SESSION 3b

ADVANCES IN YACHT TESTING TECHNIQUE

Discussion Chairman:	Prof. B. Johnson (U.S. Naval Academy, U.S.A)
Organizers:	Prof. B. Johnson
	Dr. P. van Oossanen (MARIN, The Netherlands)
Recorder:	Prof. T. Fukasawa (University of Tokyo, Japan)

3b−1 Chairman's Introduction

During the 17th ITTC in Göteborg, an informal meeting was held by attendees who were interested in the subject of yacht testing in towing tanks. A surprising number of delegates attended this informal meeting, which was taken to signify increasing interest in this area of model testing. America's Cup challenges by 12 meter yacht syndicates from various countries involved extensive computer modeling and tank tests done at member organizations of the ITTC.

At the second meeting of the Executive Committee for the 18th ITTC, a Group Discussion on Advances in Yacht Testing Technique was proposed. Prof. H. Kato invited Prof. B. Johnson to attend the meeting of the 18th ITTC Executive Committee Secretariat Group in Berkeley on July 14, 1986, to discuss the format for all the group discussions and to suggest organizers and speakers to the Executive Committee. Prof. Johnson was subsequently invited along with Dr. P. van Oossanen to organize the Group Discussion on Advances in Yacht Testing Technique.

Various potential invited speakers from model basins with considerable yacht and sailing ship testing experience were contacted to see if they could prepare and present contributions during the session. Four of those contacted were able to prepare their contributions in time to have them bound and distributed with the registrants' packets. Dr. van Oossanen was unable to attend the conference, but a MARIN written contribution was presented by Dr. A. Koops. Prof. J. Gerritsma made an oral presentation concerning data on added resistance in waves obtained at Delft University just prior to the conference. In addition, prepared discussions were presented by authors who brought written contributions to the conference. Finally, informal oral discussions were made by several delegates, including responses from a panel of the 12 meter yacht testing experts.

3b−2 Invited Contributions

1. National Research Council, Canada
   D. C. Murdey, W. D. Molyneux, and S. Killing: "Techniques for Testing Sailing Yachts", presented by D. C. Murdey

2. ARCTEC Offshore Corporation, USA
   F. W. DeBord Jr.: "Review of the Current State−of−the−Art for Sailing Yacht Model Tests and Future Challenges Facing Testing Facilities", presented by F. W. DeBord Jr.

3. Stevens Institute of Technology, USA
   P. W. Brown and D. Savitsky: "Some Correlations of 12 Meter Model Test Results", presented by D. Savitsky

4. Sumitomo Heavy Industries, Japan
   N. Takarada and J. Obokata: "Model Test of a Sail Training Ship", presented by N. Takarada

3b−3 Written Discussions Distributed at Conference

1. V. Ferdinande, State University Ghent, Belgium
   "Slamming on Race Sailing Yachts in High Waves"

2. H. C. Raven and G. Kapsenberg, MARIN, The Netherlands
   "Ready for the New Challenge", presented by A. Koops

3. J. M. Gonzalez, El Pardo Model Basin, Spain
   "New Sailing Yacht Dynamometer"

4. M. Abe, Akishima Laboratories (Mitsui Zosen) Inc., Japan
   "On Testing Method of Sailing Yacht"

5. H. Tanaka, Ship Research Institute, Japan
   "Challenging the America's Cup 1991"

3b−4 Oral Discussions and Questions to Presenters

Three oral contributions were made in this Group Discussion. Written forms of the following discussions/questions were submitted after Conference.

1. J. Gerritsma and J. A. Keuning, Delft University of Technology, The Netherlands
   "Comments on Added Resistance in Waves", presented by J. Gerritsma

2. B. Müller−Graf, Berlin Model Basin, Federal Republic of Germany
   "Comments on Measurements of Keel and Rudder Forces"

Dr. H. Kasai (MHI, Japan) asked Prof. V. Ferdinande on the experimental devices of drop tests, of which written form was not submitted.

TECHNIQUES FOR TESTING SAILING YACHTS

D.C. Murdey, W.D. Molyneux and S. Killing

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1. INTRODUCTION

Research into the performance of sailing yachts has long been of interest to aerodynamicists and hydrodynamicists who find the problem of understanding of the behaviour of a yacht under the complex action of wind and water forces a fascinating one. However, it has been the growing size of research budgets for America's Cup challenges that has stimulated the most recent developments in the field. Research and towing tank communities have been given the resources necessary to develop solutions to sailboat problems using methods previously available only to designers of commercial ships and aircraft.

