Design Optimization for the International America's Cup Class

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Claudio Fassardi
Jacobs Engineering Group Inc

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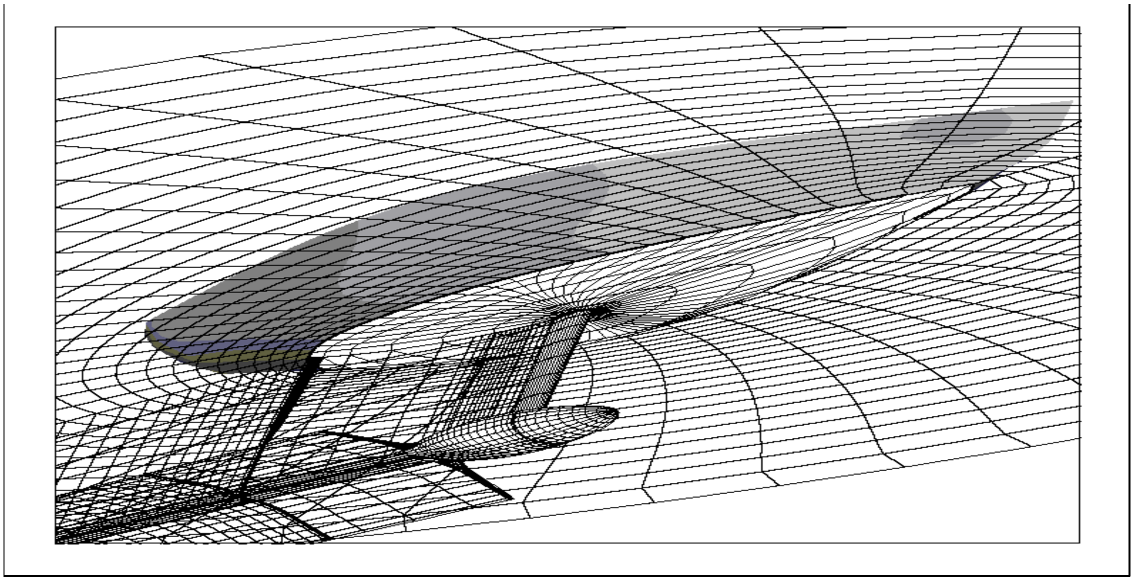
Frank DeBord, Jr., (M), BMT Scientific Marine Services, **John Reichel,** (M), Reichel-Pugh Yacht Design, **Bruce Rosen,** (M), South Bay Simulations, and **Claudio Fassardi,** (M), BMT Scientific Marine Services



ABSTRACT

Since the introduction of the International America's Cup Class for the 1992 America's Cup, more than sixty-five yachts have been designed to the class rule, and most of these have raced for the opportunity to either challenge or defend the America's Cup. The relatively large differences in performance exhibited by these boats illustrate the complexity of the design optimization problem. This paper defines the design problem from a practical Naval Architecture standpoint, reviews engineering methods currently employed to evaluate design trade-offs, and provides insight into how the various analytical and experimental tools available to the designer are used. Constraints of the class rule are analyzed in terms of general limitations and specified quantitative relationships between the major design parameters. Methods used to select major design parameters, including the designer's experience and use of velocity prediction programs are discussed, and limitations of these techniques are identified. Experimental and analytic techniques typically used to provide engineering data for the designer, and to generate input for performance modeling, are reviewed. The experimental techniques considered include tank tests, wind tunnel tests and full-scale testing. Analytic techniques include potential and viscous flow methods for evaluating hydrodynamic drag and lift, wave making drag, and seakeeping performance. The current state-of-the-art for each of these techniques is discussed, their applicability and limitations are reviewed, and specific examples of their use are provided. Finally, recommendations are formulated on how these various design tools and techniques should be used together in an integrated design program to optimize performance.

NOMENCLATURE

A, B, C	Fit coefficients
a	Wave amplitude
Bwl	Waterline beam
DSP	Displacement (m^3)
g	Acceleration of gravity
J	Base of foretriangle measurement
L	Rated length (m)
LBG	Length between girth stations (m)
LM	Measured length (m)
Lwl	Waterline length
Raw	Added resistance in waves
rho	Mass density of seawater
S	Rated sail area (m^2)
SM	Measured sail area (m^2)
Vmg	Velocity made good
V_S	Boat speed
V_T	True wind speed

INTRODUCTION

The International America's Cup Class (IACC) Rule [1] was developed specifically "to produce wholesome day sailing monohulls of similar performance while fostering design developments that will flow through to the mainstream of yachting….". A committee of designers and prospective owners, using the designers' experience and the performance prediction technology available at the time, developed the Rule prior to the 1992 America's Cup. The result was a "box-type" rating rule where sail area, displacement, and length can be varied within a specified formula, and certain overall limits. The Rule was first used during America's Cup XXVIII, held in San Diego, California and has been used for all subsequent America's Cup matches.

From the designers' standpoint, the key phrases in the above quote are "of similar performance" and "while fostering design development." In essence, these two phrases mean that the designer has the freedom to try to maximize performance *within limits*. The engineering problem can be stated as "minimize the time required to sail around the America's Cup race course, in the wind and sea conditions that will be present, within the limitations of the America's Cup Class Rule."

This paper is intended to provide insight into how the Naval Architecture portion of this design problem can be approached. It includes an analysis of the Rule, a brief discussion of the factors that affect sailing yacht performance, and a process that can be used to optimize a design to a specified set of wind and sea conditions. The application of various design tools used in the process, and their limitations are illustrated. Where possible, specific results are included to illustrate the key points, and application of these tools to other types of Naval Architecture design problems are discussed.

AMERICA'S CUP CLASS RULE

The IACC Rule presents a trade off between displacement, sail area, and length with a maximum rating equal to 24 m. The base formula is as follows:

$$(L + 1.25S^{0.5} - 9.8DSP^{0.33})/0.679 = 24m \quad (1)$$

Sail Area

Measured sail area (SM) is a measure of the actual upwind sail area in square meters, and includes the mainsail area plus the foretriangle area. Since all mainsail, genoa and spinnaker heights should be fixed at the class maximums, variations in sail areas are obtained by stretching the sail plan in the longitudinal direction only. This is accomplished by varying the J dimension (the distance from the headstay/deck intersection to the front side of the mast) and/or the boom and mainsail girth dimensions. Maximum spinnaker size is 1.5*SM and the maximum spinnaker pole length is 1.35*J.

Rated sail area in equation (1) is a function of SM; if SM exceeds a base value the Rule uses a rated sail area (S) greater than the measured sail area (SM), thus applying a penalty or "soft" limit on sail area.

Displacement

Displacement is the actual weight of the boat in measurement trim. The Rule defines measurement trim, providing a list of items that must be on board and restrictions on what cannot be on board. Sails and crew members are not included. The boat is simply lifted and weighed using a load cell. Displacement (DSP) is the weight in kilograms divided by 1.025. The boats are generally between 16,000 and 25,000 kilograms. Outside of this range a displacement penalty is applied.

Length

Rated length (L) is perhaps the most complex variable in the Rule formula. This complexity is caused by the fact that the Rule attempts to measure the overhangs and fullness of the hull at both ends, since these parameters have a major influence on the actual sailing length, and thus resistance. Measured length (LM) is a measure of the static length in measurement trim, plus the slopes of the overhangs and the fore and aft girths. The length between girths (LBG) is measured between the fore and aft intersections of the hull's centerline profile with a plane 200 mm above the floatation plane. The girths at these locations are also measured. If the fore and aft girths are at or below the specified base values, LM = LBG + 1.9 m. If the girths exceed the base values an addition is made to LM.

In equation (1), L is a function of LM; if LM exceeds a base value the Rule uses a rated length (L) greater than LM. Again, this approach applies a "soft" limit on length, including overhangs and girths.

Other penalties for excessive draft, maximum beam, minimum freeboard, and displacement outside the range given above, are added directly to rated length. These penalties have multipliers that are applied, making them very expensive, and are thus referred to as "hard" limits.

Other Restrictions

If the maximum beam is greater than 5.5 m a beam penalty is applied. All of the existing boats are well below this value so this beam penalty is not restrictive. The freeboards must be at least the base values to avoid the freeboard penalty. Maximum draft without penalty is 4.0 m, and no hollows can exist in the hull surface. Movable ballast, including water ballast is not permitted and over the years, a number of restrictions have been placed on the design of appendages and control surfaces. In addition, the hull structure must be designed to certain minimum standards and the minimum weight of the mast and rigging is limited.

Figure 1 shows the IACC "Playing Field" or design space. For any given displacement and measured length, the required measured sail area to rate at the class limit (24 m) is shown by the curves of constant sail area (SM). At both ends of the LM range it can be seen that each increment of LM becomes more expensive in terms of sail area to achieve the maximum rating. This is effectively a soft limit on length.

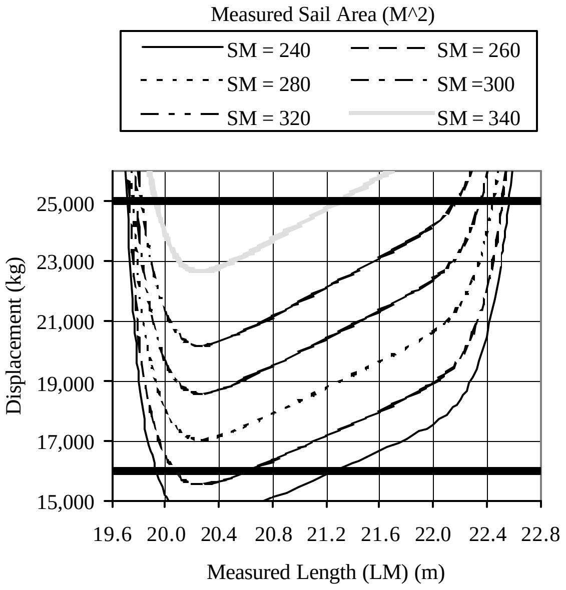


Figure 1 – IACC Rule Design Space

Maximizing performance on a given race course and for the expected wind and sea conditions is the goal. Finding the correct location on the playing field is one of the critical decisions. Other features that would normally be investigated would include beam (trading a narrow low wetted surface form for a wider higher stability form), flair, fore and aft profile slopes, longitudinal center buoyancy position, prismatic coefficient, waterplane coefficient, and any of the variety of other form coefficients. In essence, for a given displacement and length the designer is free to shape any hollow-free hull without rule restriction.

