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THE EVOLVING ROLE OF THE TOWING TANK FOR GRAND PRIX SAILING YACHT DESIGN

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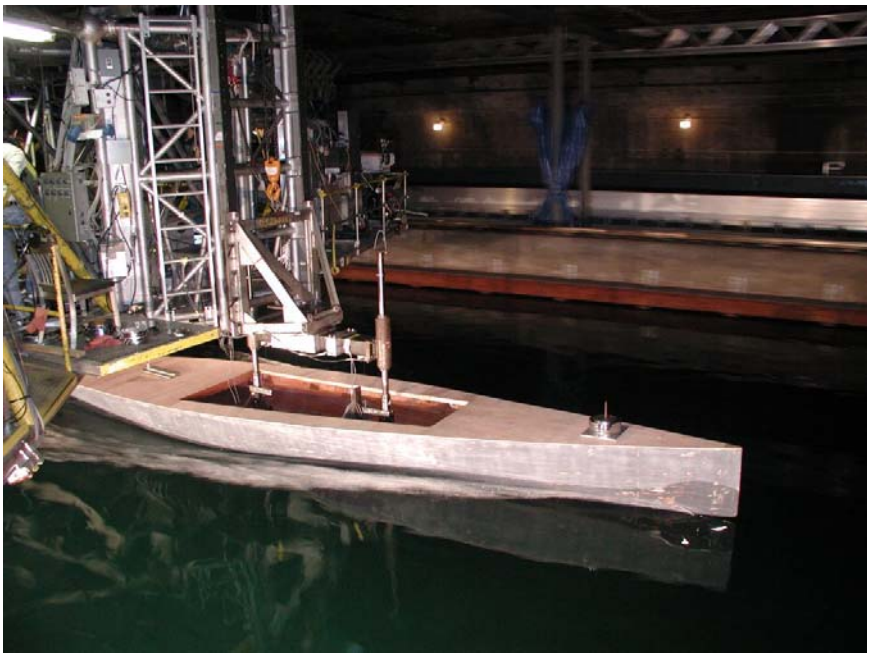

Figure 1 – MaxZ86 Racing Yacht Model on Carriage 2 NSWC Carderock (Photo Courtesy of Reichel/Pugh Yacht Design)

ABSTRACT

During the past thirty years, the use of North American towing tanks for the design of high-performance sailing yachts has changed dramatically. These changes are evident in the specific facilities completing these test programs, the quality of test equipment, procedures and results, and the way facilities interact with the designers. This paper reviews the factual history of sailing yacht testing in North America and then puts this history into perspective by reviewing the perceptions of the users, the changes that have been caused by these perceptions, and the resulting current state-of-the-art. Examples of how tank testing is integrated into current design programs are given, and some specific thoughts on ways tank testing can be made more useful are developed. Finally, given the technical advances that have been made over the past thirty years and the increased cost of test programs, renewed research on scale effects is recommended.

INTRODUCTION

In a previous ATTC presentation, Kirkman [1] documents the history of sailing yacht model testing back to Watson in 1901, when upright resistance testing was completed for the America's Cup challenger *Shamrock II*. Watson and others in the early 1900's learned that simple resistance tests were not sufficient for comparing the performance of different designs, because they did not adequately assess upwind performance capabilities.

In fact, as sailing yacht testing has evolved since 1901, it is more similar to aircraft wind tunnel testing than it is to typical towing tank resistance and propulsion testing. Given the similarity to wind tunnel testing, the authors can't help but quote a passage by Rae and Pope [2] that, "Data may *easily* "be taken all day long" – as long as they are not used to design airplanes". They go on to say "The aerodynamicist disparages the wind tunnel engineer; the wind tunnel engineer thinks the aerodynamicist wants too much; and if any poor soul is assigned the combination of jobs………".

Since the days of Watson, sailing yacht model testing has been driven by this dilemma. How can tank tests be best used by the designer given the uncertainties of scale effects, experimental errors, both systematic and random, and to date an inability to model the dynamic driving force of the sails? This situation is further aggravated by the fact that full scale driving forces are not readily available, and the most widely available model-full-scale correlations are observations of performance differences in a dynamic environment with different operators and different sails (engines), with no direct comparison of measured and predicted hydrodynamic forces.

