A Comparison of Parametric Analysis, Tank Testing and CFD Methods As Part Of An Advanced Sailboat Velocity Prediction Program.

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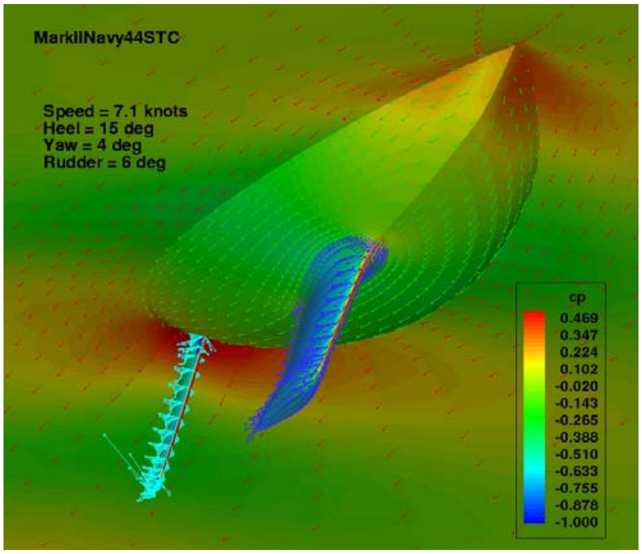

While great strides have been in the last decade, sailing performance prediction remains an uncertainty in sailboat design. Due to budget limitations, only yachts in events such as the America's Cup or Volvo Ocean Race normally have the resources to use all the available prediction methods. Today designers use three methods to predict performance characteristics: parametric analysis, tank testing, and computational fluid dynamics. Using the new Navy 44 Sail Training Craft designed by David Pedrick as an example, this study examines these prediction methods and provides recommendations for their use in combination with simple and customized velocity prediction programs. Parametric analysis was conducted using the spreadsheet Velocity Prediction Program PCSail and was compared to the 2002 IMS rating prediction. Tank testing was conducted in the 120-foot towing tank in the United States Naval Academy's Hydromechanics Laboratory using a 52-inch model. CFD computations were performed using FKS, a PC-based code from the Naval Surface Warfare Center, Carderock, and by SPLASH, a code from Southbay Simulations, Inc. The performance prediction process proved most accurate when using tank data to aid the CFD calculations. The paper also addresses how to construct an advanced spreadsheet-based VPP.

Nomenclature

Canoe body = hull without appendages
C_D = drag coefficient
C_L = lift coefficient
CE = center of effort
C_F = friction coefficient
C_p = prismatic coefficient
C_m = midships coefficient
C_T = total resistance coefficient
C_V = viscous coefficient
C_W = wavemaking coefficient
Δ = displacement
F_n = Froude number
GM = metacentric height
k = form factor
L = characteristic Length
λ = scale ratio
LCB = longitudinal center of buoyancy as percent of LWL forward of midships

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LCF = longitudinal center of flotation as a percent of LWL forward of midships
LOA = length overall
LWL = waterline length
MT1” = moment to trim one inch
Rn = Reynolds number
ρ = mass density of water
T = maximum draft of ship
τ = stress tensor

Background

Performance prediction is a critical step in the ship design spiral. Whether cruising yachts, America's Cup racers, container ships, or warships, the vessel’s speed greatly influences mission effectiveness. Three methods are commonly used to predict speed and other responses: parametric analysis based on principal vessel dimensions, tank testing, and computational fluid dynamics (CFD).

This study compared these methods, and used a small sailing craft as the example due to the complexity in their hydrodynamic characteristics. Most power-driven vessels for instance are only evaluated in forward motion. A sailing vessel however is evaluated in forward motion and for varying amounts of heel, yaw, rudder angle, and trim. The side force lifting surfaces such as the keel and rudder have a significant effect on the performance of the vessel and are also evaluated.

As sailing vessels derive their power from the unsteady wind, a velocity prediction program (VPP) solves the static force and moment equilibrium equations to predict boat speed, heel, and other factors. A VPP consists of three elements: a hydrodynamic performance predictor, an aerodynamic force and moment predictor, and a solver to link the hydrodynamic and aerodynamic solutions of the test condition (Claughton, 1999).

The first performance prediction method, parametric analysis, uses the principal dimensions of the hull and rig to make response predictions using parametric equations developed from a large database of similar vessels. This process is called a Lines Prediction Program (LPP) and it is restricted in its ability to extrapolate beyond the limits of the hydrodynamic data. Parametric analysis VPPs are used mostly for preliminary yacht design. The International Measurement System (IMS) code used for establishing handicap ratings is one example.

Over many years, the second performance prediction method, hydrodynamic tank testing, has developed to consistently yield reliable results. The measured forces from the scale-model tank tests are expanded using the Froude method to predict the forces on the full-size vessel. Due to aerodynamic forces, the towing rig must be equipped to change the sailing vessel's yaw, heel, trim, and rudder angles.

The third method, CFD, uses fundamental fluid dynamics theory in numerical codes to predict the fluid flow around the moving ship. The accuracy of the simulation is primarily a function of the quality (and complexity) of the code and the quality of the grid. In general, as CFD codes increase in complexity and accuracy, computational resources also significantly increase.

This study compared the parametric analysis predictions of the PCSail (Martin, 1999) and Delft Series (Keuning, 1997) LPPs to tank testing and to the FKS and SPLASH CFD codes. The tank testing was conducted in the 37m (120ft) tow tank at the United States Naval Academy. The PC-based FKS code was developed at the Naval Surface Warfare Center - Carderock, by Dr. F. Noblesse, in cooperation with C. Yang of George Mason University. The SPLASH code was developed by Bruce Rosen and Joe Laiosa of South Bay Simulations. Predicted sailing conditions were also compared to the 2002 IMS VPP.

The hydrodynamic prediction process shown in Figure 1 was followed. The principal dimensions were drawn from the preliminary design of the Mark 2 Navy 44 Sail Training Craft (STC) designed by David Pedrick. From these PCSail was able to predict the sailing attitudes and velocities of the Navy 44, which were used to determine the tank testing conditions. For consistency, the IGES hull lines file was used to NC-cut a 10.2:1 scale model and to create the CFD surface.

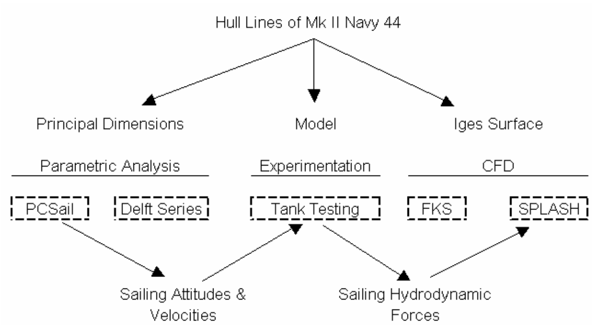

Fig. 1 Performance prediction flow diagram

Parametric analysis

Parametric analysis begins with tank testing of a range of slightly dissimilar hull forms. A regression is made in which a value (resistance, lift, etc.) varies throughout the series by the principal characteristics of the hull form. The Delft series is widely used for sailing craft. The principal dimensions used in the analysis were:

Hull Characteristics			Appendages			Sails		
LOA	43.986	(ft)	Rud.root.crd	2.574	(ft)	Main.P	51.23	(ft)
LWL	37.332	(ft)	Rud.tip.crd	1.044	(ft)	Main.E	18.00	(ft)
Beam.Deck	12.586	(ft)	Rud.span	6.043	(ft)	Main.BAD	6.05	(ft)
Beam.WL	11.181	(ft)	Rud.S	23.143	(ft^2)	Main.CE.Z	26.03	(ft)
Draft	7.148	(ft)	Rud.Vol	2.327	(ft^3)	Main.Area	461.03	(ft^2)
Canoe.draft	2.929	(ft)	Keel.root.crd	7.15552	(ft)	Jib.J	18.41	(ft)
Ltship.disp	27544.5	(lbf)	Keel.tip.crd	11.09	(ft)	Jib.LPG	27.61	(ft)
Sailing.disp	30307.7	(lbf)	Keel.span	4.775	(ft)	Jib.I	59.49	(ft)
Cp	0.523	()	Keel.S	70.886	(ft^2)	Jib.CE.Z	23.20	(ft)
Cm	0.557	()	Keel.Vol	19.214	(ft^3)	Jib.Area	859.65	(ft^2)
Lcb	-3.18%	()	Keel.CE.Z	4.728	(ft)	Spin.Pole	18.41	(ft)
Lcf	-5.35%	()	Keel.TaperRatio	1.549852422	()	Spin.Leech	58.52	(ft)
WP Area	285.892	(ft^2)				Spin.CE.Z	29.26	(ft)
k	0.169	()	Environment			Spin.Area	619.30	(ft)
Total.S	433.022	(ft^2)	nu	1.14E-05	(ft^2/s)	Mast.Diam	0.67	(ft)
Canoe.S	341.216	(ft^2)	rho	1.987578	(slugs/ft^3)	Hull.Fbd	3.73	(ft)
Total.Vol	473.558	(ft^3)	g	32.2	(ft/s^2)	Sails.Area.Nom	1008.53	(ft^2)
Canoe.Vol	452.106	(ft^3)				Sails.AspctRto	3.06	()
MT1"	2897.055	(lbf-ft)						
GML	43.239	(ft)						
GMT	4.939	(ft)						

Table 1 Principal Dimensions of the Preliminary Mk II Navy 44 STC

PCSail predicted the hydrodynamic forces from a modified 1993 version of the Delft series (Martin, 2001). A second analysis of the Delft series came from calm water resistance work (Keuning, 1997). The Hazen method was used to calculate the aerodynamic forces generated by the sails (Larsson, 2000). The characteristic lift and drag sail forces for PCSail were found via experimental data as well as theoretical calculations. PCSail only solved to equate aerodynamic drive to hydrodynamic drag and heeling moment to righting moment. Forces which were ignored included hydrodynamic side force and yawing moments. Aerodynamic side force was considered only for calculating heeling moment (Martin, 2001). Some modifications were made so that the IMS VPP and PCSail VPPs agreed in their output. One modification was the metacentric height, GM. PCSail computed GM as a trigonometric function of the righting moment at two degrees heel. While acceptable for trend studies, this approximation did not provide the righting moment accuracy needed for this study. The IMS VPP report on the Mk II Navy 44 included a table of theoretic stability based on the hull form, which was used instead.

The VPP was run at true wind speeds ranging from 6 to 24 knots. The PCSail predictions corresponded well with the IMS predictions with the exception of downwind speeds below eight knots true wind speed. This was expected as the PCSail aerodynamic algorithm is not as rigorous as the IMS algorithm for these conditions. The PCSail VPP also differed from the IMS VPP for heel predictions around a true wind angle of 90 degrees. This disagreement was based on the two algorithm’s different interpretations on when to raise and lower the jib and spinnaker. Because the sailing predictions made by PCSail compared well to the widely validated IMS VPP, PCSail was considered accurate enough to evaluate its hydrodynamic predictions. A comparison of the two codes is shown later in the paper. For the most part, the resistance equations from PCSail are the same as those used in the 1999 Delft Series (Keuning, 1999). The accuracy of these equations will be analyzed comparatively with tank testing and CFD in later sections.

Tank testing analysis

Tank testing is the traditional method of predicting vessel performance. The towing rig in the USNA 120’ tank required extensive modification so it could be set in almost any condition of heel, yaw angle, trim, heave, and rudder angle. The requirements were: yaw (0 to 10 degrees), heel (0 to 35 degrees), rudder angle (0 to 10 degrees), free to trim and heave. The recorded data included: drag parallel to motion of travel, lift perpendicular to motion of travel, yaw moment, true speed and trim. The model was built in the USNA Model Shop. There were three parts of tank testing: unstimulated upright conditions, stimulated upright conditions and stimulated sailing conditions.

The goal of the unstimulated testing was to find a baseline for the evaluation of the later-added turbulence stimulators. These stimulators were placed at a position to trip the flow where turbulent flow would begin on the vessel. Heel, yaw, and rudder angles were set at zero. The vessel was trimmed to its designed waterline and was free to trim and heave. Stimulated sailing conditions allowed for calculations of the vessel at different attitudes. For sailing conditions, the vessel had set heel, yaw, rudder, and initial trim angles.

After the unstimulated flow testing was completed, sand strips were applied to the hull to act as turbulence stimulators. Sand strips were placed on the hull 1" aft of the stem and on the keel and rudder at 25% of their chord length. A grain size of 0.5mm to 1.0mm was used with a strip width of 6 mm (0.25in). The grain size was chosen to be slightly larger the laminar boundary layer thickness at the strip location at the slowest anticipated speed in order to trip the flow. The results of both unstimulated and stimulated conditions are shown in Figure 2.

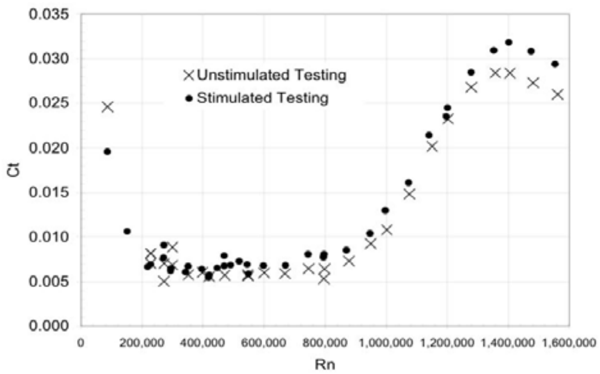

Fig. 2 Drag in upright conditions

The stimulated condition showed a uniform increase in total resistance. The added resistance was from the friction caused by the sand strips and indicated that the flow condition did not substantially change at Rn>400,000. Stimulated tests performed below Rn=400,000 showed that the fluid flow was still in the transition range on at least some part of the vessel.

Additional sand strips were added to the model to calculate the added friction from the strips. Testing of the strips populated only the lower Reynolds number conditions since the strips were used only for a Prohaska analysis of the data. The trend in the resistance curve was maintained above Rn = 300,000. All future tests used model speeds above this value (a full scale speed of 1.4 knots).

The sailing conditions were estimated from attitudes and conditions predicted by PCSail. The VPP was run at true wind speeds of 6, 12, 18, and 24 knots and at 40, 60, 90, 120, and 170 degrees apparent wind. The VPP determined the values of boat speed and heel angle for each of these 20 likely sailing conditions. These points were selected so that the true sailing conditions could be interpolated from the results matrix. As the carriage speed was only approximately set, the desired speed of each test differed slightly from the resulting speed.

Based on early tests that showed yaw and side force were approximately linearly related for small angles, yaw angles of 0 and 4 degrees and rudder angles of 0, 3, and 6 degrees were used for each sailing condition. Ultimately, the sailing matrix had 120 tests.