THE DESIGN PROBLEM

Like most engineering problems, sailing yacht performance optimization is basically evaluation of a series of trade-offs. These are constrained by the limitations of the Rule. Given the basic objective to maximize speed, the two key parameters are thrust and drag. In the case of a motor yacht or ship the problem would simplify to minimizing drag, maximizing installed power and maximizing propulsive efficiency, within the constraints of required dimensions, displacement and cost.

For a sailing yacht this problem is somewhat more complex. The sails generate thrust. However, for the upwind and reaching cases, thrust generation is limited not only by the size and efficiency of the sails, but also by the ability of the design to convert total sail force to forward thrust. This is affected by the transverse stability of the design and its capability to generate the side force necessary to counteract sail side force. In essence, the combination of sail area and stability equates to horsepower, and the efficiency generating side force to counteract sail side force is somewhat analogous to propulsive efficiency. In general, drag is also highly dependent on form stability and the efficiency of the appendage lifting surfaces used to generate side force. Therefore, the design trade-offs for a sailing yacht are quite a bit more complex than they are for a motor yacht or ship. Added to this increased complexity are the constraints of the Rule.

When considering performance around the race course, these trade-offs are further complicated by the fact that performance both upwind and downwind are important, and certain design parameters are beneficial in one mode and detrimental in the other.

DESIGN PROCESS

When the Rule was first used for the 1992 America's Cup, designers had no direct experience optimizing their designs to it. They were forced to use their related experience and existing performance prediction tools to find a starting point for optimization.

Most designers completed an initial exploration of the design space by designing candidate boats that fit within the Rule and then comparing the performance potential of these candidates. Two methods were available to evaluate the candidates, including analysis of basic design parameters and Velocity Prediction Programs (VPPs).

Variation of design parameters such as displacement to length, sail area to wetted area and sail area to displacement ratios could be used, combined with the designers' experience, to assess how variations within the Rule design space might compare. Figure 2 is an example of this type of analysis, focused on evaluating performance potential in light wind. Similar analyses can be done for other design variables to assess performance potential of parametric variations within the Rule design space.

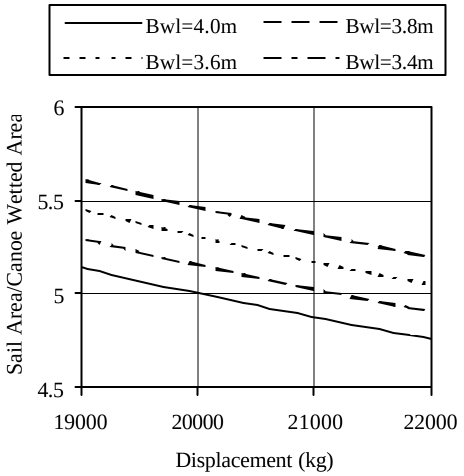


Figure 2 – Sail Area to Wetted Area versus Displacement for Constant Sail Area and Different Waterline Beams

Use of VPPs for initial parametric analyses was somewhat limited because several of these programs were used to develop the Rule formula. If the same VPP that was used to develop the formula was used to evaluate variations in principal characteristics of length and displacement, results would ideally have shown equal performance potential for all variations of these parameters within the Rule design space. However, different design offices were using different VPPs, some of which had been "tuned" to actual performance data for other types of yachts. Therefore, the exercise of exploring the Rule design space with these tools provided some insights into performance potential to differing degrees (a detailed description of how VPPs can be used is given in later sections).

Twenty-eight hull numbers were issued for the 1992 America's Cup and most of these boats were built and sailed in San Diego. The fleet included a range of displacements, lengths, sail areas and other principal characteristics, and at the conclusion of racing it was obvious which sets of characteristics exhibited the best performance in San Diego conditions. At this point, designers had a much better idea of where to start when developing designs for subsequent events.

The design process, as discussed here, assumes that a designer with some experience in the class and knowledge of the results of previous America's Cups is tasked with developing a new design for a new set of wind and sea conditions. The Naval Architecture portion of this task includes design of a new hull and new appendages. The process is similar to most rational engineering projects in that it would include the following steps:

1. Specify the design problem.
2. Define the state-of-the-art.
3. Identify and prioritize potential areas for improvement.
4. Develop design candidates.
5. Evaluate candidates.

As shown in Figure 3, these steps are an iterative process, where knowledge gained from evaluation of candidates is fed back to Steps 3 and 4 and the evaluation is repeated. In addition, during the process, tools used to evaluate candidate designs are refined and improved.

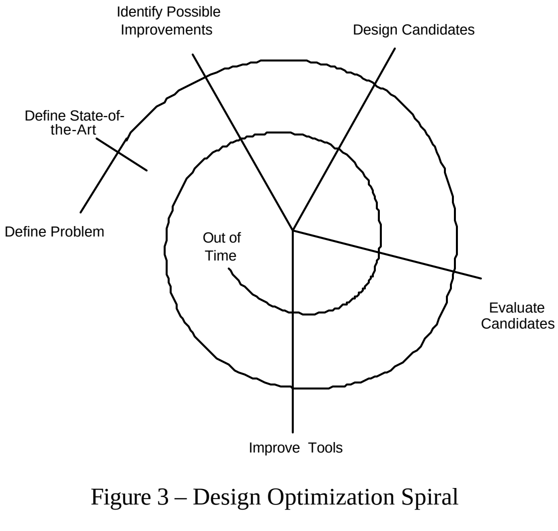


Figure 3 – Design Optimization Spiral

Specification of the design problem includes understanding the Rule in its latest version, definition of the race course(s) to be sailed, and definition of the wind and sea conditions expected during competition. The owner may have some additional special requirements such as weighting upwind performance more than downwind performance, or a willingness to sacrifice some straight-line speed for maneuverability.

Ideally, wind and sea conditions would be specified as distributions of wind speed versus frequency of occurrence, such that candidate designs can be evaluated on a probabilistic basis. If sufficient data is available, these distributions could be developed for each phase of the competition, e.g., Round Robins, Semi-Finals, Finals and America's Cup, since racing takes place over several months. To be meaningful, development of these types of weather data requires a significant amount of historical data, and in some cases this is not available. In reality, a number of design efforts use average wind strength, a typical range of variation in this wind strength and perhaps how these vary with time over the period of racing.

In most cases, definition of the state-of-the-art consists of developing a baseline design believed to be representative of the winner from the previous series and/or the best previous design developed by the design team working on the current project. Typically, use of a good boat with available design information and known performance as compared to the winner is a better choice than estimation of the winner's design characteristics from photographs. This is due to the fact that performance differences and the associated hull form differences can be relatively small, and any errors in estimating hull shape could be misleading.

Once the baseline is defined, the first set of design variations can be formulated. These are typically identified based on one or more off the following:

1. Observation of design features that appeared to be beneficial during the previous series.
2. Analysis of design changes that should be suitable for a new set of wind and sea conditions.
3. Incorporation of design ideas developed subsequent to construction of the last boat designed for the previous event.
4. Experience gained during full-scale testing and racing for the previous event, and improvements to design evaluation tools based on actual sailing data from the previous event.

Given a prioritized set of design features to be investigated during the first cycle, candidate designs are developed that incorporate these features. Typically, it is best, at least early on in the process, to vary one feature at a time to the extent possible. Also, in the authors' opinion, it is critical that all design candidates are designed as legal America's Cup Class yachts, including appendages sized and located for the required flotation. During the process of prioritizing candidates, the construction schedule must be kept in mind to insure that the maximum amount of available time can be used for optimization of parts that have to be built first, such as hulls.

Evaluation of the candidate designs is the most important and most difficult step in the design process. Unlike ships or motor yachts, where speed is a relatively simple function of hull resistance, propulsive efficiency and installed power, sailing yacht performance is dependent on sail thrust and side force, stability, and hull/appendage resistance at the side force required to counteract sail side force. At steady state, the sailing yacht assumes a speed, heel angle, leeway angle and rudder angle combination that results in equilibrium between the aerodynamic and hydrodynamic forces. Performance prediction requires a solution for these equilibrium conditions based on knowledge of all forces and moments acting on the yacht, for each wind speed and relative wind angle to be considered.

The Velocity Prediction Program, in its various forms, has become the method most used to compare the performance of candidate design variations. However, as discussed in the following paragraphs, these programs rely on input data from a number of different sources including empirical and semi-empirical relationships, experimental results and results of sophisticated analysis techniques. The VPPs are merely tools used to find the equilibrium sailing conditions, and without accurate input data from these other sources, they are virtually useless. Figure 4 illustrates how information from these other sources feeds into the VPP. Note that in all cases, multiple sources of information are available to define the same parameters.

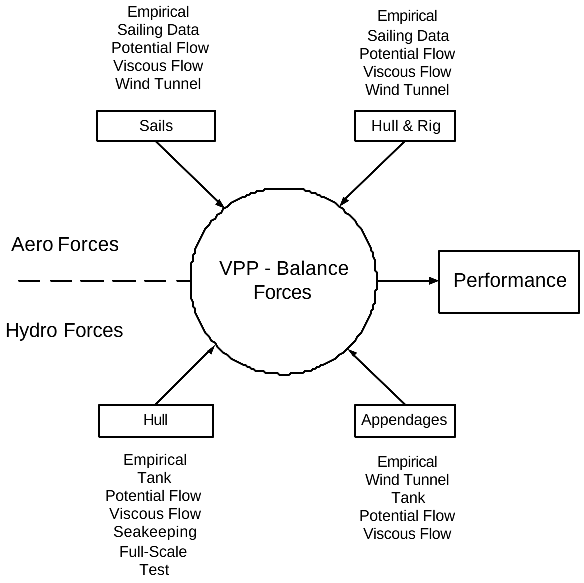


Figure 4 – Summary of VPP Inputs

Once the required input data is computed for the design candidates, and the VPP is run to compare racecourse performance for these candidates, results are evaluated and ideas for design candidates for the next iteration are formulated. Results, as shown in Figure 5, are analyzed in an attempt to determine which design features are most promising for further development and which should be discarded. This figure shows speed differences, in seconds per mile, between the candidates and the baseline design around the entire racecourse, versus wind speed. Time differences between candidates are used in the figure so that small differences can be seen. When a candidate has positive seconds per mile difference, it is slower than the baseline boat. Note that a critical part of this process is comparison of results from the different sources of information, assessment of the limitations of each source for the particular design feature under consideration, and interpretation of results with full knowledge of these limitations.