The lack of high-quality correlations between tank tests and full-scale forces, combined with the difficulty of conducting the tank experiments, and the fact that very small performance differences are significant during racing, have all contributed to a tenuous relationship between the yacht designer and the towing tank. The primary purpose of this paper is to present a factual history of how the use of towing tanks by sailing yacht designers has evolved over the past thirty years, and to make some suggestions on how the test facilities, yacht designers and researchers in related technical areas might improve the utility of yacht tank testing in the future.

HISTORY

The problem of using scale model tank testing to predict the upwind performance of sailing yachts was first solved by Ken Davidson at the Stevens Institute of Technology in the 1930's [3]. Beginning with tests in the campus swimming pool (Figure 2), where small-model testing techniques were developed and correlation with large model and full-scale forces was demonstrated, Davidson went on to oversee the construction of a proper towing tank. Tank 1 was fitted with a dynamometer capable of measuring side force as well as drag, and was used by Davidson to develop a method for predicting upwind performance differences [4]. Davidson and the Tank 1 dynamometer are shown in Figure 3.

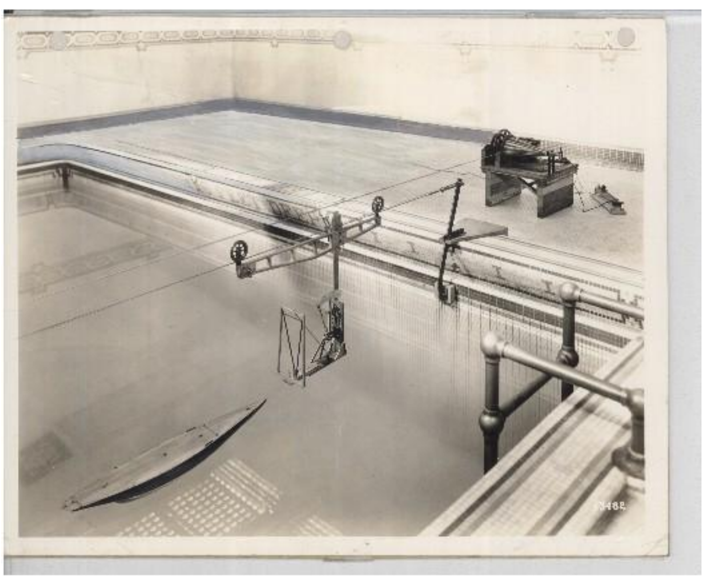

Figure 2 – Davidson's Early Test Setup in the Stevens Institute of Technology's Swimming Pool (Photo Courtesy of Davidson Laboratory)

Results from tests with side force measurements were combined with full-scale data from the sailing yacht *Gimcrack* to develop the upwind performance prediction methodology. Working closely with the yacht designer Olin Stephens, Davidson formulated a set of "sail force coefficients" from the *Gimcrack* tests, and used these in conjunction with tank data to determine drag at the points where heeling moment due to the sails was equal to the righting moment of the hull.

Figure 3 – Ken Davidson Demonstrating the Stevens Institute Tank 1 Yacht Dynamometer (Photo Courtesy of Davidson Laboratory)

After demonstrating the capability of tank testing to compare upwind performance by successfully predicting relative performance of the 6 Meter yachts *Jack* and *Jill*, the first significant application for the new technology was during the design of the J-Class yacht *Ranger*, winner of the 1937 America's Cup Match. After the 1937 America's Cup, the event was suspended due to war, and little activity related to yacht testing is reported in the literature until 1958.

Between 1958 and 1967 the Davidson Laboratory completed America's Cup model test programs for both challengers and defenders. During this period, test equipment and techniques had been improved, but testing was still being conducted with small models in Tank 1, and the basic method for predicting upwind performance developed by Ken Davidson was still being used. Several significant advances were made during this period, including development of a technique for testing models in realistic upwind sea conditions (Spens et al [5]), and numerous research projects completed by Davidson Laboratory staff and Stevens students.

MODERN DEVELOPMENTS

This brings us to what we refer to as the "modern" era, from 1970 to the present. Over this time period there have been many changes in the world of grand prix yacht racing and design, including the transition from amateur to professional competition for the America's Cup, the adoption of a completely new class of yacht for America's Cup racing, a trend toward lighter, higher performance racing yachts in general, and yacht racing campaigns becoming near-full-time design/build/race "businesses". One thing that has remained constant over this time period is the designers' need for very accurate performance comparisons. As shown in Figure 4, very small differences in predicted drag, at sailing lift, have a significant affect on the outcome of a race, with a 1% drag difference equating to thirty-five seconds, or seven boat lengths around an America's Cup race course. Whether the competition is amateur, with personal and national pride at risk, or professional, with big money at stake, the designer's frustration obtaining reliable performance comparisons with the desired accuracy becomes the test engineer's (or CFD analyst's) burden.

