIC COMPONENTS

The drag and lift properties associated with hydrodynamic components include that of the:

- Keel
- Bulb
- Rudders
- Other appendages such as daggerboards

The breakdown of hydrodynamic forces on each element includes:

- Viscous drag
- Lift and induced drag
- Wavemaking drag
- Interaction between the elements such as downwash angle and wake effects

4.2 AERODYNAMIC COMPONENTS

The aerodynamic components include:

- Sails, various different types
- Mast and rigging including windage

These are comprised of aerodynamic forces including:

- Viscous drag
- Lift and induced drag
- Drag due to separation
- Interaction effects such as bi-plane and blanketing

4.3 VPP

The VPP used (WinDesign6) can incorporate different force models for each component, such as the Delft Systematic Yacht Hull Series for the canoe body, ORC aerodynamic sail coefficients and built in models based on theoretical and experimental regressed models.

Sections 2 and 3 have briefly summarised the creation of models specific to a particular vessel which can be used directly within a VPP.

Discussed here is a 4 DOF approach, whereby the VPP aims to resolve the force and balance equations:

$$\sum F_x = (\text{driving force}) - (\text{resistance}) = 0$$
$$\sum M_x = (\text{heeling moment}) - (\text{righting moment}) = 0$$
$$\sum F_y = (\text{hydro sideforce}) - (\text{aero sideforce}) = 0$$
$$\sum M_y = (\text{hydro yaw moment}) - (\text{aero yaw moment}) = 0$$

The WinDesign 6 software uses a modified multi-dimensional Newton Raphson iteration scheme to resolve these equations.

It must be borne in mind that each of the parameters listed above are functions of a number of variables. A breakdown of the simplified case of a 2 DOF VPP is detailed in [9].

For direct input of the externally derived hydrodynamic or aerodynamic data WinDesign 6 uses a thin plate spline (TPS) with radial basis function (RBF) which allows the program to apply reliable fits to multivariate, irregular data. In the majority of testing situations the authors endeavour to use systematic test programmes that allow the creation of well populated datasets covering as much of yachts sailing performance envelope in terms of speeds, heel, leeway and rudder angles as possible and ensure that the data is fair and extended to cover the entire condition range (as per section 2) prior to use within a VPP.

It is often the case in a design environment that the data available to create a hydrodynamic or aerodynamic vessel specific fit is relatively sparse and the data points are not distributed regularly. This often results from limited results to base a fit upon which is often due to budget restraints as each data point comes with a cost implication or time constraints in the project plan, or computational constraints if using CFD. This is the case when using offwind sail data derived from Direct Eddy Simulations (DES) [10] where a comprehensive matrix of test results would be prohibitive. The RBF component of the spline fit allows the program to interpolate points and develop a smoothed surface across parameter space that is then used as a hydro or aerodynamic force component.

For ease of understanding the aero/hydro balance problem parameters such as CLR and CEA have been used, whereas they each relate to a 3-D vector and as such this is what needs representing within the VPP modelling, and is defined in terms of boat axis Fx, Fy, Mx and Mz.

6 WORKED EXAMPLE

A VPP is a primary tool in the design decision process, and therefore being able to use a mixed economy of input sources is very powerful. It is possible to use experimentally derived data and with minor adaptations to replace, or add new appendages. This can allow the user to build a complete hydrodynamic model around limited data, using built-in internal models and their own regressions.

The worked example in this presentation aims to highlight the possibilities of changing and replacing rudder configurations. This has been focussed upon because the rudder arrangement is the primary longitudinal balancing control for a superyacht. Changing rudder angle can produce much larger changes in CLR than alterations to sail trim can make to the CEA. Also by controlling CEA with sail trim you inevitably lose driving force and efficiency. Sails are at their optimum at a single CEA position, whereas the hull resistance is less sensitive to change in CLR, as shown in Figures 1 & 2. Relative to rudder usage, sail sheeting and setting changes outside a reasonable restrictive range typically result in large losses in driving force.

It is based on actual results derived from tank testing and wind tunnel sail testing and this scenario applies equally to CFD developed data, where a designer has commissioned various simulations. Following this programme of work particular features are modified which is not uncommon during a project. In the case of a luxury yacht project, various specifications may change. Therefore the previous derived yacht data will need to be modified to suit the new design requirements.

A case study was undertaken using Windesign 6 using experimentally derived hydrodynamic and aerodynamic data for a very large multi masted schooner rigged superyacht. The tank testing was conducted with a single centreline semi-skeg rudder.

The hydrostatic data such as GZ and displacement for each option is determined directly from geometry surface files of the hull and appendages, LCG and VCG definition and applied directly in the VPP.

The design change simulated using the VPP was swapping the single rudder for a twin rudder arrangement. This example presents the results for both the single and twin rudder options and the resulting changes in rig/sailplan location in order to maintain acceptable helm angles and sailing performance.

The original scaled and fitted tank data incorporates the combined effects of the canoe body, stub keel and single centreline semi-skeg rudder, with limited rudder variation data. In order to build on this, it is manipulated to allow the VPP to use a virtual rudder that uses the internal rudder model (in terms of induced drag and lift) with a prediction of downwash and angle of attack effects. The force model components are shown in Table 1.