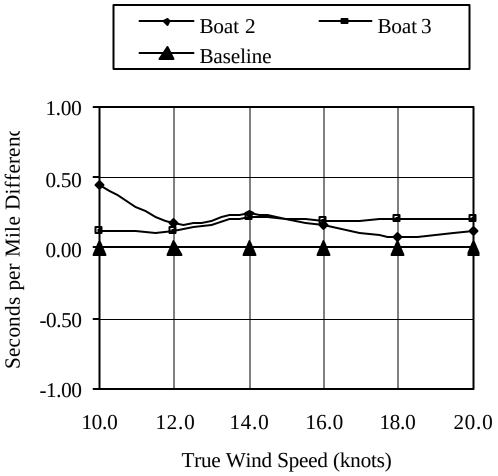


Figure 5 – Example VPP Comparison of Two Design Candidates to a Baseline Design

The final step shown in Figure 3 that is critical to the overall success of the design process, is continued evaluation and improvement of the tools used to compare design candidates. All sources of information that input to the VPP, and the VPP itself, must be continuously scrutinized and questioned. The availability of multiple sources of data should be used to verify predictions in cases where results from each source compare favorably, and to raise flags regarding the validity of the predictions when they produce conflicting results. In order to insure that the process is successful, the designer's engineering judgment (experience) must be respected, and all available information should be used in a knowledgeable way to try and minimize the possibility that flawed design tools will cause the design process to go astray.

The discussions presented in the following sections of this paper attempt to emphasize this last point by illustrating the limitations of the tools typically used to evaluate candidate designs. In addition, areas where these tools can be used to check results are identified. Perhaps the most important point to be made regarding the design process is that there is no single method of performance evaluation, such as large scale tank tests or a specific numerical optimization scheme, that will reliably lead the design team to an optimum solution. The key to a successful program is intelligent use of the available tools and sound engineering judgment.

As a final point, note that the design spiral shown in Figure 3 ends at the point labeled "out of time". Although funding, personnel or other resources may be limited, it is usually time that governs the number of iterations that can be completed in the design optimization process.

VELOCITY PREDICTION PROGRAMS

A method to solve for the equilibrium conditions for a yacht sailing upwind was first published by Davidson [2][3]. The method consisted of measuring the resistance, side force and heeling moment for a model yacht tested over a parametric range of speeds, heel angles and leeway angles, and then solving for the equilibrium conditions using this hydrodynamic force data combined with a simple set of non-dimensional sail forces. The method is based on determining the side force (due to leeway angle) where the heeling moment due to the sails is equal to the righting moment, for each speed and heel angle tested. Given a sufficient number of tested heel angles and speeds, optimum upwind performance could then be computed for a range of wind speeds.

Since completion of the Irving Pratt Project at MIT in the 1970's [4], the Velocity Prediction Program has become the preferred approach for determining equilibrium-operating conditions for a sailing yacht. Several of these programs (for example FastYacht [5] and WinVPP [6]) have been commercially available for some time and various design offices and consultants have developed a number of proprietary derivatives. In addition, the VPP developed during the Pratt Project formed the basis for the Measurement Handicap System (MHS) and International Measurement System (IMS) rules used to handicap racing yachts.

All of the Velocity Prediction Programs mentioned above solve for equilibrium operating conditions of a sailing yacht by finding a set of conditions where aerodynamic forces are equal to hydrodynamic forces. For a given wind speed and true wind angle, an iterative process is used to find the heel angle, leeway angle and speed where the sum of these forces is zero. To complete this process, the following relationships must be specified:

1. Aerodynamic thrust, side force and overturning moment versus apparent wind speed, apparent wind angle and heel angle.
2. Hull righting moment versus heel angle.
3. Hydrodynamic drag and overturning moment versus heel angle, side force and boat speed.

In it's simplest form, the VPP could get this information from other sources, and merely serve as an equilibrium solver. However, to improve their utility to designers, most VPPs provide methods to calculate these relationships internally, with options to permit the user to input certain data from outside sources. When the programs are run based on internally calculated forces, these forces are usually computed based on first principles, empirical results from systematic experiments, or experience gained with a relatively large set of actual sailing performance data. Examples of specific data from outside sources that might be used include tank test results, wind tunnel test results and results from various computational methods.

In the context of optimization of IACC designs, there are two very separate possible uses of Velocity Prediction Programs:

1. Screening of principal characteristics during preliminary design using internally calculated forces.
2. Evaluation of candidate designs during the design optimization process discussed in the previous section.

In the first case, the force calculation methods internal to the VPP can be used to provide an initial look at what areas of the Rule design space might show the most promise for a given set of wind conditions. For the commercially available VPPs, this analysis is limited to very preliminary screenings due to the way forces are computed internally. These calculation methods were developed to handle a wide range of sailing yacht configurations and sizes, and they were implemented with relatively simple algorithms to compute forces based on rig and hull characteristics. Therefore, they are not appropriate for comparing candidate designs with relatively small differences in hull form or principal characteristics.

To illustrate this point, Figures 6 and 7 give comparisons of upright drag and upwind speed differences for two IACC yachts using hydrodynamic forces calculated internally by WinVPP [6] and results from large-scale tank tests. The speed predictions are based on identical aerodynamic models, as calculated by the VPP internally. In general, the VPP-calculated forces are remarkably good. In terms of both drag and upwind speed, results based on VPP forces rank the two boats the same as results based on the large-scale tank test. In addition, the boat-to-boat differences from the two methods are roughly the same. However, closer inspection of Figures 6 and 7 illustrates why the internally generated forces from the VPP cannot be used to optimize a design.

The drag predictions given in Figure 6 from both sources indicate that Boat A has significantly higher drag than Boat B throughout the range of typical sailing speeds. At a boat speed of 9.5 knots, the VPP predicts that the drag of Boat B is 2.5 % lower than Boat A, while the tank predicts a drag difference of almost 5% at this same speed. It must be noted that for illustration purposes, the two boats used in the example have very different hull forms. For the situation where very small design changes are being evaluated, as is usually the case during final optimization, these types of differences in the relative drag between two boats would be much smaller.

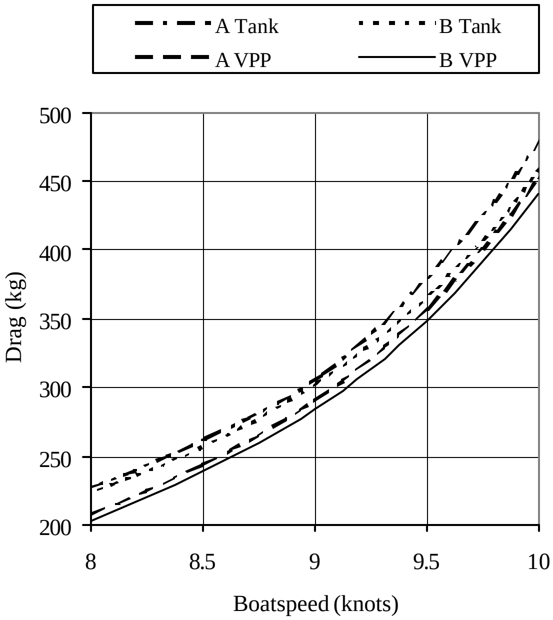


Figure 6 – Upright Drag Comparison for Two Boats from Tank and WinVPP

Speed predictions shown in Figure 7 show a similar result. The baseline boat in this figure is Boat A using tank data. For a true wind speed of 12 knots, the prediction based on tank data indicates that Boat B is 3.7 seconds per mile slower than Boat A, while the prediction based on internal VPP forces predicts that Boat B is 1.7 seconds per mile slower. Again, from the perspective of preliminary design, the two methods show the same trends and the VPP using internal forces should be very useful when selecting overall characteristics. However, for design optimization, this method is quite limited. In the current example, use of internal forces predicts a time difference around the America's Cup racecourse that is 30 seconds less (50% less) than that predicted by the same VPP using tank forces.

Given the need to use external force data for design optimization problems, the next question is how to input this data to the VPP in a way that will preserve accuracy while insuring that the VPP is able to find solutions. Most VPPs require smooth surfaces of each force as functions of speed, heel and side force (due to leeway), such that the iterative process used to find equilibrium can truly find the conditions where boat speed is maximized for a given wind speed and angle. Internally calculated force data are based on equations that produce continuous, smooth surfaces. However, many external sources of data, such as tank test results, are obtained as discrete data points. Some method must be used to transform these discrete data sets into continuous, smooth surfaces, and the method chosen can influence the ability of the VPP to find equilibrium solutions, and the accuracy of those solutions.

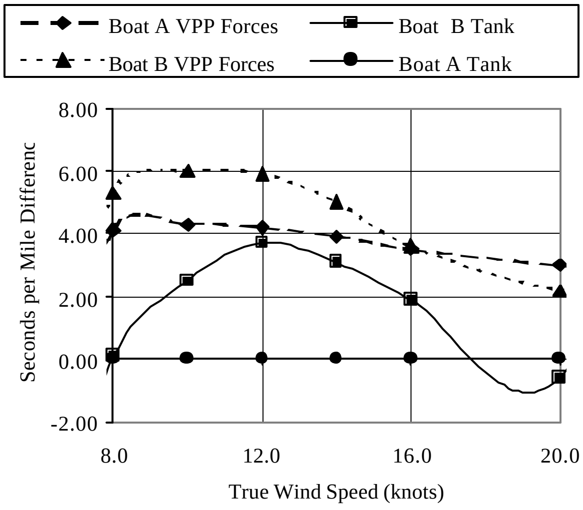


Figure 7 – Upwind Speed Predictions for Two Boats from Tank and VPP Forces

Figure 8 is a very simple illustration of this problem. A spline can be fit through data points such that it passes through every point. However, the amount of tension and end conditions specified for the fit will affect the shape of the spline between data points. A least-squares polynomial will rarely pass through all of the data points (unless the fit order is equal to the number of points) and the shape of the fit between data points is dependent on the fit order and specific values of the data points. This situation is much more complicated than indicated by this example since each force must be represented as a function of heel and side force (or leeway), in addition to boat speed.