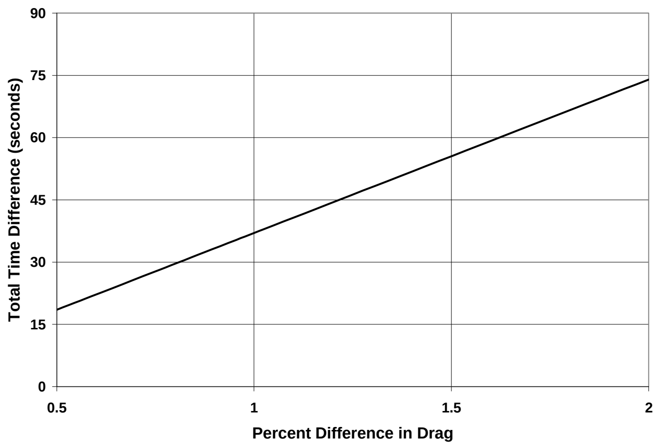

Figure 4 – America's Cup Course Time Differences Versus Drag Changes

For the 1970 America's Cup, defenders were tank tested per prior practice, at 1:13 scale in Tank 1 at the Davidson Laboratory. Two of the resulting defenders exhibited questionable performance, as was the case during the 1974 America's Cup trials with the poor performance of *Mariner*, a design developed in the tank that had an extremely full after body (more on this later). Although, as later published by Brown and Savitsky [6], the tank results did properly predict the poor performance of *Mariner* relative to its competitors; these results could not at the time be made public. Also in 1974, Kirkman and Pedrick [7] published a very well researched and documented paper that came to the conclusion that models with waterline lengths less than twelve to fifteen feet provided questionable correlation with full-scale results. Much of the basis for this work came from a series of geosym tests (including full scale [8]) completed at tanks worldwide with the 5.5 Meter yacht *Antiope*. This combination of events led to the end of 1:13 scale testing for America's Cup yachts.

In addition to keeping designers away from the 1:13 scale models of previous America's Cup cycles, these developments also led to a general decline in the use of tank testing by North American yacht designers. For the 1977 America's Cup, the *Enterprise* design program included tests of 1:3 scale models at Hydronautics combined with 1:8 scale models in Tank 3 at Davidson Laboratory. Tank testing continued to decline during the 1980 and 1983 America's Cup matches to the point where the 1983 defender, *Liberty*, was never tested in a towing tank.

Everything changed in 1983 when the America's Cup was lost for the first time to the scientifically developed *Australia II*. For all America's Cup cycles from 1987 through the present, tank testing has been recognized as a vital part of successful design programs. Most of this work has been done with large models (1:3 scale) but a number of groups have successfully integrated smaller scale (1:8 and 1:10) testing into their design programs ([6], [9]). Throughout this period, improvements have been made to test facilities, test procedures, model construction and data analysis. These changes are summarized in Table 1. A brief discussion of each of these areas follows.

Table 1 – Evolution of Testing State-of-the-Art

1970	Present
1:13 Scale Models	1:3 Scale Models
"Equilibrium" Testing	Matrix Testing
Sand-strip Turbulence Stimulation	Developmental Turbulence Stimulation
Models Hand-Shaped from Wood Lifts	Models NC Machined
2-D Data Extrapolation	3-D Data Extrapolation with Appendage Stripping and Lift Effects
No Blockage Correction	Experimentally Verified Blockage
Tank Circulation Neglected	Much Attention Paid to Tank Circulation
"Gimcrack" Sail Forces	Sophisticated VPP Usage
	Special Code Validation Testing

Model scale has already been discussed. Current practice is to test 1:3 scale IACC models, the maximum size permitted by the rules. Many syndicates have also opted to integrate

Figure 5 – Small-Model Setup at Davidson Laboratory Tank 1 circa 1970 (Photo Courtesy of Davidson Laboratory)

smaller models into their projects, mostly for reduced cost and quicker turnaround. Figures 5 and 6 show the test setups at 1:13 scale (Tank 1 Davidson Laboratory) and 1:3 scale (NRC Institute for Ocean Technology). Figure 1 also shows a 1:3 scale setup at NSWC Carderock.