In order to predict the performance of a sailboat it is necessary to determine the point at which the hull forces balance the forces developed by the sails. Traditionally the sail forces are derived from aerodynamic data or full scale trials, while the towing tank is used to provide information on the hydrodynamic forces and moments developed by the hull at various combinations of heel and yaw. The first system developed to measure the forces acting on a model sailboat under realistic conditions was produced by Davidson, and described in [1]. This system constrained the model in heel, yaw, surge and sway. Forces and moments were measured at selected forward speeds. This basic approach has been well accepted by towing tanks around the world, and descriptions of similar dynamometer systems are given, for example, in [2,3,4,5,6]. An alternative method was proposed by Allan, Doust and Ware [7]. For this approach the model was towed from a point corresponding to the centre of effort of the rig, but was otherwise completely unconstrained, and therefore free to take up its natural position in the water. Further developments of this technique are described in [8,9,10]. Both approaches have been successfully used for both large and small scale models, and each system has its own advantages and disadvantages, which will be reviewed below.

Perhaps the greatest developments in the technology over the last half century have not been in the model test techniques themselves, but in numerical modelling methods, which enable performance predictions to be made without the use of scale models. This allows the designer to quickly evaluate basic design concepts before going to the towing tank for detailed evaluation. The most recent America's Cup challenge saw the practical application of many advanced numerical techniques, of which those associated with the winner, 'Stars and Stripes' were noteworthy [11,12]. The design team for this yacht made extensive use of numerical prediction methods for determining the wave resistance of the hull and the hydrodynamic characteristics of different keel configurations.

It is essential that the designer be able to translate changes in hydrodynamic characteristics directly into seconds gained or lost on the race course. This is done by use of a velocity prediction program (VPP), which solves a series of equations to balance the aerodynamic and hydrodynamic forces acting on the yacht for an assumed true wind speed and direction relative to the yacht's course. The results of these calculations can be combined with meteorological data for the race area and alternative designs numerically sailed around the race course, and the design most likely to win determined.

The Institute for Marine Dynamics of the National Research Council of Canada was involved in the 1983 Canadian Challenge for the America's Cup. For this project, 1/5 scale models were built, and tested in the Ottawa towing tank. The opening of the new facility in St. John's brought with it the opportunity for testing the larger 1/3 scale models now usually required by the design community. It was also timely to review the current techniques and technology of sailboat testing in anticipation of working on designs for the 1991 challenge. IMD asked 12m designer, Steve Killing, who was actively involved in Canadian challenges for both the 1983 and 1986 America's Cup events, to work with them in developing the approach to sailboat testing which could be implemented in the St. John's towing tank. The present paper is based on this work.

2. DESIGNER'S REQUIREMENTS OF THE TOWING TANK

The towing tank is required to provide information to assist in the development of the design. The detailed nature of the data output from the test of any hull or keel must therefore be of such a form as to relate directly to other influences on the design, and to enable confirmation or rejection of hypotheses which lead to a particular configuration being tested. This consideration influences the test method used as well as the presentation of results.

The information produced by the tank may be incorporated in the design process at three separate, but related levels. The first is the velocity prediction for a particular design around a race course. This is most easily interpreted if it is presented in terms of polar plots of yacht speed against true wind angle for various true wind speeds. This requires a large number of experiments over a wide range of speed, heel and yaw angle combinations. The second level of application is the optimization of a particular aspect of performance, for example, the effect of small changes in design on speed made good (VMG). This involves many repeat tests, but over a limited range of sailing variables. The third level of application is to provide information required to refine mathematical models, and therefore allow the designer to develop more accurate and reliable techniques to estimate the performance of design variations. This third requirement may lead to a test program including, for example, runs at various yaw angles at zero heel or tests of the hull alone, without the keel.