The two commercially available VPPs referenced above include methods to input tank data (or discrete hydrodynamic data from other sources) using a spline fit for upright drag and different least-squares regression techniques for incremental drag due to heel and side force and side force versus leeway angle. In addition, a not yet released version of WinVPP has been developed that has the capability to input a set of spline coefficients that specify the complete force surfaces.

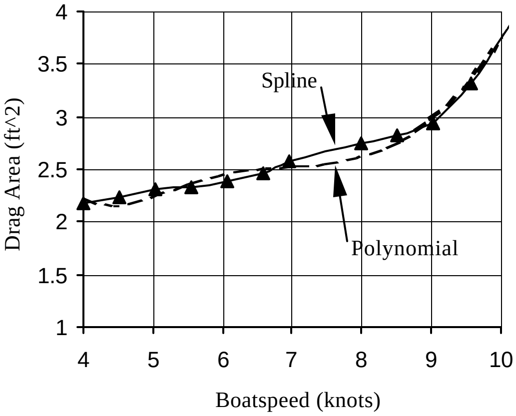


Figure 8 – Upright Drag Area versus Speed from Tank

Figure 9 shows a comparison of upwind speed predictions from the same set of tank data using three different fitting techniques in one of the commercially available VPPs. The baseline in the figure is the method used for the previous examples, which is fitting splines through drag, side force and overturning moment versus speed, heel and yaw. Fit 1 and Fit 2 in the figure are two different least squares techniques that use algorithms with specified forms to fit drag due to heel, induced drag and the relationship between leeway angle and side force. These increments in drag are applied to the upright drag curve to calculate total drag at any given heel angle, boat speed and side force. It is obvious from the figure that the magnitude of the predicted performance differences is significant. Boat-to-boat comparisons using one of these methods may in fact be better than comparisons between the different methods, but the differences shown in the figure should raise serious questions regarding how well the VPP is representing input force relationships. Figure 10 compares upwind speed predictions using tank data for two boats with two different spline fit methodologies.

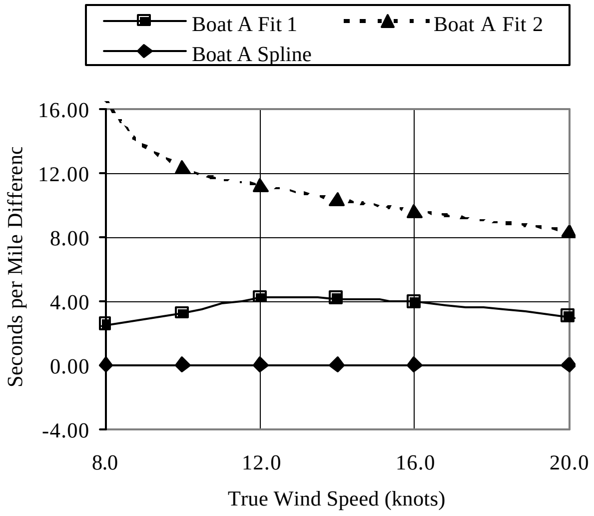


Figure 9 – Comparison of Upwind Speeds for Different Fits to Tank Data (Baseline is Spline Fit)

The basic method consists of fitting splines to forces versus speed and yaw for each heel independently, while the revised method uses spline surfaces across speed, yaw and heel simultaneously. Note that in this figure the base boat is Boat A. The two predictions are more similar than the least squares results shown in the Figure 9, but it is evident that this methodology also requires care when specifying fit parameters, the tension specified for the spline fits and the end conditions.

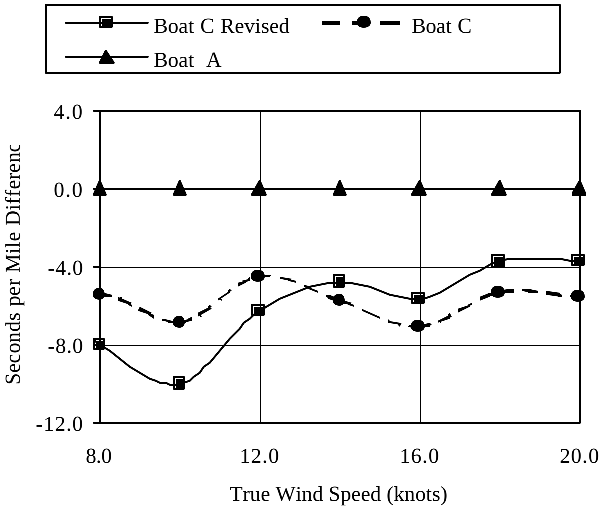


Figure 10 – Comparison of Upwind Speeds for Two Different Spline Fits to Tank Data

The final point relating to the use of VPPs to optimize a design is representation of sail forces. Analysis of sail forces is not within the scope of this paper, since the discussion here is limited to the Naval Architecture part of the design optimization problem. However, an understanding of how sail forces might affect comparisons of different candidate hull and appendage package designs is relevant.

Sail forces in the original Irving Pratt Project VPP [4] were first developed using a combination of aerodynamic theory, and full-scale observations combined with hydrodynamic data from tank tests [7] [8] [9]. Most VPPs in use today rely on a set of sail force coefficients that have evolved from those developed for that project. Typically, sail thrust and side force coefficients are specified versus apparent wind angle, and the types of sails that are in use. In addition, a center of effort for each sail set is calculated. The evolution differs for each commercial and proprietary VPP, but in most cases it has been based on further full-scale sailing data combined with analytic techniques. Some of the proprietary codes have been developed for very specific sail plans (such as IACC yachts), while the commercially available codes have been developed for much more general application.

There are two questions related to sail forces that are relevant to the current discussion. First, is the VPP generating performance predictions that are accurate? Second, and more importantly, does the code accurately predict relative differences between candidate designs? The second question is seemingly more important but it is related to the first one, since a design can be optimized for a very specific range of boat speeds, and the actual operating boat speed is therefore very important. Another issue that is at least as critical is the relationship between sail thrust and side force. This relationship governs the optimum value for hull stability, which is typically increased with an associated drag increase. In the case of IACC yachts, it therefore governs the selection of beam, and can influence the design of the appendage package.

Figure 11 gives optimum upwind boat speeds from full-scale sailing results compared to two different VPP predictions. Both of the predictions use large-scale tank results for hydrodynamic forces. The prediction labeled Default Sails is based on the default sail coefficients for the specific sail plan, from one of the commercially available VPPs. The prediction labeled Tuned Sails was produced after the default sail coefficients were modified to better predict the observed performance for the full-scale boat. Note that the speed differences are quite large, and could be significant when optimizing hull form parameters, such as prismatic coefficient, for a particular operating speed.

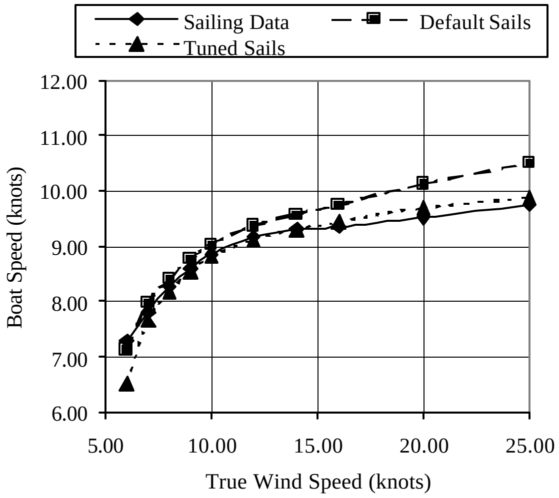


Figure 11 – Actual and Predicted Optimum Upwind Boat Speeds

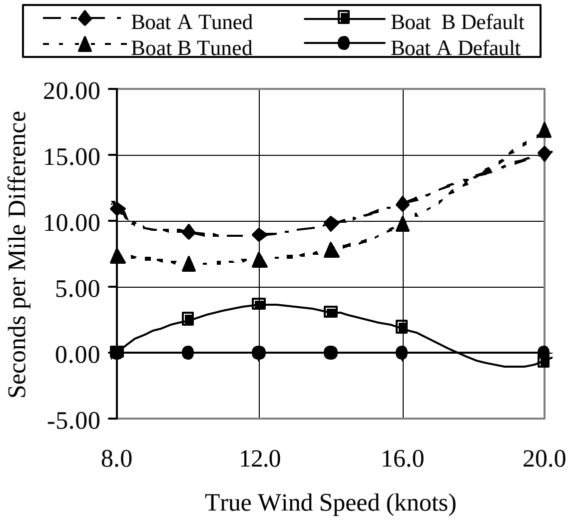


Figure 12 – Upwind Performance Predictions for Two Boats Using Different Sail Coefficients

Figure 12 is an illustration of the second issue discussed above, sail forces affecting the relative performance predictions for candidate designs. The baseline boat in this figure is Boat A with default sail coefficients. Comparison of the seconds per mile for both boats shows the tuned sail coefficient predictions significantly slower than the predictions using default sail coefficients, as indicated in Figure 11. In addition, the default coefficients predict that Boat A is faster upwind while the tuned coefficients indicate that Boat B is the better boat upwind. The results shown in the figure are actual predictions, and they are based on exactly the same sets of hydrodynamic force data. The message here is designer beware. The tools used to evaluate candidate designs, and how these tools are used can greatly affect the outcome of a design optimization project.

Discussions in the previous paragraphs have been limited to velocity prediction programs that predict heel and speed at equilibrium side force. It must be noted that there has been a recent trend to also consider yaw balance, where yaw moments generated by the sails and hull are included and equilibrium sail trim or rudder angles are predicted. None of these newer methods are currently available commercially, but they are in use by certain hull and sail design organizations.

EXPERIMENTAL METHODS

Tank Testing

There was a time when any serious America's Cup design effort relied almost exclusively on tank testing to provide hydrodynamic characteristics of candidate designs. Although the tank is no longer the only source of this information, it is still a very important part of the design optimization process, and in fact, some projects still rely on tests of many candidate designs as the primary source of hydrodynamic data. Tank test programs usually consume a significant percentage of the available resources of an America's Cup design program. However, given the other tools currently available to evaluate hydrodynamic performance, the effort expended on tank testing can be minimized if it is properly integrated into the overall design program. This shift in emphasis does have a price, since use of the tank as a verification tool requires an improved understanding of uncertainty in results and better documentation of test conditions, as compared to simple evaluation of candidates.