The unstimulated and stimulated upright tests were analyzed using Prohaska plots to find the form factor of the model. The Fn^4/C_f Prohaska plot produced the best-fit line, so the value of 1+k for the form factor in unstimulated flow was 1.009. The same method was used for stimulated flow. The Fn^4/C_f Prohaska plot produced the best-fit line, so the value of 1+k for the form factor in single strip stimulated flow was 1.168. The data for both extra sand strips were analyzed and the ordinal-intercept of the two sand strips plot was 1.290 and of the three sand strips plot was 1.356. The delta for the sand strips was 0.065. Assuming that the testing with only one sand strip indicated the true flow conditions around a full-size vessel, the difference from the sand strips was subtracted from the stimulated form factor. Therefore, the adjusted form factor was 1.103. (Van Manen, 1988)

With the form factor determined, the viscous component of resistance was subtracted from the total resistance to determine wavemaking resistance. Figure 3 shows the predicted and measured upright resistance from the Delft, PCSail, and tank results. Agreement was found for upright resistance up to 9 knots. Above 9 knots, the tank testing resistance was substantially greater than either the Delft Series or PCSail. Although the Mk II Navy 44 STC was within the range of hull form parameters as that of the parametric series, this disagreement could be a function of added resistance due to spray generation.

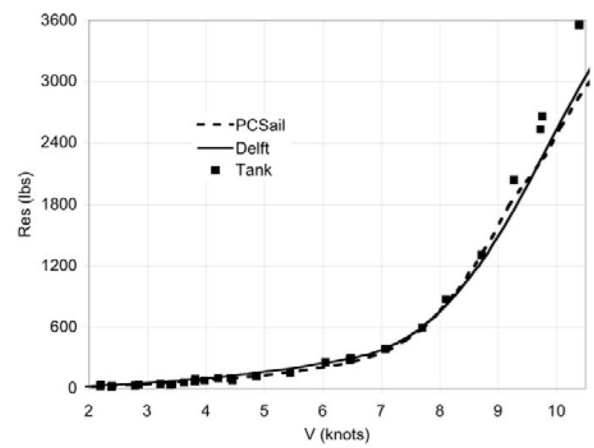

Fig. 3 Upright resistance of tank testing and parametric methods

One difficulty throughout the project was the presence of transient noises in the system (Figure 4). Fourier-transforms were performed unsuccessfully on the data to try to identify the source. Ultimately, it was shown from an oscilloscope that the noise had a beat signal. Although the source of the beat could not be found, the data acquisition system was modified to truncate the data near the zero-crossings of the beats. This method adjusted the starting and ending points to find the lowest standard deviation. In addition, the sampling rate was increased to 143 Hz. The data was then averaged to find the steady-state force.

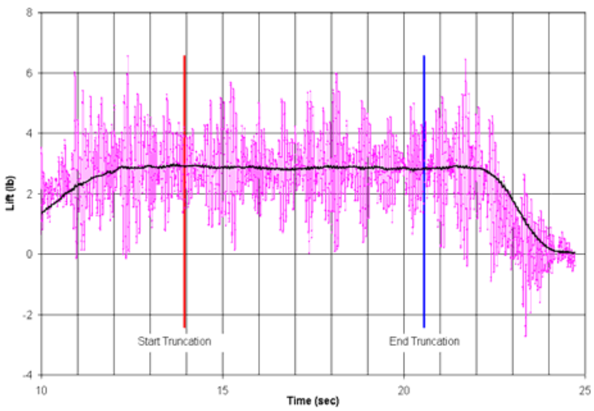

Fig. 4 Fwd-lift force block raw data for typical sailing test

CFD analysis

CFD uses various numeric approximation methods based on fundamental fluid dynamics equations to calculate the water velocity over the hull. Three CFD methods are typically used for ship analysis. The fastest method uses strip theory to compute the local velocities against the hull. Using the Havelock formula, these local velocities can be used to determine the farfield waves and thus the inviscid wavemaking drag (Percival, 2001).

The second method assumes the system is inviscid and finds the potential flow. The wave-making resistance of a ship is largely an inviscid process so potential flow is an acceptable model for computing C_W. The surface of the hull is covered with a series of constant sources and sinks which satisfy the governing incompressible, inviscid potential flow equation (Degrez, 1992). Viscous resistance accounts for much of total ship resistance however, and semi-empirical equations are used to add the resistance due to viscosity after the potential-flow simulation has been completed (Anderson, 1992).

On the higher end of CFD, there are viscous methods which include Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and the Reynolds-Averaged Navier Stokes simulation (RANS). DNS provides great accuracy but even supercomputers can only evaluate simulations with Reynolds numbers up to 200. Vessels generally have Reynolds numbers between 10^6 and 10^9. LES solves the whole motion of flow by modeling only small-scale motions. However, LES is yet too time-consuming to implement on bodies as large and complex as ships. Amongst the viscous codes, the most practical for ships is RANS. In a RANS code, all unsteadiness in the flow is averaged, but unfortunately, this makes turbulence an approximation rather than a physical simulation. Instead, turbulence models are used, and the computation time of RANS is much faster than LES (Anderson, 1992).

The turbulence model is the most problematic part to model accurately in the RANS codes. The common Boussinesq assumption, in which τ_{zx}, the Reynolds-stress tensor, is assumed to be linear to strain, breaks down for high shear flows. Since high shear flows predominate at the stern of a ship, separation remains a problem (Johnson, 1990).

The advantages of CFD are that it can evaluate changes to a design quickly without having to build a new and costly physical model, and it is not subject to problems of dynamic similarity because it is the actual ship's dimensions which are put in the calculation, not those of the model. The disadvantage of CFD is that it is only as accurate as the quality of the code, the mathematical model of the flow solved by the code, and the capabilities of the computer resources. The free surface complicates ship hydrodynamic problems since it often causes numerical singularities.

Furthermore, different effects of fluids such as viscous flow, transom separation, and lifting surfaces usually must be modeled in the code separately. Thus, like turbulence modeling, the results of these actions are not true simulations, but experimental approximations.

FKS analysis

FKS is an inviscid free-surface CFD code developed from the work of Dr. Noblesse of NSWC-CD. It runs quickly on a PC, which allows for rapid comparisons for preliminary design. However, because FKS uses slender-ship approximations in explicitly solving an integral equation, there is error present in non-slender bodies (such as the Mk II Navy 44).

The Havelock formula calculates the resistance caused by waves through a calculation of the farfield wave-spectrum. The farfield wave-spectrum can be calculated as a function of disturbance velocity, or the velocity of water particles due to the ship's velocity, along the hull. This calculation, the Fourier-Kochin representation of farfield waves, was used to develop FKS (Percival, 2001).

FKS calculates the disturbance velocity at the hull using a slender-ship approximation. This approach treats a hull as a set of cylinders without end conditions. The benefit of this approach is that calculations can occur on limited resources. The negative aspect of this method is that the approximation breaks down once the ship's beam is too large for its length. Slender-ship theory's assumptions will fail when the beam is much greater than the total wavelength (Lloyed, 1998).

In order to calculate the disturbance velocity, FKS needed to be able to make calculations along a numerical representation of the hull. Figure 5 shows the submerged area panel grid developed using the GRIDGEN code by Pointwise. As FKS calculates the hull above the waterline as a linear continuation of the hull from below the surface, some error is created if the topsides significantly change shape. An example would be if the boat were heeled to where the deck touched the free-surface. At this point, FKS would perform its calculations as if there was still more hull for the free-surface to attach, rather than the actual condition where the deck is awash.

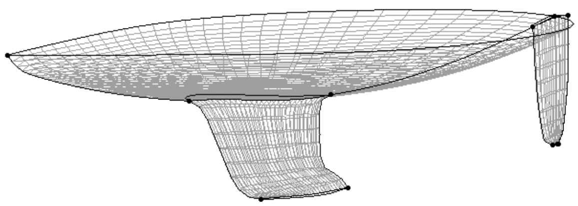

Fig. 5 Nondimensional Mk II Navy 44 STC with trapezoidal mesh

To validate FKS, a Wigley wedge-hull was compared to a published closed-form wavemaking solution (Van Manen, 1988). Figure 6 shows the calculated wave profile on the Wigley hull. FKS performed well compared to the published coefficient of wavemaking.