Component	Data Source	Force Data
Hull Keel Rudder	Tank results	Resistance, SF, Mx & Mz
Virtual Rudder	WD 6 internal model	SF, CLR and Induced Drag

Table 1: Single Rudder Hydrodynamic Force Model Components

In this way the CLR relationships and rudder volume contribution effects in the original data are retained, but the virtual rudder angle can be varied by the VPP solution algorithm to maintain the force and moment balance with the sails.

This is then run through the VPP using the experimental derived aerodynamic data. The predicted rudder angles across a comprehensive range of true wind speeds and angles are presented in Figure 6. This shows that the rudder angles for the standard single options are within a reasonable range across the matrix of true wind speeds and angles.

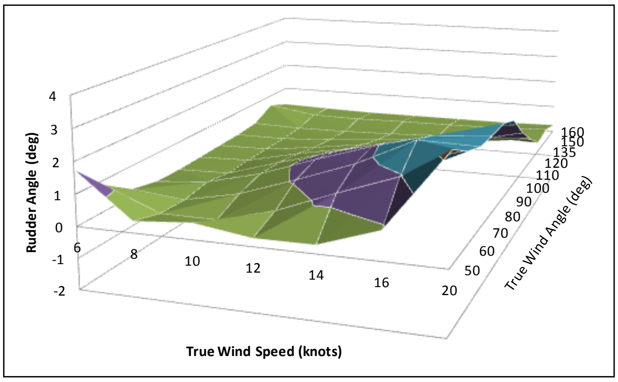

Figure 6: Rudder angles for single centreline rudder.

It also leads to respectable sailing speeds as detailed on the polar plot of Figure 7.

To model the twin rudder configuration the tank data was re-analysed to remove the viscous drag of the single centreline rudder and the force model components were adapted as shown in Table 2.

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Component	Data Source	Force Data
Hull Keel Rudder	Re-analysed Tank results	Resistance, SF, Mx & Mz
Twin Virtual Rudders	WD 6 internal model	SF, CLR and Induced Drag

Table 2: Twin Rudders Hydrodynamic Force Model Components

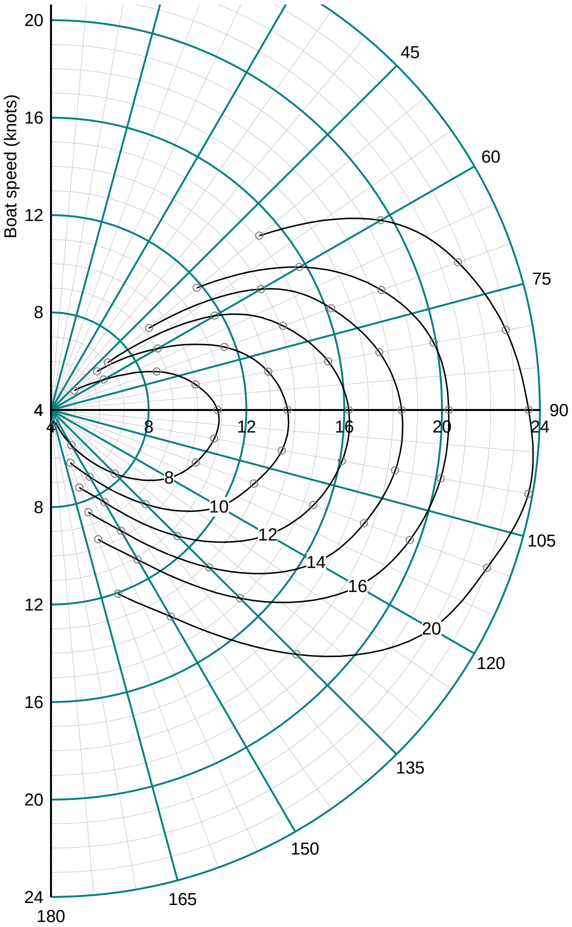

Figure 7: Polar performance plot in the single rudder condition

The predicted rudder angles are presented in Figure 8.

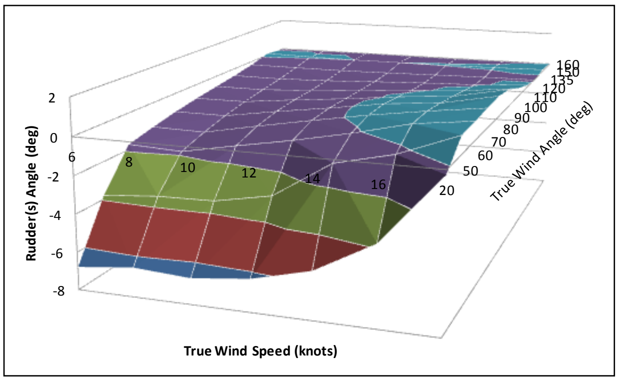

Figure 8: Rudder angles for twin rudders and original sailplan

Changing directly to the twin rudder option shifts the CLR 7% of the LWL aft leading to highly negative rudder angles in the light upwind wind range. This results in part from the increased rudder effectiveness due to twin rudders having less influence from keel downwash, angle and wake that the single rudder experiences.