The tank is the only place where data can be collected in a controlled environment, in the presence of a free surface. However, viscous effects are not properly modeled, and must be accounted for separately. Objectives of a modern tank-testing program typically include:

1. Direct determination of hydrodynamic force data for use in performance predictions.
2. Collection of force data, flow visualization and special data for verification of analytic techniques.
3. Confirmation of results from other design studies, in the presence of a real free surface, and without simplifying assumptions.

In all cases, testing in calm water and waves may be included.

Key factors to be considered when planning and executing a tank-testing program are:

1. Facility and scale selection.
2. Quality and history of test equipment.
3. Model construction.
4. Test procedures.
5. Data analysis techniques.

Unlike a typical yacht design project, the conditions of the America's Cup matches require that tank testing be conducted within the challenging (or defending) country if suitable facilities exist in that country. This limits the number of facilities that can be considered, and in the case of the USA, proven capabilities only exist at the Naval Surface Warfare Center, Carderock Division (large models) and the Davidson Laboratory (small models). Kirkman et el [10] give an excellent discussion on scale effects for sailing yacht tests and recommend a minimum model size of 15 ft waterline length. However, the authors have completed meaningful test programs at scale ratios ranging from 1:8 to 1:2.8 for IACC yachts (waterline lengths of 7 to 22 ft). When selecting a scale ratio, the specific objectives of the test program must be considered along with the increased viscous effects and the requirements for better absolute precision as model size is decreased. These factors should be weighed against the increased cost and time required for larger models.

The quality and history of test equipment, and the availability of experienced personnel are at least as important as model size when selecting a test facility. Sailing yacht tests are probably the most demanding tests completed by most towing tanks, in that the objective is to measure small differences in drag in the presence of very large lift forces and overturning moments. Test equipment should have a demonstrated history with these types of experiments, and personnel must have a complete understanding of the issues affecting success.

Key factors for test equipment are the carriage and test dynamometer. The carriage should be sufficiently rigid to keep deflections within acceptable limits for the maximum expected model loads, and its mass must be sufficient to insure steady motion if tests in waves are planned. Also, speed should be maintainable within 1 part in 1000. The test dynamometer must be rigid enough to limit deflections under load to acceptable levels, and calibrations and cross-axis sensitivities must be well understood and repeatable. Unlike wind tunnels, where force balances are routinely well calibrated for interactions between force components, towing tanks do not routinely go through this process and typically don't provide the necessary corrections on a routine basis. This can be a major source of error as illustrated in Figure 13, and the form and magnitude of these interactions will vary depending on the design features and fabrication quality of the specific dynamometer.

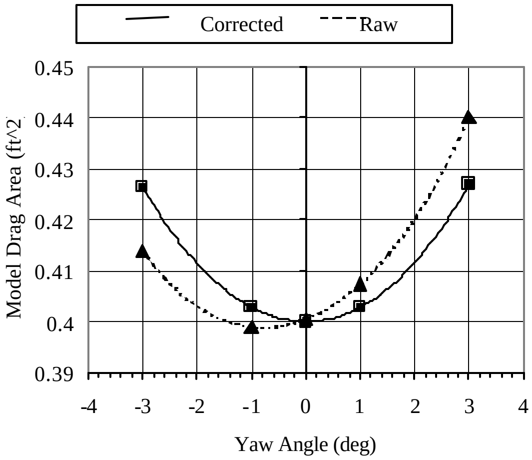


Figure 13 – Typical Drag Error Due to Cross-Axis Interaction with Roll Moment for a 1:3 IACC Model

Additional facility issues include the data acquisition system and experience with the effects of repeated tests at angle of attack on basin circulation. The data acquisition system must be capable of maintaining the required accuracy from the sensors through signal conditioning to digitization. In addition, users should have the ability to review time histories of data signals and select segments to be used in analysis. Both raw data and data in engineering units, with corrections applied should be recorded. Circulation and large-scale turbulence after repeated angle-of-attack tests have been found to be present in certain tanks but not others, and the characteristics of these problems can vary. Figure 14 illustrates the variation in measured side force during a "steady" test along with variations in angle of attack measured using a two-axis velocity probe. This figure shows an 8% variation in side force during the test. If these types of variations are present, collection of accurate force data is impossible.

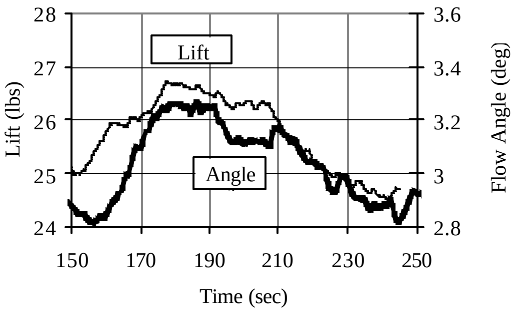


Figure 14 – Variation in Apparent Angle of Attack and Side Force Due to Basin Current

Whether models are provided by the test facility or another source, they must be accurately built and rigid. The differences in shape that are being investigated for IACC boats now that there is experience from three America's Cups are very small. To accurately model these differences, model shapes must be maintained within close tolerances and should be documented after final finishing. Shape must not change under test loads and the alignment of fixed and movable appendages must be accurately set and maintained under load. These factors are not only important to insure accurate evaluation of candidate designs, but they are also critical when using tank tests to verify results of calculations.

As with any experiment, care must be taken to use test procedures that are consistent and appropriate for the expected accuracy. These include model surface preparation and maintenance, waiting times between test runs, duration of steady data collection, instrument calibration checks, and control of independent variable settings such as yaw angle, rudder angle, trim tab angle and trimming weight placement.

Finally, since viscous effects are not modeled in the tank, data analysis techniques are important, and this issue is magnified as model size decreases. Model viscous forces must be subtracted from the model data and full-scale viscous forces must be added back once the residuary forces are scaled. Use of Prohaska's method [11] to scale hull viscous resistance using a flat plate friction formula and a form factor has become fairly standard. However, prior to applying this method the viscous forces acting on the appendages must be computed and subtracted. A number of methods have been used for this "stripping" of appendages, including a handbook method described by Teeters [12], direct use of wind tunnel data collected at model Reynold's Numbers, and computations using boundary layer codes. In all cases, it is important that turbulence levels are known. Most tests are completed using turbulence stimulation on the hull and appendages to "fix" the transition from laminar to turbulent flow at know locations. The specific type of stimulation used can have a major impact on both drag and lift results, and parasitic drag due to the stimulation must be computed and considered during data expansion. This issue can cause significant uncertainties when tank results are compared to analytical results (see Figure 27).

Additional sophistication in data expansion has included using actual at-speed and heel wetted areas and wetted lengths when computing hull viscous resistance, and computing variations in viscous drag of appendages with lift. Both of these can be computed given access to the appropriate analysis tools, and wetted lengths and areas can also be determined using underwater photography. Historically, lift and lift-induced drag have been assumed to obey Froude scaling. This may also be an area where further refinement in data analysis techniques would be productive.

The data analysis techniques discussed in the pervious two paragraphs may seem overly complex since the details of viscous scaling techniques have only minor effect on model-to-model-comparisons where tests are conducted with identical appendages and hull forms are similar. However, in a design program where testing is integrated with analytic techniques, these details become very important in understanding how the various design tools are working, and adjusting the assumptions used in theoretical calculations. Figure 15 illustrates this point by showing differences in (full-scale) residuary drag predicted from one set of tank data, using two different viscous stripping techniques, handbook appendage drag calculations [12], and determination of appendage drag from wind tunnel data. At typical upwind sailing speeds the difference in residuary drag is 3.9%. Experimental verification of computational methods for wave-making drag is therefore extremely difficult.

Wind Tunnel Testing

Wind tunnel tests are commonly used for evaluating different appendage configurations. The appendage packages on IACC boats typically include a fin keel with a trim tab, bulb and winglets, and a separate rudder. The fin/bulb/winglet packages look very much like an aircraft wing (with flap) with a tip tank and winglets. Appendages must counteract the side force generated by the sails and provide stability from the ballast bulb, at minimum drag. The primary trade-offs are stability versus drag, and induced drag versus side force.

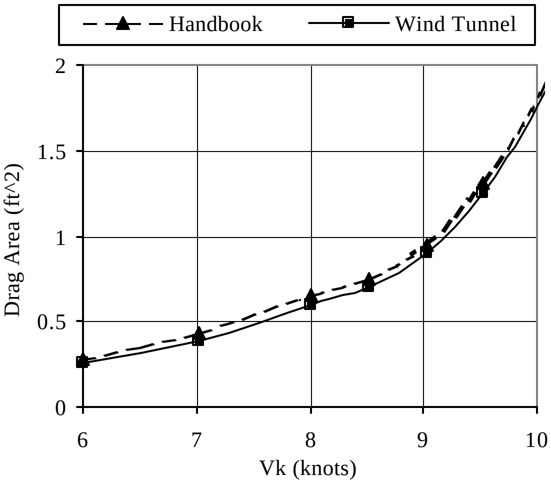


Figure 15 – Prototype Residuary Drag Using Two Different Viscous Scaling Techniques

Therefore, the primary test objective in the wind tunnel is determination of drag at zero side force and lift induced drag for various configurations. This data can be used for direct performance evaluation and verification of analytic techniques. In addition, flow visualization can be extremely valuable in understanding how design features impact performance, and verifying assumptions used by analytic techniques.

Testing issues in the wind tunnel are very similar to those discussed above for tank tests. Fortunately, most wind tunnels routinely test wing and aircraft configurations, and are therefore experienced at measuring small changes in drag in the presence of large lift forces. Force balances are typically extensively calibrated for cross-axis interactions and corrections are routinely applied in data reduction software. In addition, flow conditions in the test section are usually well documented and blockage corrections are well understood. Barlow et al [13] provide a comprehensive discussion of wind tunnel design and testing considerations.