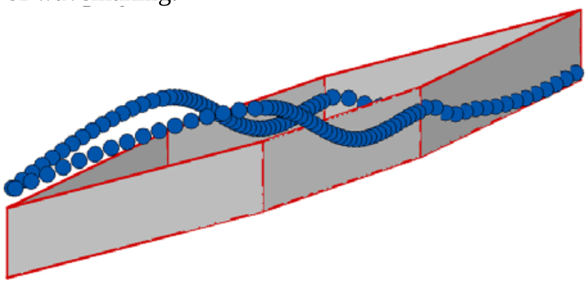

Fig. 6 Wigley hull in FKS At Fn=0.60

For the Mk II Navy 44, a script was written in TCL language to automate generating grids. This script received as input any heel, yaw, rudder, or trim angle. Heave and the number of panels could be set internally in the script. Two subsequent scripts were written in the BASH shell which would automatically run FKS over a set range of speeds.

Two sets of FKS analysis were performed on the Mk II Navy 44: upright and sailing conditions. For the upright condition, all attitude angles were set to zero. The range of speeds was set from Fn = 0.05 to 0.70. Each condition took approximately 20 seconds to analyze on a Pentium 4 laptop running Linux. Sixty-six conditions were analyzed.

Sailing conditions were composed of a test matrix which varied speed, heel angle, yaw angle, and rudder angle. Speed ranged from Fn = 0.1 and 0.5. Heel varied from 0 to 27.5 degrees. Yaw and rudder angle were set as in the tow tank. Five hundred forty sailing conditions were analyzed.

Figure 7 shows that FKS worked well in predicting the wavemaking resistance coefficient with a complex hull form like the Mk II Navy 44. The divergence above Fn=0.5 is believed to be from a highly non-linear free-surface with spray formation which is not calculated in FKS. To get total resistance the ITTC viscous corrections are added. For FKS this allows the humps and hollows to remain. As mentioned earlier, the parametric analysis methods smooth through the wave interactions. In reality, the humps and hollows are typically reduced due to viscous effects.

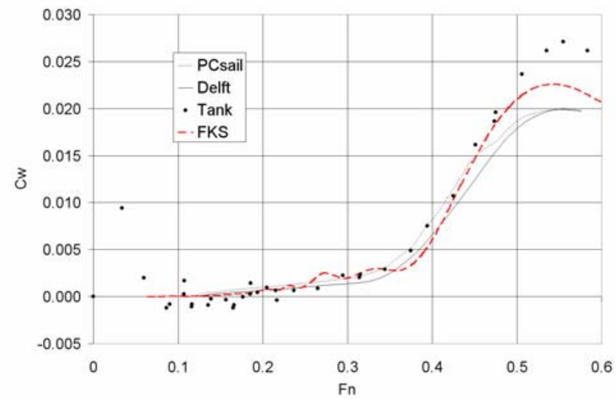

Fig. 7 Wavemaking resistance coefficient from FKS, tank testing, and parametric analysis

SPLASH analysis

SPLASH is a free-surface CFD code developed specifically for sailboats. Used extensively in the America's Cup, it is considered one of the leading CFD codes for sail craft. SPLASH is a panel-based code, meaning that it calculates potential flow, and much revision has gone into the code to evaluate the effectiveness of lifting surfaces (Rosen, 2000). SPLASH is inviscid and assumes incompressible flow.

SPLASH was compiled on an IRIX SGI machine with eight processors. As in FKS, the first step was to generate a mesh around the body using GRIDGEN. SPLASH uses sail forces from either a VPP or tank testing data to generate an equilibrium condition. The tank test data of the Mk II Navy 44 was used. For the upright condition, 40 analysis points were selected. For the sailing condition, heel angle was set at 0, 10, 15, 20, and 25 degrees while speed ranged from 0 to 10.5 knots. Yaw and rudder angle varied as in the FKS and tank testing – using six tests for each heel and speed combination.

As with tank testing and FKS, the output from SPLASH consisted of upright and sailing data. Figure 8 shows how SPLASH compared the upright resistance to tank testing and FKS predictions. At high velocities, SPLASH predicted slightly greater resistance compared to FKS and the parametric analyses. One explanation for this is in the viscous drag calculation, called "viscous-stripping." In tank testing and FKS, viscous drag was computed using a standard wetted surface area. SPLASH calculated the changed wetted surface area for each sailing condition however, and the updated area was used in the calculation.

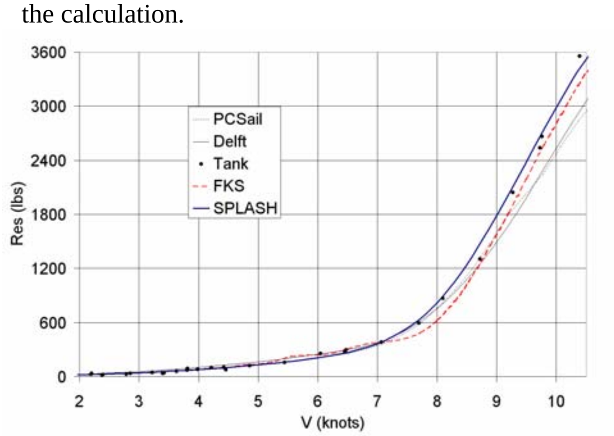

Fig. 8 Resistance of all upright data

Noticeably, SPLASH did not have the minor humps and hollows in the coefficient curves that were present from FKS. Since SPLASH is a panel code and FKS uses slender-ship approximations, some of the wave interference effects were minimized when compared to FKS. The actual coefficient of wavemaking curve was estimated to be between the curves of SPLASH and FKS. The use of a viscous CFD code could help to identify where discrepancies exist.

Sailing data analysis

Due to slight differences in each methods approach, the tank results, PCSail, FKS, and SPLASH data sets did not exactly correspond in their inputs. To get comparable results, MATLAB was used to interpolate between the data points (in model scale). The interpolation technique took the sparsely populated data matrix and transformed it into a square matrix using splines to calculate intermediate points. Since the transformed matrix was both square and dense, linear interpolation through this matrix could be used to find the required values for any velocity and heel angle. Each yaw angle and rudder angle condition created six matrices each for the drag, lift, and yawing moment variables.

Making square matrices of the tank data provided not only a method to perform interpolation, but also visualization and analysis of the acquired sailing data. The splines however created very slight negative values in order to smooth their curves outside the test range. The square matrix in Figure 9 was modified so the calculations reported null answers for any data which was not in the range of interpolation.

The parametric analyses predicted that drag did not change between heel angles, but Figure 9 shows that there was a change in drag across a range of heel angles with constant model speed. This shows where tank testing and CFD have greater resolution. The change in drag across a range of heels is a function of the particular hull and the LPPs were not able to detect these fine changes.

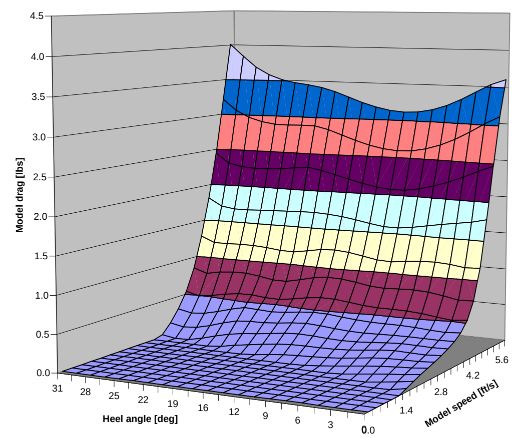

Fig. 9 Tank testing drag with 0 degrees rudder and 0 degrees yaw

A disadvantage of the square matrices method for the sailing conditions dealt with resolution. Individual points could have a great effect on the shape of the matrix. Notice that above 1.3m/s (4.2fps), around 10 degrees of heel, a dip was present in the tank data of Figure 9. The precision of the test at this point could be drawn into question. If the matrix were developed concurrently with the testing, this approach would quickly identify suspect data.