A practical consideration of great importance to the design team which must also be taken into account is the possible influence of the test technique on the time and cost of carrying out the experiments. Tank testing is a crucial phase in the whole development of a design. However, there are other no less critical phases, such as sail development, full scale tuning and crew training. All these elements are competing for time and money, both of which are limited. The situation may be made even more difficult if, as happens in practice, the early design iterations did not fulfill expectations and additional model tests are required at a late stage in the overall schedule. In such circumstances, the tank must be able to respond by quickly making or modifying a model, and carrying out tests following a minimum set-up time. This implies a degree of simplicity and flexibility is required in the test apparatus, as well as efficient model making techniques.

Many of the changes in hull form among which the tank is required to differentiate are very small. This is in some ways a consequence of the 12m rating rule, which restricts the designer's freedom to a large extent. The test apparatus must therefore be accurate and capable of being set up in a consistent manner. This requires transducers which are not only stable, but also easily calibrated or checked. The results of a test must be available for immediate use, without a lengthy evaluation or checking period. The risk of requiring a repeat test for checking purposes must be reduced to an acceptable minimum.

3. EVALUATION OF TEST METHODS

3.1 Semi-captive Systems

This is the term used to describe those systems developed along the lines suggested by Davidson [1], who demonstrated that any realistic modelling technique must include the effects of heel and leeway angle. After making the simplifying assumptions that the aerodynamic forces always acted perpendicular to the mast, and that there were no unbalanced moments caused by the aerodynamic forces, he proposed a force balance system for a yacht moving at steady speed. A towing dynamometer was then designed which accommodated the force system acting on the hull. The model was fixed at a prescribed heel and yaw angle, and two lateral deadweight dynamometers measured side forces fore and aft. The towing system constrained the model in surge and sway, and the normal resistance dynamometer was used to measure the force component along the tank centreline. The resulting system could then measure the two force components, yaw moment, and dynamic heeling moment. This basic system has been refined over the years, and has been replaced at the Davidson Laboratory by an equivalent system using electromechanical force measuring transducers, and capable of being used with models up to 2m long, [2]. The principal components of this dynamometer are shown in Figure 1.

A key element of Davidson's original approach was the use of small models (typically about 1.2m), since this kept costs for model production and testing in line with typical yacht designers budgets, and the scales similar to those used in his facility for small conventional ships. Other tanks adopted similar dynamometers for use with models of a similar size [3,4]. However, in the mid 1970's there were some results published [5] showing the effect of model size on the correlation of lift and drag forces generated by different size models for various yacht designs. This work indicated that more reliable results were likely to be obtained from models with a waterline length around 4.5m. This size of model is now requested by most designers, at least for the testing of the final design configuration.

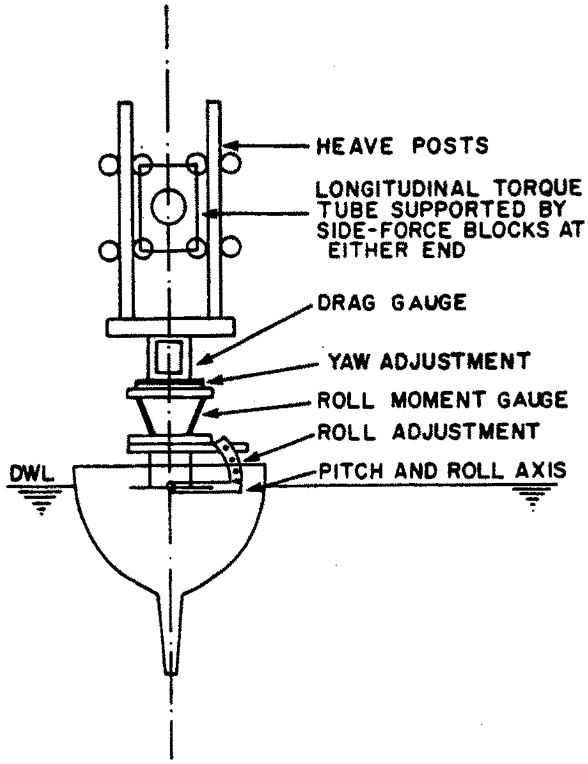

Fig.1: Semi-captive System in use at the Davidson Laboratory

The semi-captive system was developed for these larger models first by Hydronautics [5], and later by Offshore Technology Corporation [6]. As with Davidson's system, the model is constrained in all motions except pitch and heave. The forces are measured by six single axis electromechanical forces gauges. Typically the model is fitted under the carriage as shown in Figure 2.