Figure 6 – Towing Carriage at IOT Showing Installed Yacht Dynamometer 2004

"Equilibrium" testing in Table 1 refers to the practice of only completing test runs upright and near realistic sailing conditions upwind. Davidson's method of using the Gimcrack sail forces proved to be very robust over the years, but it was limited to true upwind sailing conditions. With the advent of Velocity Prediction Programs in the mid 1970's, a capability to predict performance on all points of sail became available, and this is now the current practice. Most current test programs include testing at a systematically varied wide range of speeds, heel angles and leeway angles to permit these types of predictions. During the 1980's test apparatus were developed at NSMB [10] and NRC [11] that let the model assume sailing equilibrium during a run. Although successful for the *Australia II* project, this approach never gained wider acceptance, and the standard today is semi-captive tests bracketing possible operating points with a large test matrix.

Some of Ken Davidson's original work in the Stevens swimming pool verified the use of sand strips for turbulence stimulation on small models. This technique was a highly developed standard for the 1:13 scale models tested in 1970. Subsequently, much development effort has gone into appropriate stimulation methods for hulls and appendages on the larger models. This development effort continues currently, both in towing tanks and wind tunnels since it has implications for lift, drag and yaw moment scaling.

Advances have also been made in the area of model construction, primarily due to the availability of large numerically controlled machines. Figure 7 shows a 1990 vintage IACC model hand carved from wood lifts, similar to those used for the 1:13 models in 1970. This figure also illustrates the test setup for 1:8 scale tests in Tank 3 at Davidson Laboratory. This setup has been used in several recent programs for several highly successful racing yachts including *Morning Glory* and *Pyewacket*.

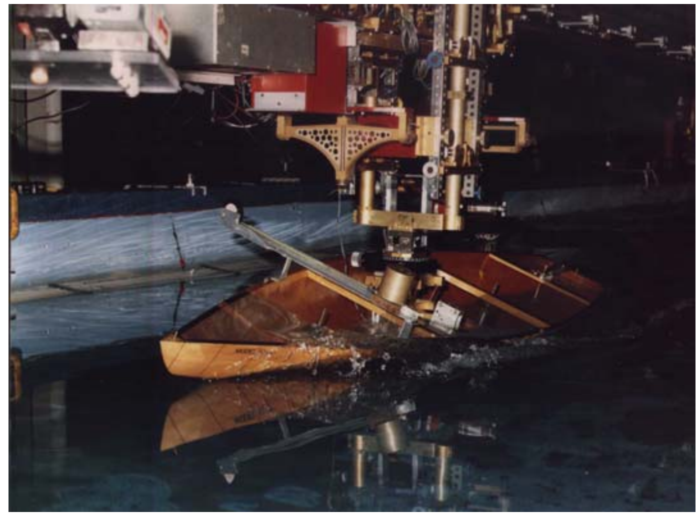

Figure 7 – 1:8 Scale Wooden IACC Model in Davidson Laboratory Tank 3 (Photo Courtesy of Davidson Laboratory)

Figure 8 shows a 2004 maxi yacht design during machining IOT. This type of construction is now typical, but it must be noted, that in most cases hand finishing is still required, as was the case for the wood models.

Figure 8 – Large Maxi Racing Yacht Model Setup in Mill (Photo Courtesy of NRC Institute for Ocean Technology)

The next area where standard practice has changed dramatically since 1970 is viscous scaling. At that time, viscous drag was estimated using the ATTC friction line with a multiplier applied to length when calculating Reynolds Number. The multiplier essentially provided for an effective length of the combined hull and keel, and static wetted surface area was used. As shown in Figure 9, this approach was probably adequate for a 1970's era 12 Meter, given the keel geometry. In the 1980's, the practice of individually "stripping" off appendages from the model and adding them back in for the prototype using semi-empirical expressions for airfoil viscous drag became standard. In addition, hull viscous drag was typically calculated using an experimentally

Figure 9 – 1:8 Scale 12 Meter Model (Photo Courtesy of Davidson Laboratory)

determined form factor. The next level of sophistication was added in the early 1990's when actual running wetted lengths and wetted areas were used to calculate hull viscous drag. Since that time many projects have also investigated different methods for lift and lift-induced drag scaling. Figure 10 shows a modern racing yacht with multiple high-aspect ratio appendages and a ballast bulb. Although IACC yachts are not this complex, they do have very high aspect ratio keels and rudders, and a ballast bulb. Clearly these types of configurations require care when computing viscous drag.