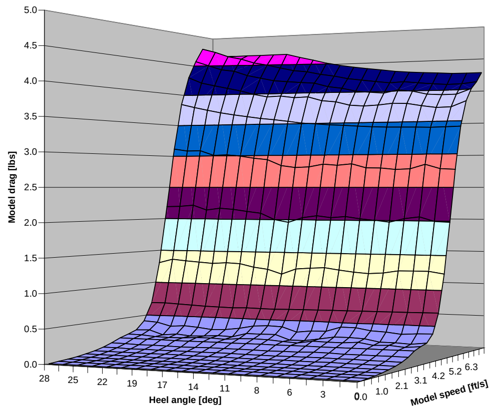

Fig. 10 FKS drag with 0 degrees rudder and 0 degrees yaw

FKS did not show the dip in drag at 10 degrees of heel (Figure 10). However, FKS showed questionable humps underneath 2.2N (0.5lb) of drag. These were investigated and were found to be unrealistic results caused by the limitations of FKS in predicting heeled sinkage and all side forces.

The test speeds in SPLASH were limited to 1.52m/s (5 fps) while tank testing went to 1.7m/s (5.6 fps). Figure 11 shows that SPLASH did not predict as much drag variation as a function of heel angle as compared to tank testing, however this discrepancy could be a function of a single tank test data point. Although the hull was remeshed during the calculations, the data which provided the aerodynamic force balance was calculated from tank testing data. This meant that the accuracy of the remeshing was only as good as the precision and accuracy of the tank testing.

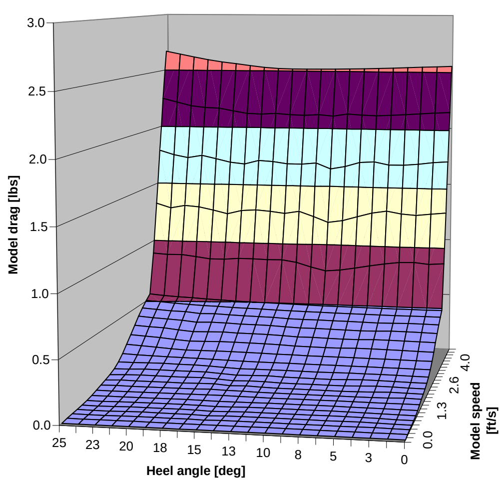

Fig. 11 SPLASH drag with 0 degrees rudder and 0 degrees yaw

Tank test data and SPLASH compared favorably for yawing moment. The yawing moment was a difficult measurement to make in the tank because of scaling. As the rudder was so small, it had a high chance of laminar flow and separation, thereby not creating the necessary lift across the rudder or yaw moment for the entire hull. The yawing moment was also a difficult computation to make in CFD but for different reasons. On a sailboat, there is a strong interaction of flow between the keel, the hull, and the rudder. If part of the mesh around an appendage, or between an appendage and the hull, were flawed, then the entire lift circulation calculated by the appendage would be in error.

However, there were differences. For instance, in the tank there was a measurable force in the aft sideforce shaft at high velocities even when the rudder and yaw were zero. This moment was attributed to large amounts of heave and trim in the model at high speeds. The effect of this movement was that the distance between the aft-pin and the force block tried to lengthen and therefore put tension on the aft-lift force block. The presence of this effect is visible in Figure 12. This effect was compensated for in the data analysis.

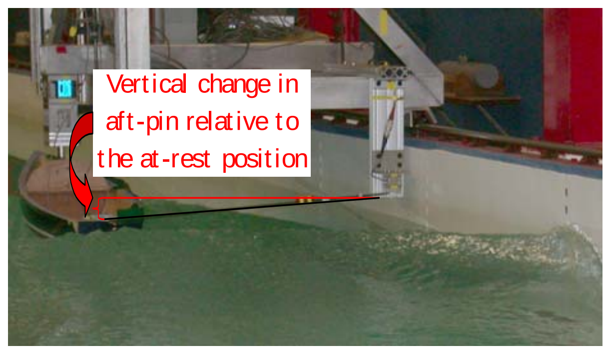

Fig. 12 High speed 0 degrees yaw, heel, rudder tank test

From a sailing-analysis perspective, both methods showed interesting results in that heeling created a large amount of yaw. The meaning of this is that the more the Mk II Navy 44 heeled over, the more it wanted to put its bow into the wind, giving "weather helm." Both SPLASH and tank testing predicted approximately the same speed for the maximum yaw moment effect; 7 to 7.5 knots.

One of the useful abilities of SPLASH was in its visualization of each test. Figure 13 shows the result of the flow calculations visually which helped analysis in two ways. First, visualization helped ensure that there were no meshing errors associated with the calculations. Additionally, the contour plot of the pressure distribution across the entire hull and free-surface and the velocity stream vectors could aid with the development of the hull form and appendages. The figure shows that tip of the rudder for instance, was not a fair surface.

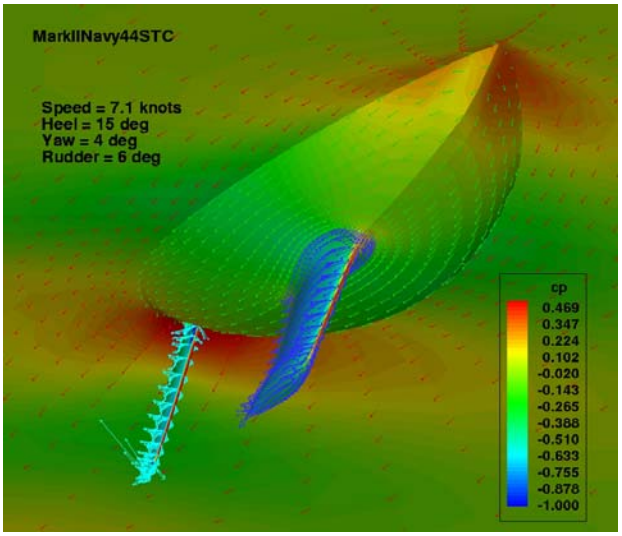

Fig. 13 Potential flow visualization in SPLASH

An analytical method was used to process the independent variables: yaw and rudder angles. Since all dependent variables were considered to behave linearly in yaw, an equation for yaw angle was formed which could interpolate through the data set. Similarly, there were three rudder angles tested for each point. A quadratic regression was used to solve between different rudder angles. Ultimately, a function was created which treated yaw and rudder as two axes of a three-dimensional surface. The function was defined by a polynomial fit in terms of rudder angle and yaw angle.

Now, all dependent variables of drag, lift, and moment could be determined as a function of speed, heel angle, yaw angle, and rudder angle. From this, a comparison was created between CFD, tank testing, and parametric analysis. Figure 14 represents the upwind sailing conditions of the Navy 44. For tank testing and SPLASH, the lift and drag forces on the boat were evaluated at discrete yaw angles (ranging from zero to five degrees). As an initial approximation, the rudder angle was set at half the yaw angle. Although the upwind sailing conditions are not the same between tank testing and SPLASH, there exists the same trend. This trend is that the effect of heel angle on lift and drag is not a function of heel angle to the 1.7 power as used in parametric analysis. Instead, heel angle has an effect on both drag and lift as a function of yaw angle.