It must be borne in mind that the negative rudders presented in Figure 8 are referenced to boat centreline and that the local angle of incidence will reflect the actual rudder loading which is a function of leeway and downwash effects.

There is also a noticeable reduction in boat speed due to the hull and keel taking a greater proportion of the lift which is at the expense of greater induced drag. As can be seen in Table 3, where speed differences are significant, negative means that the twin rudder option is slower. This highlights the important of maintaining good hull sailplan balance.

		True Wind Speed (knots)					
		8	10	12	14	16	20
True Wind Angle (deg)	60	-0.95	-1.67	-2.71	-1.82	-1.42	-0.98
	70	-1.80	-1.87	-1.33	-1.12	-1.23	-0.68
	80	-1.39	-1.28	-1.03	-0.90	-1.01	-0.52
	90	-1.04	-0.99	-0.87	-0.75	-0.78	-0.41
	100	-0.71	-0.80	-0.74	-0.67	-0.62	-0.42
	110	-0.49	-0.53	-0.55	-0.53	-0.49	-0.38
	120	-0.35	-0.39	-0.43	-0.43	-0.42	-0.42
	135	-0.24	-0.26	-0.29	-0.32	-0.34	-0.34
	150	-0.28	-0.14	-0.14	-0.16	-0.18	-0.21
	160	-0.10	-0.14	-0.09	-0.10	-0.12	-0.15

Table 3: Reduction of boat speeds (knots) between single and twin rudders option

The rudder areas used are considered reasonable to maintain adequate manoeuvring qualities whilst under motor and sailing conditions. The remaining options to adjust balance are: to shift the CLR by moving the keel or longitudinal movement of the rigs and sailplan.

In light of the speed reduction with twin rudders a revised sailplan was modelled with the CEA shifted aft. This brings the rudder angles into a more acceptable range, slightly negative at the lower upwind speeds moving to positive at the higher speeds as can be seen in Figure 9.

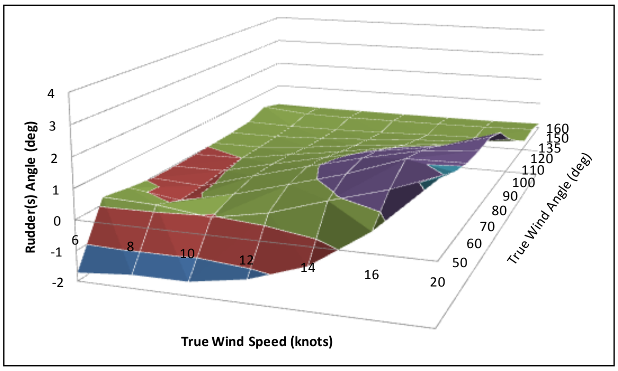

Figure 9: Rudder angles for twin rudders with sailplan aft

As can be seen in Table 4 the rig and sailplan shift afward results in significant less boat speed reduction when compared to the single rudder option. This speed difference is now primarily related to the additional viscous drag of the additional rudder over that of induced drag differences.

		True Wind Speed (knots)					
		8	10	12	14	16	20
True Wind Angle (deg)	60	-0.36	-0.44	-0.36	-0.24	-0.18	-0.12
	70	-0.33	-0.33	-0.24	-0.20	-0.16	-0.14
	80	-0.14	-0.28	-0.23	-0.18	-0.20	-0.12
	90	-0.29	-0.30	-0.26	-0.22	-0.22	-0.10
	100	-0.29	-0.32	-0.29	-0.26	-0.23	-0.13
	110	-0.24	-0.27	-0.28	-0.26	-0.24	-0.17
	120	-0.21	-0.24	-0.26	-0.27	-0.26	-0.24
	135	-0.17	-0.21	-0.24	-0.26	-0.28	-0.27
	150	-0.20	-0.11	-0.13	-0.15	-0.16	-0.19
	160	-0.08	-0.10	-0.09	-0.10	-0.12	-0.14

Table 4: Reduction of boat speeds (knots) between single and twin rudders with aft shifted sailplan

This process shows that if the twin rudder option is taken then an aft shift of the entire rig is necessary in order to maintain acceptable sailing rudder angles

6.1 DESIGN SOLUTION

Experimental testing offers a very cost effective way to generate accurate force and moment charactersitics for a sailing yacht hull, capturing the wavemaking effects of lifting surfaces and the Munk moment from the canoe body when yawed. The type of analysis described shows how this data can be used as a baseline to simulate alternative configurations, using either the VPP internal models, or specific CFD tests on individual components.

7 CONCLUSIONS

This paper has highlighted an integrated approach using experimentally derived hydrodynamic and aerodynamic data and a 4 plus DOF VPP to evaluate the yaw balance and predict steady state sailing rudder angles and boat speed optimisation across a complete range of true wind speed and angles for sailing yachts.

The benefits of this approach to aid the design process and additional versatility to existing data sources has been outlined. It also addresses particular issues relating to the study of large sailing yachts.

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The Wolfson Unit was awarded the RINA Small Craft Medal in 2013 for its long standing service to the small craft industry.