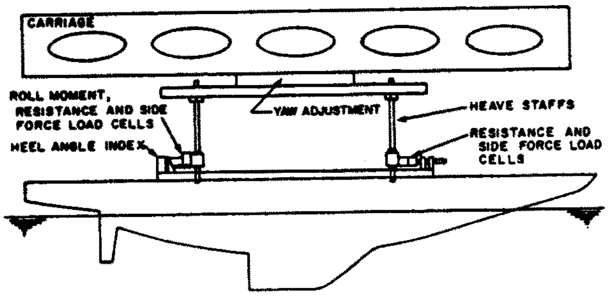

Fig. 2: Semi-captive System Suitable for Large Models

The model is attached to the carriage using two heave posts. Resistance and side force are measured at the forward heave post, and resistance, side force and dynamic roll moment are measured at the aft one. The design incorporates pivots to ensure the model is free to pitch and no roll moments are transmitted at the forward post.

The two developments of the semi-captive dynamometer differ in the locations of the force gauges and the method of attachment of the model. In the Davidson system the force blocks are permanently oriented with respect to the carriage, and the model attached at a single point. Thus forces are measured directly in tank axes. In the Hydronautics/OTC approach, the model is attached to the carriage at two points, and the force gauges are mounted in the model. This is a result of the need to balance yaw moments on a larger model. It has the disadvantage, however, that forces must be resolved from model axes to tank axes in order to provide conventionally defined lift and drag data. This implies the yaw (leeway) angle must be accurately known. Furthermore, the apparatus must be carefully designed so that interaction effects from the orthogonal force components are minimized.

In the semi-captive system, the model is ballasted to the correct displacement, but since it is mechanically restrained in heel, the vertical position of the centre of gravity for the model is not critical. To minimize loads on the roll gauges a movable weight is used to set the static heel angle. An additional ballast weight is added to allow for the effects of the vertical components of the sail force, assumed normal to the mast. Also some consideration must be given to the position of the towing point relative to the model, since this has an effect on the running trim.

The test program for a semi-captive model arrangement consists of a matrix of runs where heel, yaw and speed are varied to cover the required range of sailing conditions. The parameters for the experiments may be determined with the help of preliminary predictions made with a VPP. It is generally necessary to carry out several experiments in order to interpolate an actual sailing condition. This leads to more test runs being made than the theoretical minimum needed to predict performance. A typical test program to fully cover the three applications discussed in Section 2 above, would require approximately 100 runs (covering 5 speeds, 5 heel angles and 4 yaw angles). Extra experiments are needed at the beginning of the test program to determine the effect of additional drag due to turbulence stimulators, and these are usually done for the model upright only. Once the test program is completed, the results are cross-faired, and predictions made for the sailing performance, based on the model data and the available sail force data.

The semi-captive system has the advantage of providing the designer complete freedom to investigate any combination of yaw and heel, even if this does not represent a realistic sailing condition. This allows the the many physical phenomena influencing the behaviour of the vessel to be explored. The results may be easily related to the theoretical approach to sailboat design. It is even possible to study the hydrodynamics of the hull alone, since tests may be carried out with the keel removed.

The models used with the semi-captive system can be constructed entirely from wood, foam or glass reinforced plastic with no need for a metal keel, as would be fitted to the prôtotype. Hence any modifications to the keel which may be required as testing progresses are simple and cheap to carry out.

3.2 Free Sailing Systems

An alternative to the semi-captive system for testing sailboats is the free sailing system. The first version of this system was described by Allan, Doust and Ware [7]. The model, which was completely unconstrained, was towed from the top of a mast, located at the centre of effort for the sail. The forces generated by the hull were measured along axes parallel and perpendicular to the tank centreline with two single axis dynamometers. The measurements were made in a plane parallel to the water surface, which was adjusted vertically to allow for the change in height of the mast as the model heeled. The model was unconstrained in yaw, but the torque needed to maintain equilibrium was measured at the top of the mast.

The basic system was simplified at NRC in Ottawa [8], by applying the towforce perpendicular to the mast, and adjusting the vertical position of the attachment point on the carriage as the model heeled. The test arrangement is shown in Figure 3. In carrying out a test, rudder angle and speed were selected and the resulting heel and yaw angles measured together with the towforce for each run. Yaw moment was balanced by the moments induced by rudder and trim tab. For this test method, in contrast to captive testing, the model must be ballasted to a representative vertical position of centre of gravity. For 12m yachts, this requires a hull strong enough to take the stresses from a metal keel.