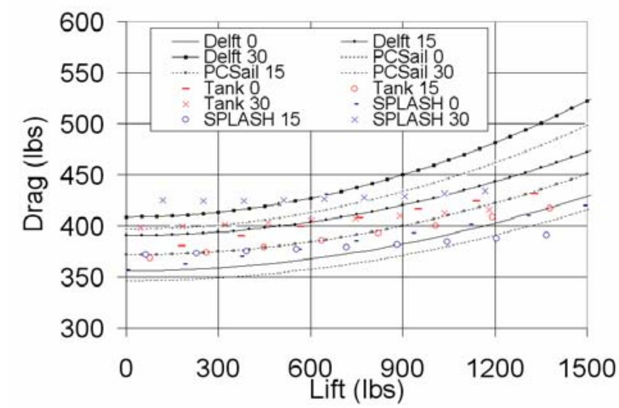

Fig. 14 Lift versus drag for the close-hauled sailing condition of all methods

Secondly, although there is a change in slope to each individual plot of drag to lift, the curvature of each plot for parametric analysis is not as pronounced as that for tank testing or CFD. In parametric analysis, this was governed by the effective draft term. It is suggested that the power of this term be reduced for vessels like the Mk II Navy 44.

Finally, for both tank testing and SPLASH, there is a cross over point of lift and drag between 0 and 15 degrees heel. This suggests that the effective draft term used in parametric analysis be modified to incorporate heel angle as a function. The end-result of the hydrodynamic program was to incorporate an aerodynamic solution to the Mk II Navy 44 and create a customized VPP.

Recommended performance-based design approach

A refined design process was created using the best features of each method while addressing their limitations. For instance, FKS is a very fast free-surface CFD code that can be run on a PC, but is limited to upright conditions with no side force. Nonetheless, it can be used for initial hull lines development.

In a complete design, the performance prediction phase would be one step in the design spiral. Using the tools of tow tank testing, a simple parametric VPP, a simple CFD code (FKS), and a complex CFD code (SPLASH), an accurate method of predicting performance can be made through design iteration in the following procedure.

1. Preliminary Design:
   A. From the design requirements obtain the initial principal dimensions of the hull, sail plan, and center of gravity.
   B. Iterate using the PCSail VPP to find the target boat speed and hull form coefficients.

C. Develop preliminary hull lines from the hull form coefficients.
D. Run upright conditions in FKS for a range of Froude numbers from 0.05 to 0.7 to determine the effective horsepower (EHP), and make an initial engine selection. Also, determine the tow tank drag and lift force block sizes from force estimates. Refine the hull lines based on the predicted wave profile from FKS.

2. Design Experimentation
   A. Construct a scale model with a basic keel and rudder from preliminary design estimates
   B. Run upright tank tests with and without turbulence stimulators for the likely speeds predicted by PCSail.
      i. Determine the form factor using the sand strip correction factor.
   C. Run tank tests at 6, 16, and 24 knots of true wind speed at true wind angles of 40, 90, and 120 degrees using heel and speed estimates from PCSail. Include yaw angle tests of 0 and 5 degrees and rudder angles of 0, 3, and 6 degrees. Record drag, lift, and yaw moment.
   D. Standardize SPLASH's trimming moment estimations with the tank testing data. Use the form factor found from tank testing for the viscous component from SPLASH.
   E. Run SPLASH for the full sailing matrix at wind speeds of 6, 12, 18, and 24 knots and wind angles of 40, 60, 90, 120, and 170 degrees. Include yaw angles of 0, 3, and 5 degrees and rudder angles of 0, 3, and 6 degrees.
3. Experimental Data Analysis
   A. Export experimental data to a custom VPP based on PCSail. Replace the parametrically estimated lift and drag values with measured values.
   B. Export updated lines to a hydrostatic program to obtain the static righting moment.
   C. Use the SPLASH data in the custom-VPP and run the full polar prediction.
   D. Fit the SPLASH data to the custom parametric VPP and create a least-squares regression to update the accuracy of the parametric VPP
4. Design Revisions
   A. With the custom VPP, make small design changes.
      i. Modify the sail areas to maximize boat speed for the desired sailing conditions.
      ii. Evaluate high pressure and large vortex regions on the appendages in SPLASH and create modified appendages.
   B. Run SPLASH appendage predictions until satisfied the upwind and downwind performance.
   C. Utilize SPLASH for testing upwind and downwind conditions at yaw angles of 0, 3, and 5 degrees with rudder angles of 0, 3, and 6 degrees.
   D. Run VPP predictions from updated SPLASH appendage data.
5. Design Finalization
   A. Obtain the final EHP and final engine selection from the SPLASH upright predictions.
   B. Run VPP predictions from finalized SPLASH sailing data until satisfied by the predicted aerodynamic performance.
   C. Assemble matrix of mast rake and trim predictions.
   D. Provide the resistance data, rig and trim predictions, and righting moment curve to a sailmaker for evaluation in an aerodynamic CFD program.
   E. If needed, reevaluate the performance and potential rating using the updated sail coefficients.
   F. Generate the final hull lines and assemble the predicted aerodynamic forces for the structural and construction design phase.

By using this performance-based design process in the design spiral, the predicted performance is maximized by varying the hull, the appendages, and the sails in an efficient manner. Through utilizing the strengths of each component of the performance design process, the predicted error is minimized. Further, because the experimental elements of the process have been shown to correlate well to other prediction methods, validation tests of the components are not required unless the hull shape deviates significantly from those used to develop the process.

Ultimately, while performance prediction remains a process of extrapolation to the full-scale, the methods used in prediction will continue to change as theories improve and technology evolves. Additionally, the procedure is amenable to changes to suit different budgets. For instance, a combination of FKS and PCSail would represent a significant increase in accuracy without a significant increase in cost over just using a VPP.

Custom VPP

Having the hydrodynamic data acquired from multiple sources, the two missing components of a VPP were aerodynamic data and a solver. Because of its ability to show internal results and generate plots useful in evaluating the code, Microsoft Excel was chosen as the platform to handle the code.

Acquired data from tank testing, FKS, and SPLASH were stored in a worksheet, and most of the code was written in Visual Basic as well as cell functions in the spreadsheet.

As in PCSail and IMS, the aerodynamic data was calculated using the Hazen method. For the Mk II Navy 44 these variables were in the predicted IMS certificate. Each sail has its own coefficients; however, interaction between the headsail and the mainsail is neglected and becomes a source of uncertainty in the results. For the mainsail, curve fit functions were created to turn the predictions into a usable form for the VPP code. Figure 15 shows how both lift and parasitic drag vary as a function of apparent wind angle. (Claughton, 1999)

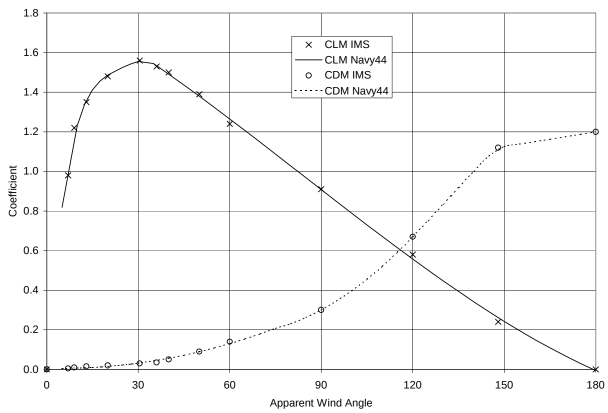

Fig. 15 – Mainsail lift and parasitic drag coefficients

The coefficients of lift and parasitic drag for the jib are presented in Figure 16. With the wind aft of 100 degrees the jib was assumed to be blanketed by the main and would be replaced by a spinnaker. (Claughton, 1999)