Figure 10 – 1:4 Scale Model of a Modern Racing Yacht Prior to Installation at IOT (Photo Courtesy of Reichel/Pugh Yacht Design)

The next technology items listed in Table 1 relate to tank effects. Tank blockage has become significant as model sizes have increased relative to tank size, and completion of testing at different scales to investigate scale effects has required that data be corrected for blockage. Kirkman [12] and Campbell et al [9] both provide discussions on this subject. Typically, a simplified form of Scott's method [13] has been found to be very effective. The second tank effect, which has only recently been recognized, is circulation and/or eddies induced in the tank by repeated tests with lift. As reported by DeBord et al [14] and Brown et al [15], these can cause scattered or biased lift and drag versus angle of attack and/or speed results. Various facilities have set criteria for waiting times between runs and have installed different types of baffle systems to minimize these effects. These effects have been found to be significant and must be considered.

Changes in the way that driving and heeling forces of the sails are combined with tank results to predict performance were discussed briefly above. Current practice uses Velocity Prediction Programs (VPP's) to solve the force balance between aerodynamic and hydrodynamic forces and thus predict operating speed, heel and leeway for a given wind speed and direction. This is not unlike Davidson's original approach using the *Gimcrack* Sail Coefficients, except that now, the analysis is completed over a wide range of wind directions. Still, in July 2004, much uncertainty exists related to the sail force models used in VPP's, and variations in these models can affect performance comparisons and selection of the optimum design for a given set of wind conditions [14].

TYPICAL TANK TESTING PROGRAMS

As was the case in the early 1900's, developments in the area of sailing yacht tank testing are closely tied to America's Cup design projects. During the past thirty years, as typical model sizes have increased, costs have increased dramatically to the point where smaller projects cannot justify the expense. The exceptions to this are other major events such as the Volvo Race, and design projects for very large racing yachts with very competitive owners. Table 2 provides a brief summary of the key elements in an America's Cup testing program and a typical custom maxi-yacht program.

Table 2 – Typical Test Programs

America's Cup	Maxi-Yacht
3 to 10 Tank Sessions Over 2 to 4 years	1 or 2 Tank Sessions
8 to 20 Configurations	1 to 3 Configurations
Appendage Testing Secondary	Appendage Variations Important
Code Verification Very Important	Long Term Data Base for Design Office
Budget $500k to $2 million	Budget $50k to $200k

The principal requirement for the America's Cup project is to generate results that are accurately comparable over a long period of time. This time period might be several America's Cup cycles depending on whether or not the specific team survives past one event. Although these projects will typically require some appendage testing, it would probably be secondary due to rule limitations and the fact that most AC projects include wind tunnel testing. The ability to do special testing to validate other design tools is also important, since most America's Cup efforts include significant R&D. The one-of custom racing yacht projects are driven by a different set of requirements. Budget and fast delivery of results are most important, and data comparisons over a long period of time are less significant, though not unimportant. These projects typically do not have time for R&D, but given the rapid development in configurations recently, they will probably include comparisons of alternate appendage configurations.

In both cases, tank results will probably be used in conjunction with computations, so documentation of test conditions and results is important. In addition, proper use of all available design tools is critical to success. Current America's Cup projects are using potential flow methods to screen a very large number of candidate designs for wavemaking drag prior to selecting the few candidates to be tested in the tank. In addition, viscous flow calculations are becoming more common and these are also used for some aspects of hull design as well as appendage design. The larger America's Cup programs will also have opportunities to complete full-scale testing for certain design features, and these tests are most effective when integrated with the tank and computational programs.

Depending on the specific design office, calculations may or may not be part of the maxi-yacht project, and the requirements for the tank test will depend on this. In some cases, budget constraints have led to tank testing one model and using calculations anchored to this model to evaluate alternatives. For these projects, calculations are typically limited to potential flow calculations.

CURRENT ISSUES

In some respects, the current issues facing the testing and yacht design communities are identical to those they faced in 1970. Much has changed in the past thirty years, but relatively speaking, the key issues are similar. These are:

1. Scale effects are still not well understood;
2. Quality Assurance must be thorough and consistent; and
3. Designers need to be guided away from configuration testing, toward parametric testing.