From the design project standpoint, the key elements are model design and fabrication, test planning and data analysis. Similar to tank testing, models must be accurate and rigid. The performance of airfoil sections can be significantly degraded due to small changes in section shape or irregularities, and test loads in the wind tunnel can be quite high (equal to full-scale loads if full-scale Reynolds Number is achieved). In addition, time in the wind tunnel is expensive, so models must be designed for ease of installation and configuration changes. Test planning is important primarily to permit efficient evaluation of multiple configurations, and to insure that configurations are varied in a logical manner, so the effects of different form variations can be isolated.

As was the case for tank testing, wind tunnels cannot perfectly model full-scale sailing conditions. First, the free surface is not present, and representation of flow modifications due to the presence of the hull is difficult at best. Secondly, full-scale Reynolds numbers cannot be achieved in most facilities. The keel fin on a full size IACC yacht operates at Reynolds numbers of about 4 million at typical upwind sailing conditions, and at a scale ratio of 1:3 most facilities can achieve Reynolds numbers around 1.5 million (as a comparison, tank testing at 1:3 scale results in Reynolds numbers of about 0.8 million).

Typically, turbulence stimulation is used on the wind tunnel models to insure that the flow regime is predictable. This technique does not eliminate the dependency of forces on Reynolds number, but it does make this dependency better behaved. Figure 16 shows the variation in drag for two fin/bulb/wing packages with Reynolds number from a 1:3 scale wind tunnel test. For reference the slope of a widely used flat-plate friction line is also plotted for keel fin Reynolds Numbers. When using wind tunnel data for direct application to full-scale predictions or for viscous stripping of tank data, this variation with Reynolds Number must be considered.

Full-Scale Testing

Full scale testing, usually using two boats side-by-side, has become standard practice for most America's Cup programs. The primary purpose of these tests is to optimize rig and sail setup and tuning, and to evaluate specific sail designs. However, they also provide an opportunity to check hull and appendage designs, and this can be extremely valuable since all of the design tools currently in use have limitations and/or underlying assumptions. In addition, special full-scale tests can be completed to gain a better understanding of the physical processes being modeled with these design tools.

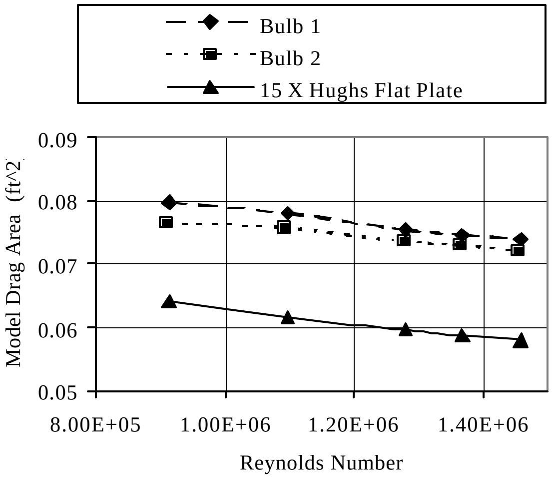


Figure 16 – Variation of Wind Tunnel Appendage Drag with Reynolds Number

Like all experiments conducted outside the laboratory, yacht full-scale testing is extremely difficult because the experimenter has little control over the independent variables. In this case the primary problems are wind speed and direction, and their variations with height above the water and between locations horizontally. In addition, sea conditions are highly variable. Added to these variations are the problems associated with accurately measuring wind speed and direction from the boats, and seemingly minor variations in sail trim from boat to boat and with time. All of these factors result in an experiment with an enormous amount of scatter.

A typical test procedure is to align two boats such that they don't interfere with each other's wind and to conduct speed tests at a given true or apparent wind angle for a specified time period (usually about 10 minutes). The velocity and/or velocity made good for the two boats are then computed, usually based on differential GPS positions, at the beginning and end of the test. Wind speed and direction averages are obtained from the boat instruments or from an instrumented support boat.

Figure 17 gives an example data fit from two-boat performance tests with IACC yachts. The plus and minus 10% curves are shown to illustrate the limits of scatter in the results. Data points have not been included for simplicity in this small figure. The point here is that individual data points vary from the trends by an order of magnitude more that the difference between the two test boats.

Statistical analysis of these highly scattered data sets is necessary, and the form of the fits given in the figure are per Letcher et al [14]:

$$V_S = (AV_T^{-4} + BV_T^{-2} + C)^{-0.25} \qquad (2)$$

Where:

V_S = Boat speed or speed made good
V_T = True wind speed

This form works well since for low wind speeds, boat speed is proportional to wind speed, and at high wind speeds, boat speed approaches a constant. However, in many cases, test results are better evaluated by the sailors on the two boats than by formal data analysis.

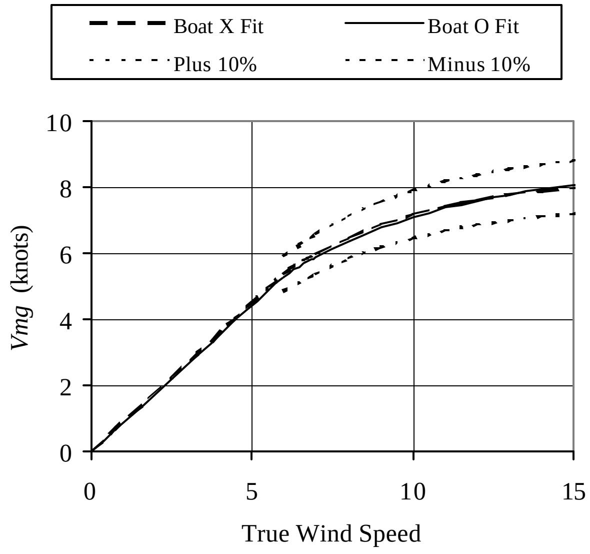


Figure 17 – Example Full Scale Test Data Fit

The second productive use of full-scale testing mentioned above is collection of special data to investigate the physics of performance factors and/or provide confirmation for assumptions used in analyis tools. An excellent example of this is given by Lurie [15] where full-scale tests were used to determine the extent of laminar flow acheivable on yacht appendages.

ANALYTICAL METHODS

As the following discussion illustrates, there is a wide range of tools available for analysis and design purposes relating to the hydrodynamic characteristics of a sailing yacht.

The simplest tools are often just a few equations or a set of curves from a figure in a book (e.g., [16]), and these are often of great use to estimate the potential benefit of some new design aspect. The tools may be derived from simple physical considerations, or they may be empirical in nature, merely organizing experimental observations in an intelligent fashion so as to enable predictions across a range of design variables or test conditions. Figure 18 shows an example of a handbook type "stripping" approach for estimating 2D airfoil viscous drag, similar to the Teeters approach [12].

Many of the VPP software programs that are available will incorporate a "Lines Processing Program" (an LPP). An LPP uses simple handbook type tools to estimate overall yacht characteristics, including primary hydrodynamic characteristics such as lift and side force, lift-induced drag, wave drag, and viscous drag.

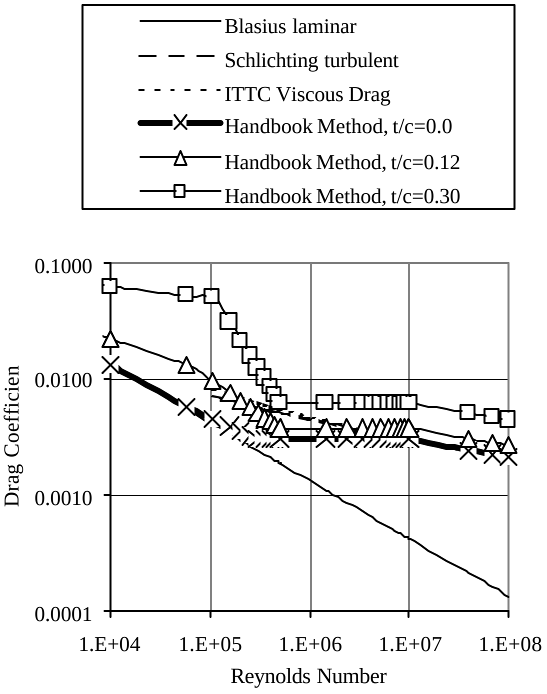


Figure 18 – Handbook Drag Calculation for Airfoils

More sophisticated tools may be classified as computational fluid dynamics (CFD) methodologies. These provide more detailed information about hydrodynamic characteristics by providing more sophisticated fluid flow simulations, with higher levels of realism and fidelity, made possible by calculating the flow simulation details numerically on a computer. Many CFD methods were originally developed for aircraft design, although in many cases they have been developed or extended for specific hydrodynamic application, particularly those tools with the ability to include free-surface wave effects.

One very useful type of CFD methodology is the panel code (e.g., [17] and [18], and their many derivatives). Here the potential (inviscid and irrotational) flow approximation is made, and distributions of source and/or doublet singularities are located on or close to the surfaces of interest (these being the yacht, its wakes, and perhaps also the free-surface) so as to yield the desired flow field. Such potential flow methods range from simple 2D airfoil analysis codes to those that allow treatment of fairly arbitrary 3D surface shapes including complete aircraft and yacht configurations.

Potential flow codes can be augmented by also incorporating some type of viscous flow model in the form of an attached or mildly separated viscous boundary layer adjacent to the vehicle surface. Such tools have been highly successful when incorporated into 2D airfoil analysis codes. They have yielded some of the best methods available for studying and predicting airfoil boundary layer characteristics, especially the transition from laminar to turbulent flow and its effect on drag both at zero lift and in the presence of appendage lift or side force. For example, Drela has developed a panel-code-based tool (XFOIL, [19]) as well as a finite volume Euler solver interacting with an integral boundary layer model (MSES, [20]).

Unfortunately the assumptions inherent in most viscous boundary layer approximations compromise their use in conjunction with 3D panel codes. This compromise is caused by the inability of most boundary layer theories to properly account for the highly three-dimensional viscous flow phenomena which occur for example at component junctures, or due to one surface on another at a downstream location, and for the hull at the waterline. While 3D panel codes may include such a viscous treatment for foil sections, or for hull or bulb body-type components, the utility of the viscous results from these codes (beyond those of their purely 2D counterparts, or simple handbook viscous drag buildup) may be questionable.

The ability to include the free-surface wave effects is not a trivial matter, and special panel codes have been developed specifically for this purpose, to varying degrees of success.