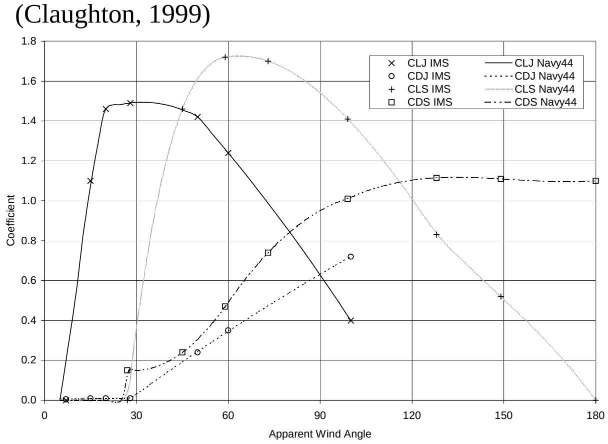

Fig. 16 – Headsail lift and parasitic drag coefficients

To calculate the total aerodynamic forces, a few corrections were made. To address overpowering as the wind increased, the "flat" and "reef" adjustments were added to prevent heel that would cause deck immersion. Vertical wind shear was calculated using Milgram's logarithmic function (Martin, 2001). The vertical and longitudinal centers of effort of each sail were calculated using approximations. For the mainsail and jib, the vertical center of effort was 39 percent from the bottom of the sail assuming the sail is semi-triangular in shape. The vertical center of effort of the spinnaker (CE_{sz}) uses a calculation also similar to the mainsail. Because of the shape of the spinnaker, the center of effort was assumed to be 50 percent from the bottom of the sail. (Marchaj, 1988)

The longitudinal centers of effort of each sail were estimated to provide the yaw moment arms. For a triangular three-dimensional foil under typical sailing conditions, the longitudinal center of effort can be approximated from Figure 17 (Marchaj, 1988).

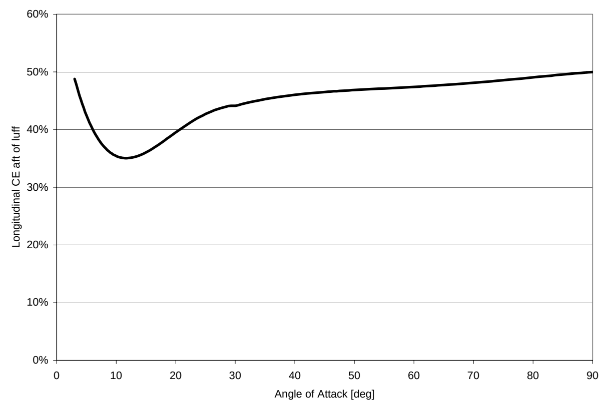

Fig. 17 – Center of effort for a three-dimensional triangular foil with moderate camber

Hydrodynamic and Aerodynamic Solution

Since both the aerodynamic and hydrodynamic forces could now be calculated, a solution was needed to balance the forces and moments. Model data was converted to full-scale using the Froude hypothesis. The viscous prediction using the 1957 ITTC friction equation and the form factor from the tank was used for both the tank data and for SPLASH.

The VPP was set to determine the maximum speed for reaching conditions and the maximum VMG for beating and running conditions. Initially, the built-in SOLVER function in Excel was used. By holding the solver to the requirements that the four equilibrium equations must not exceed 0.05% error, one variable, maxspeed, could be maximized. Items changed were boat speed, yaw angle, heel angle, rudder angle, reef, and flat. While some results were acceptable, the inability to constrain the SOLVER resulted in predictions which were generally unreasonable. The SOLVER was very sensitive to small dips in the drag curve for a given heel angle. In its rounding, the SOLVER would therefore predict the same heel angle for a large speed range. Finally, with four sets of equations as well as large matrices of data used for interpolation, the SOLVER was very slow.

A new method was created which used circular functions in Excel. All four equilibrium conditions produced a set of four simultaneous equations. By breaking the equations into their hydrodynamic and aerodynamic components, a matrix could be formed which represented the equations. The four tank data equilibrium equations in matrix form are shown in Eqn 1.

$$\left[\begin{array}{cccc|c} resistance & 0 & 0 & 0 & Drive \\ 0 & -Liftfwd\cdot\lambda^4\cdot\frac{1}{2}Draft_{keel} & -Liftaft\cdot\lambda^4\cdot\frac{1}{2}Draft_{rud} & RM(\Phi) & HeelMoment \\ 0 & Liftfwd\cdot\lambda^3 & Liftaft\cdot\lambda^3 & 0 & Sideforce \\ 0 & 0 & Liftaft\cdot Arm\cdot\lambda^3 & 0 & YawMoment \end{array}\right] \quad (1)$$

By taking the matrix multiplication of the inverse hydrodynamic matrix with the aerodynamic matrix, an equilibrium solution matrix was formed. Similarly, the solution for the SPLASH data represented the factors by which resistance, righting moment, lift, and yawing moment should change.

Four simplifications were made in the iterative approach. First, resistance was assumed to be a function mostly of velocity. Secondly, righting moment was assumed as a function of heel angle. For the tank data, Fwd-lift was assumed as a function of yaw, and aft-lift was assumed as a function of rudder angle. For the SPLASH data, lift was assumed as a function of yaw, and yawing moment as a function of rudder angle. By modifying these four variables by small amounts, the spreadsheet iterated to a solution. Each condition took at most five seconds to solve.

Step size was an important consideration. Large steps would cause divergence beyond the acceptable tolerance. The problem with setting the steps too small, however, was that the program could take hours. The solution was to automatically reduce the step size per the number of iterations. If the solution diverged, it would automatically reset and start again at a new initial position with a smaller step size.

After many trials with the new VPP, it was found that the rudder angle was not always correctly predicted. This was due to the estimated longitudinal aerodynamic center of effort. While this calculation approximated the center of effort for moderate wind speeds and close-hauled angles, the approximation broke down as reef and flat changed the shape and size of the sail. Additionally, mast rake and other sail controls can significantly change the aerodynamic yawing moment of the boat without much loss of boat speed. The solution was that this fourth equilibrium condition was temporarily taken out of the solver. Instead, the rudder position was set at 0 degrees while reef and flat iterated. Once a final sail solution was found, the rudder angle would iterate between 0 and 6 degrees to maximize VMG. The Yaw-moment imbalance has plagued researchers and has not yet been adequately solved. This partial solution improves the process by providing the mast rake value for a balanced helm.

VPP Prediction Summary

Polar diagrams are plots in which boat speed is a function of true wind angle for a given wind speed. The 6-knot wind speed polar diagram (Fig. 18) showed the most deviation between each prediction method for a given wind speed. Still, the average deviation was within 0.19 knots (~4%). SPLASH showed results which were very consistent with the IMS predictions with an average deviation of less than 0.08 knots (~1.6%). Due to questions over laminar flow on the small models, the tank results were the most suspect.

The 12-knot wind speed data (Fig. 19) showed excellent correlation for all methods. The deviation was less than 0.08 knots (~1%). The results at this wind speed were significant in that 12-knots true wind speed is the normal wind speed the Mk II Navy 44 STC will see.

At 16-knots true wind (Fig. 20) all methods also predicted very similar results upwind (45-60 degrees). However, as the boat turned downwind, SPLASH predicted lower boat speeds. At the higher speed range, SPLASH and tank testing predicted velocities an average of 0.14 knots lower than the IMS. Since the SPLASH and tank VPPs solved the yaw balance, this error was thought to be in the IMS VPP since it did not calculate the induced drag effects of the modified lifting surface angles. The average deviation for the methods was less than 0.10 knots (~1.3%).

At 20-knots, the tank and SPLASH VPPs continued to predict boat speeds generally lower than the IMS VPP (Fig. 21). The lower boat speed of SPLASH as compared to tank testing near beam-reaching angles (85-105 degrees) again reflects the differences in the viscous calculations used by both methods.