The continuing overriding problem is that many designers expect the tank to give "the answer", when in fact, as most test facilities know; the tank is only capable of shedding light on certain aspects of the physics. In those cases where we are confident that the physics are well represented, or corrected for, the inevitable limitation of experimental accuracy comes in to play. This places a twofold demand on the test facilities. First, everything reasonably possible MUST be done to improve long term Quality Assurance and documentation of results. Secondly, continuous education of the designers or project teams with respect to achievable repeatability and proper design of experiments is required.

How do recent developments in Computational Fluid Dynamics affect the tank testing community? First, use of tank data for code validation places additional requirements on the tank for verifiable and well-documented results. This has been discussed at previous ITTC and ATTC conferences, and doesn't require further elaboration here. Secondly, code validation can be greatly improved through special testing such as flow mapping, pressure measurements, boundary-layer surveys, and wave cut measurements. Finally, there is a real potential for using some of the more advanced CFD tools to gain a better understanding of scale effects.

Two final issues are cost, and cooperation between the tanks and design teams. Everything is relative, but testing costs have gotten to the point where even the largest America's Cup projects are actively seeking alternate ways to evaluate performance. In some cases, this has been taken to the point where the projects have suffered, but in many cases it is now less expensive and equally accurate to do full-scale experiments. In addition, a great deal of effort is being expended developing and validating CFD techniques that may or may not prove as useful as tank testing. Non-America's-Cup projects are simply walking away from tank testing and using the approach of learning from on-the-water experience. This trend might be irreversible, but any facilities that can improve productivity and efficiency to reduce cost should be well positioned, especially in light of the fact that there is no longer a nationality requirement for the America's Cup.

The sailing yacht R&D world has long accused America's Cup syndicates and design offices of not doing a good job sharing technical developments with the community in general. The authors believe that the test facilities share part of the blame for this in that the test facilities themselves do not invest in R&D to the extent that they did in the past. Each America's Cup effort is expected to bear the full cost of any development effort intended to improve quality of results, and the test facility then uses these developments for future projects. It seems that a better approach might be cooperative R&D efforts between the teams and the facilities, and more basic research coordinated by the facilities with support from multiple users. Hydronautics, the Davidson Laboratory, the David Taylor Model Basin (now NSWCC) and the Institute for Marine Dynamics (now IOT) supported many of these types of efforts in the past, and there are some critical technical issues detailed in the final section of this paper that would be well served by similar support currently.

RECOMMENDED TECHNICAL DEVELOPMENT

Two primary issues dominate the current requirements for a better understanding of how to analyze and use tank test results. These are (1) scale effects and (2) sail forces. Scale effects, and the related issues of turbulence stimulation and viscous scaling, have become increasingly important due to the types of appendages currently being used on racing yachts. In addition to simply "removing" the appendages to assess different hull forms, a better understanding of appendage drag and lift scaling would permit appendage optimization and assessment of handling characteristics to a much higher level. Even in the area of hull form development using very large models, some designers are beginning to question how testing at scale provides misleading information related to optimum fullness at the ends (déjà vu 1974) and details of bow shape. Perhaps the issue of scale effects requires a modern equivalent of the *Antiope* tests, using a modern hull form and appendages, and testing at least two different hull forms at various model scales up to 1:1? Could this series also quantify the limitations of tests with different size models, all using modern analysis techniques, such that designers could intelligently assess the cost versus scale trade-off for different projects?

The issue of sail forces may be outside the range of interest of the test facilities, but any developments would be equally as valuable as better insight into scale effects. The issue is definition of actual lift, drag, heeling moment and yawing moment acting on a yacht with a specified sail plan. This includes a specification of how these forces change as the sails are adjusted to de-power the boat. Again, this is not really a tank issue, but improvement is necessary to make better use of tank results.

Two final improvements that are becoming increasingly necessary are related to seakeeping and maneuvering. Many America's Cup campaigns have tried to use the tank and/or computer models to compare the added resistance in waves of competing designs. For the most part this has been unsuccessful, and a great deal of money has been spent to only gain a qualitative understanding. Development of a system for completing reliable, realistic and affordable seakeeping tests would be a major advance. Similarly, maneuverability is becoming an area of increasing interest. What is needed is a methodology to compare different designs with respect to speed loss, or loss of velocity made good, during specified maneuvers. In addition, handling (ease of maintaining course) qualities seem to vary significantly from boat to boat, and any technique that could predict these difference in advance would be extremely useful.

In closing, much progress appears to have been made during the past thirty years. However, many of the issues remain the same as they were in 1970, and still require further work by the test facilities and the users. The good news for those of us active in this business is that there are many difficult and interesting problems to be addressed.

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