Some free-surface codes make use of so-called Havelock singularities, such as sources, which individually satisfy not only the potential flow equations but also a highly linearized form of the free-surface boundary condition. Havelock type singularities, although apparently difficult to evaluate numerically, form the basis of many approximate methods ranging from slender ship theory to more 3D methods (more often than not, non-lifting).

A number of fully 3D free-surface potential flow panel codes have been developed. These use singularities distributed over the free surface itself, as well as over the yacht and its wakes, thereby enabling more accurate free-surface calculations. Nonlinear effects due to the free-surface waves, and sink and trim, are quite significant for yachts, and call for even more sophisticated free-surface flow models. Such tools can capture simultaneously the wave and lift-induced drag components, as well as the interaction between lift and wave effects.

Since good yacht designs are typically characterized by highly streamlined flow, with minimal flow separation, the viscous effects overlooked by potential flow CFD methods can often be reasonably estimated with a handbook type of viscous drag estimate. As a result, such tools have been highly successful when applied to grand prix yacht design. The SPLASH free-surface panel code [21] plus viscous stripping was used for the examples shown in Figures 19, 20 and 21.

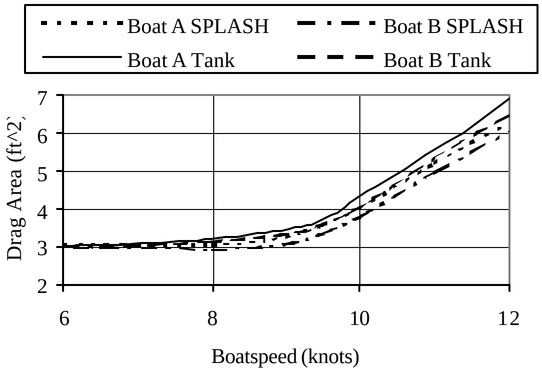


Figure 19 – Upwind Drag Comparisons from SPLASH and Tank Test

The discussion to this point has been restricted to analysis methodologies. A number of the analysis tools have been extended to be used directly for design and optimization purposes. Such design tools can yield optimum shapes or other optimum design features, such as span load distributions, to minimize drag or to match specified target pressure distributions, at specified conditions and subject to specified constraints. Many

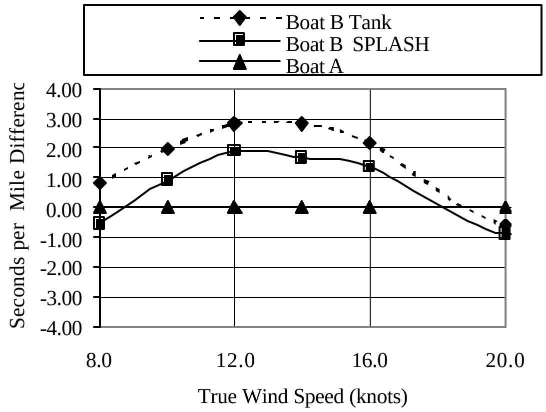


Figure 20 – Comparison of Course Time Differences from Tank Test and SPLASH

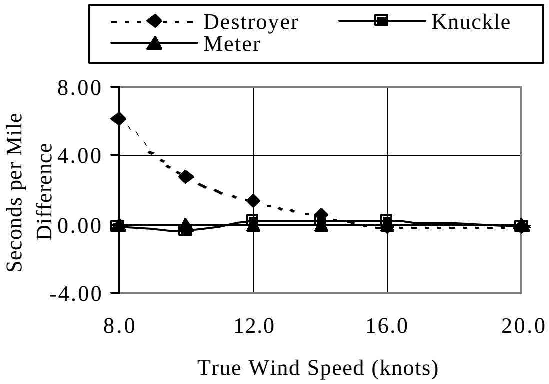


Figure 21 – Course Times for Bow Profile Series from SPLASH

such tools are available for inviscid and viscous design of airfoils (including transitional boundary layer effects), for minimizing 3D foil lift-induced drag (also known as vortex drag), and for minimizing volumetric wave drag.

Fully viscous flow methodologies typically incorporate the highest level of flow simulation fidelity. Compared to potential flow methods, which are (mostly) surface or singularity based, viscous flow codes are usually classified as field methods, requiring meshes throughout the entire flow domain of interest and on which the more complicated viscous fluid flow equations are discretized and solved.

While viscous codes offer another step up in prediction accuracy, their application is similarly more difficult, requiring considerably greater manpower and computer resources. It is not an exaggeration to say that viscous flow analyses can require one to two orders of magnitude more resources than corresponding inviscid analyses.

There are also many open questions regarding the turbulence models commonly employed within Reynolds Averaged Navier Stokes (RANS) viscous flow solvers. Turbulent fluctuations are unsteady and occur at temporal and spatial scales too small to be practically resolved by most methods. Transition from laminar to turbulent flow is another area where much work remains before such effects can be reliably calculated or modeled. While there are some highly specialized tools intended for calculating very small scale flow phenomena, their use has been restricted to basic research in transition and turbulence. So most if not all viscous flow methods for complex 3D configurations and flow fields (such as those associated with fully appended yachts) resort to some form of sub-scale turbulence model. Few if any include a reliable transition model.

A few examples illustrate some of the uses of RANS codes. Figures 22 and 23 show the use of the CFL3D code [22] for bulb fineness ratio studies. The use of CFL3D and “blocked” multiple grids for more complex appendage package flow studies are shown in Figures 24 and 25. The OVERFLOW code [23] with “overset” grids, and grid “holes,” was used by Joe Laiosa (Fluid Motions Analysis, Inc.) during the Young America 2000 design effort to generate viscous flow simulations for complete yacht configurations. Results appear in Figures 26 and 27, the latter showing how the viscous code was used to resolve discrepancies between SPLASH and tank-derived side force levels.

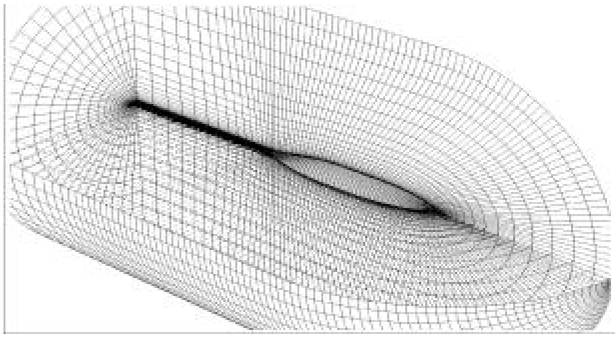


Figure 22 – Isolated Bulb Viscous Flow Grid

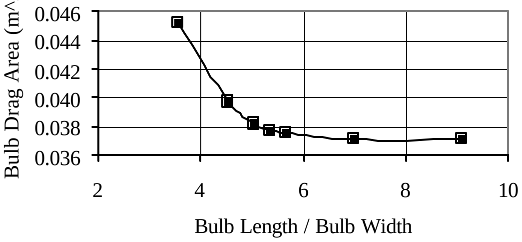


Figure 23 – Bulb Drag versus L/B from Viscous Flow Code

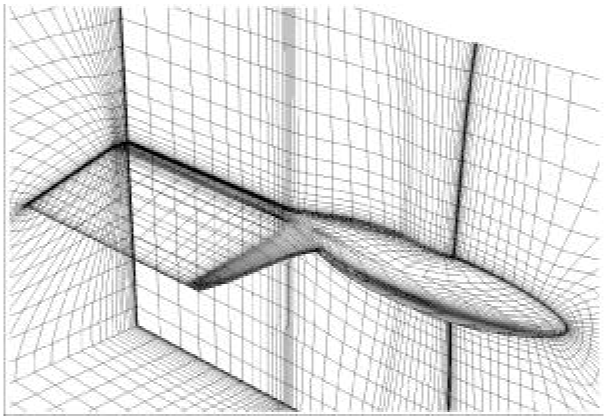


Figure 24 – Appendage Grid

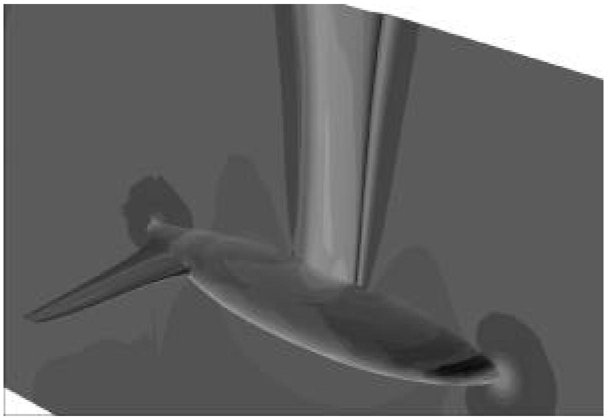


Figure 25 – Appendage Flow Field

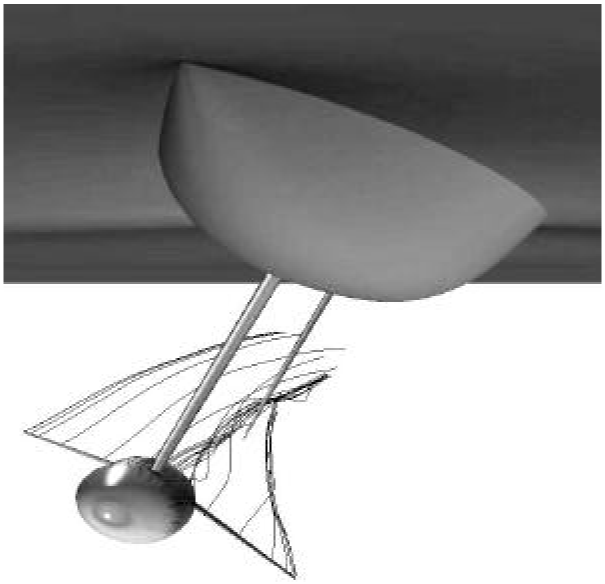


Figure 26 – Fully Appended Yacht Flow Field

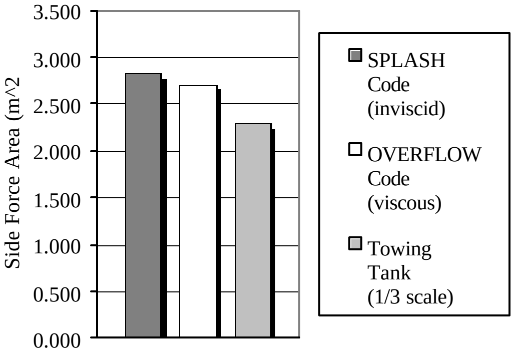


Figure 27 – Comparison of Upwind Side Force Predictions

Several viscous free-surface flow codes have also been developed. These very sophisticated tools treat the complexities of both the viscous flow and the nonlinear free-surface effects (the waves, and the sink and trim). They are highly specialized and extraordinarily complicated. A recent calculation of this type for a simple unappended hull form was reported to require 30-50 hours of CRAY G90 CPU execution time per test point [24]. This is in contrast to an inviscid free-surface panel code, such as SPLASH, with which full model tests covering 100-200 distinct test points can be completed in 12 hours on a 1 GHZ PIII CPU (running the Linux operating system).