While PCSail showed minimal deviation with the IMS prediction for downwind courses, PCSail overestimated boat speed in close-reaching conditions (65-85 degrees). Figure 22 shows the final overall polar using a best-fit between SPLASH and tank testing.

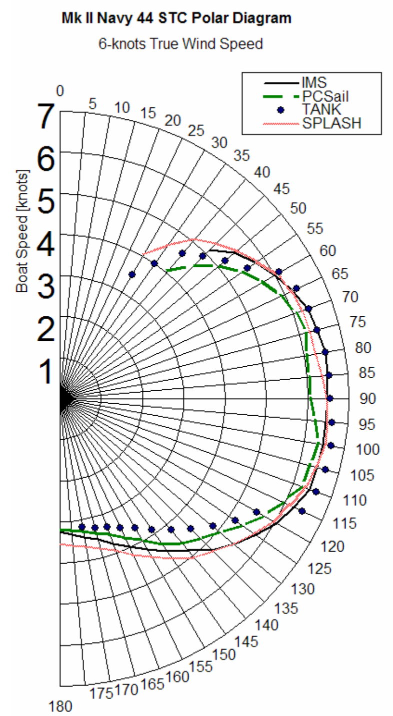

Fig. 18 – Polar diagram for 6 knots true wind

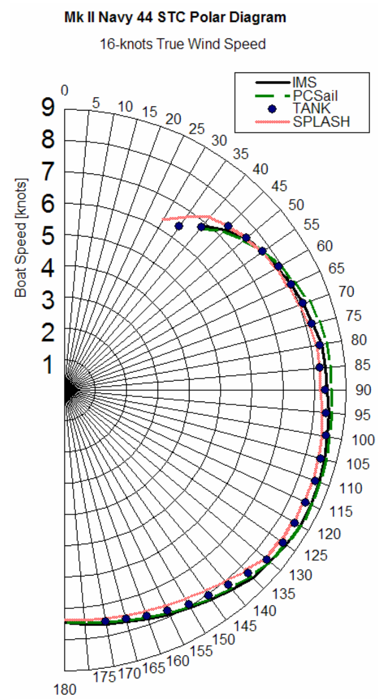

Fig. 20 – Polar diagram for 16 knots true wind

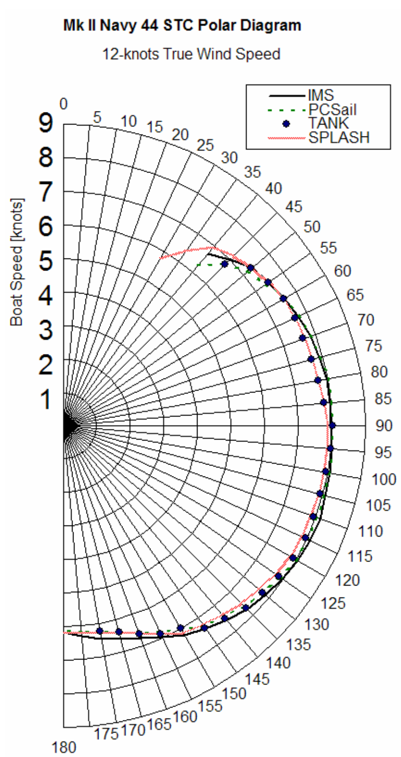

Fig. 19 – Polar diagram for 12 knots true wind

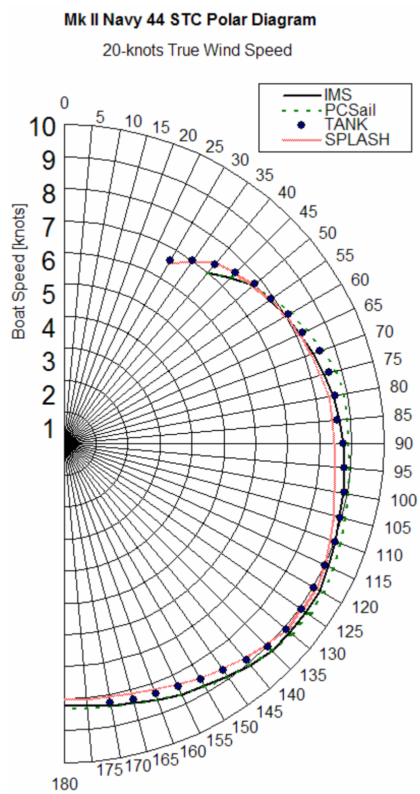

Fig. 21 – Polar diagram for 20 knots true wind

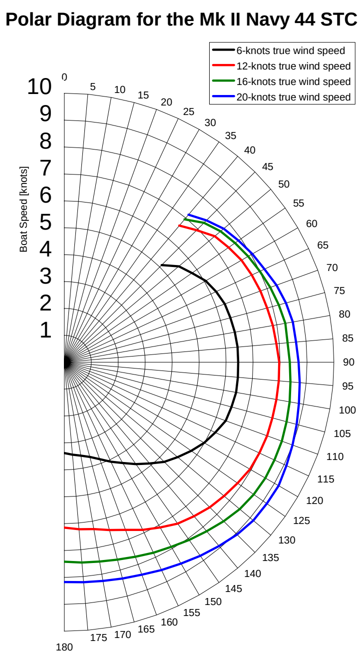

Fig. 22 – Polar Diagram for Mk II Navy 44 STC

Design Revisions

The VPP can be used as a baseline for potential modifications. As the VPP is composed of hydrodynamic and aerodynamic sources, it is easy to explore aerodynamic modifications. Focusing on upwind and downwind VMG, the VPP was optimized for a windward-leeward racecourse. From these two processes, boat speed was decomposed into seconds-per-mile for each leg and various rig modifications were investigated. Figure 23 for example, shows the effect of increasing sail area by increasing the mast height 5 feet. A dramatic speed improvement is seen in the lower wind speeds of 6 and 12 knots of true wind. However, when going to windward in heavier conditions, performance falls off due to the lack of stability and increased aerodynamic drag.

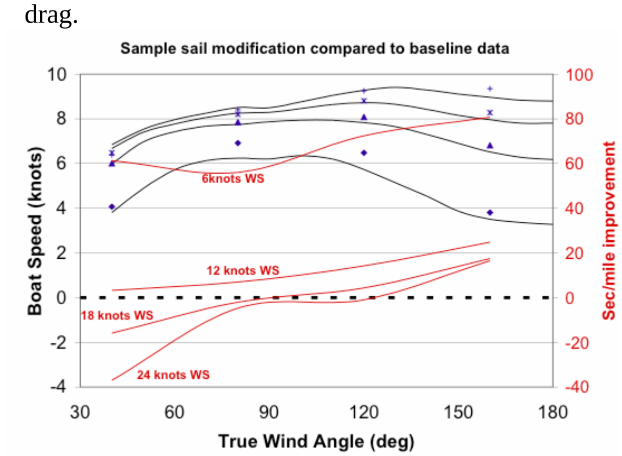

Fig. 23 – Sample Sail Modification Results

Hydrodynamic modifications require more effort. Using the tested baseline, small perturbations from the hull shape and appendages can be explored using parametric analysis with some confidence. Larger deviations would require new model testing or CFD. A combined tank and CFD rudder study was performed in this study but will be reported in a separate paper.

All three performance prediction methods tested in this study produced results acceptable for most sail craft design. While parametric analysis using programs such as PCSail produce inexpensive results, increasing accuracy could be achieved (in order) through the additional use of FKS, tank testing and CFD. Combining the methods produced a composite prediction that addressed the limitations of each method. Depending on the level of accuracy needed, a designer could select a particular approach that best suits their needs and budget.

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