Another design consideration is performance in waves. A number of methods can treat the unsteady flow and motions that results as a yacht moves through waves.

The Ship Motions Program (SMP) [25] does so by way of strip theory, whereby the ship is treated as a series of longitudinal cross sections, and a simple 2D frequency-domain free-surface wave solution is then mapped onto each cross-section. Various 3D and forward speed corrections can also be incorporated. The strip approach works well at low speed, for wall-sided hull forms, and for small wave heights and motions. It does not perform as well for typical grand prix type hull forms and at the high speeds at which they often operate.

A number of fully 3D potential flow free-surface panel codes have also been extended to treat unsteady flow, either in the linearized frequency domain, or directly in the time domain. The frequency domain codes consider small sinusoidal oscillations due to encounters with a unidirectional and monochromatic wave train. The time domain codes can in principal treat encounters with waves, which vary in both heading and frequency, as well as the nonlinear unsteady free-surface effects.

The time domain codes require considerably greater computer resources. The first-order forces and motions, and the second-order added resistance in waves (the time average of the resistance in waves versus that in calm water), are all highly sensitive to the computed flow field details. Perhaps for these reasons, in practice the frequency domain codes have so far been found to be more practical and more reliable.

Validation of unsteady methods remains a high priority, due the difficulties surrounding both the unsteady calculations and the unsteady experiments. Validation of the SPLASH code’s unsteady frequency domain capabilities with tank data for a rather simple generic Wigley ship hull form appears in Figure 28. A similar validation, but for an appended yacht at heel and yaw, was made by Dr. Warren H. Davis, Jr. for the AmericaOne 2000 design effort and appears in Figure 29.

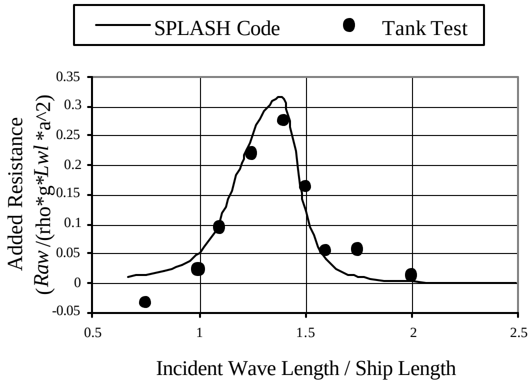


Figure 28 – Comparison of Added Resistance Operators from Tank Test and SPLASH for Wigley Hull

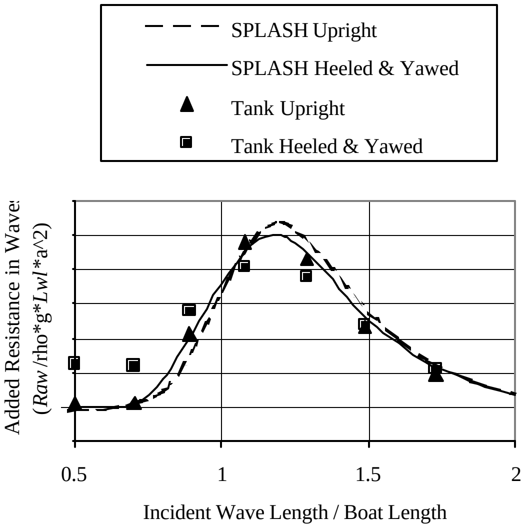


Figure 29 – Comparison of Added Resistance Operator from Tank and SPLASH for IACC Yacht

One common approach for including unsteady seakeeping effects in the VPP involves combining computed added resistance operators with the spectrum of incident wavelengths, headings and amplitudes expected on the racecourse. This yields a time-averaged added resistance in waves that is also included in otherwise steady VPP analyses. Figures 30 and 31 illustrate the results of this approach, as applied to two different hull forms and to two different sizes of wings, respectively.

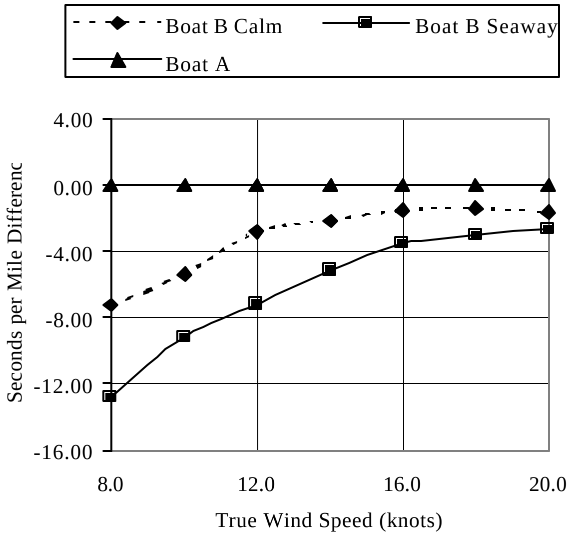


Figure 30 – Comparison of Two Boats Upwind in Calm Water and a 5 ft Significant Height Seaway from SPLASH

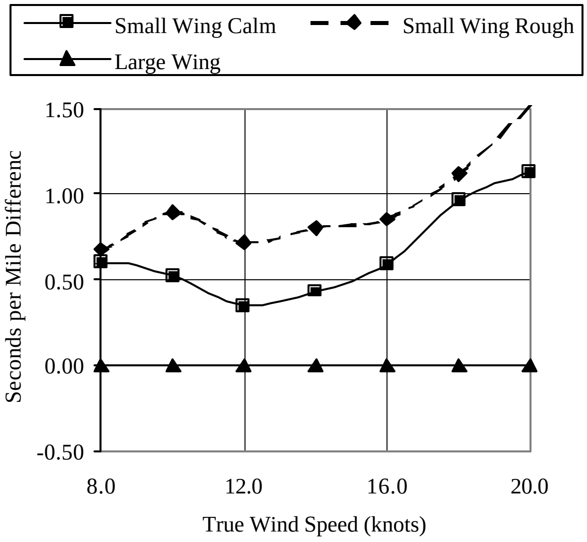


Figure 31 – Upwind Wing Size Effects in Calm Water and a Seaway from SPLASH

Most viscous free-surface code calculations are formulated in the time domain. Local time stepping and other “pseudo-time” acceleration techniques are used to minimize CPU time required for steady flow solutions. Most codes can also be run in time-accurate mode, opening the door to unsteady simulations and improved numerical predictions for forces, motions and added resistance in waves. In practice the resources required are generally prohibitive for design. Also, due to the extraordinary complexities surrounding such types of calculations, the utility of the results is not yet generally accepted.

The picture that emerges is as follows. While no one method is yet fully reliable, easy to use, practical, and of highest accuracy, there are nevertheless sufficient tools available for significant progress to be made in the design of sailing yachts. It is in the hands of the designer, or the design team members, to recognize which tools may be useful to attack which design problems. Thus CFD remains as much an art as a science, and the results from any one tool should always be checked against as much information from other sources as is possible.

SUMMARY

This paper has attempted to describe the engineering problem of designing a winning America’s Cup yacht and the current state-of-the-art in tools and techniques that can be used during the design process. The basis of the approach discussed here has been modeling the performance of candidate designs prior to construction. There are several key points related to this that should be emphasized:

1. Velocity Prediction Programs, which are the central tool used to model performance, are only as good as the hydrodynamic and aerodynamic data employed. Users must have a detailed understanding of data that is used implicitly (built into the program) as well as data that is input explicitly by the user. Also, methods of inputting data to these programs must be carefully formulated.

2. All sources of force data used as input to the VPP have limitations and underlying assumptions. These should be clearly understood by the user such that the most appropriate tools for evaluating a specific design feature are used. Where possible, multiple sources should be used to provide confirmation of results.

3. There is no one technique, such as tank testing, or a specific analysis tool, that will insure success of a design optimization program. All of the techniques discussed in this paper have limitations, and reliance on any single source of data will more than likely result in flawed predictions of the relative performance of candidate designs.

4. The success of the design optimization process will be highly dependent on how available resources (money, time and personnel) are allocated among the available techniques used to evaluate candidate designs. A program that is appropriate for a resource-limited project will be very different from one with unlimited resources. However, given intelligent use of available resources, even a more modest program can have a good chance of success.

5. Continued evaluation of existing design tools and development of new tools should be an integral part of any project. In addition, verification of results using actual full-scale performance should be a continuous process.

Table 1 provides a summary of how the various design tools discussed in this paper might be used. This is certainly not a complete list, but it does provide a fair representation of the current state-of-the-art. Again, multiple sources of information are available in every category. Also, in almost every case, final verification is provided from actual sailing results, even though this data is extremely difficult to obtain. In the end, success will depend on intelligent use of the available information, or restated, the experience and judgment of the designer.

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Table 1 – Recommended Application of Design Tools

	Principal Characteristics	Hull Form	Rudder, Keel, Wings	Bulb	Appendage Details	Rough Water
Handbook			P	P		
Lines Processing Program	P	P				P
Potential Flow			E	E	P	
Free-Surface Potential Flow	E	E	E	E		
Viscous Flow		E	E	E	E	
Free-Surface Viscous Flow		D	D	D		Someday
Unsteady Potential Flow	E	E				E
Tank Test	F	F				F
Wind Tunnel Test			F	F	F	
Full Scale Test	V	V	V	V		V

Key:
P – Preliminary
E – Evaluation
F – Final
V – Verification
D – Tool Under Development

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