In the initial work on the development of the free sailing system the mast was fixed relative to the hull. A consequence of this was that at some speeds the model was not directionally stable, with fixed rudder and trim tab angles, or the angles were so large that they were unrealistic. Gommers and van Oossanen [9] developed a solution to this problem at MARIN by moving the mast position relative to the hull, to ensure directional stability throughout the test program. An additional benefit of this was the ability to control yaw angles, and increase the number of independent variables which may be tested. The speed and yaw angle may be selected before a test and the resulting heel angle and force components measured. Rudder angle is no longer a basic test variable. The problem of directional stability around zero degrees leeway angle was also solved at MARIN by adding a torque sensor to the mast, and a feedback circuit to ensure that the mast torque was always zero.

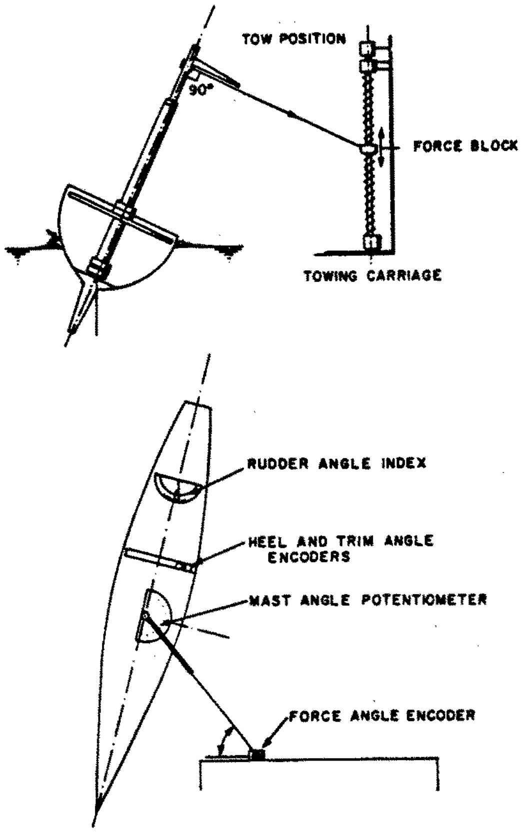

Fig.3: Free Sailing System at IMD (Ottawa)

The NRC system was modified for use with small models at B.C. Research, as described by Stensgaard [10]. This facility uses 1/6 to 1/10 scale models.

In developing this apparatus it became clear that the option of moving the mast as described above was not practical for small models since the available hardware was just too large. The resulting system included the addition of automatic alignment of the towforce normal to the mast, and the resolution of towforce components directly by using stacked single axis force gauges.

Since in the free sailing system there is only one combination of speed and heel angle which balances the resulting towforce, there is potential for reducing the number of experiments required to produce a performance prediction. A test program to determine VMG at 5 heel angles with a free sailing system can be carried out with as few as 20 runs. However, experience with the IMD system in Ottawa would suggest between 30 and 40 are usually required. This would compare to between 60 and 80 for a semi-captive system. Polar plots can be determined with approximately 60 runs for the free sailing system and 100 for the semi-captive system.

The handling of a large free model does bring with it practical problems during the acceleration and deceleration phase of a test run, since it is difficult to arrange a mechanical clamping and release device. Furthermore, the time required for the model to settle at an equilibrium attitude can make certain conditions difficult to achieve even with the adjustable mast position capability. The free sailing system assumes that the centre of effort remains constant regardless of heel angle. Although little information is available on variations in this parameter, the captive system can more easily accommodate possible changes. Since the model requires the specific stability of the prototype it may need to be retested if the position of the centre of gravity changes as the design develops.

3.3 Review of Options

In developing a dynamometer for testing sailboats with heel and yaw a choice has to be made between the two basic approaches described above. Both methods have proved to be successful in practical applications for design development, and each system has some advantages and disadvantages.

The main advantage of the free sailing system is that it has the potential for minimizing the number of experiments required to produce the performance prediction for a sailboat, since each experiment is an actual sailing condition. This has the added advantage that the designer can observe the hull in realistic conditions of yaw and heel. The shorter test program may be expected to compensate for the extra expense required to build and outfit a model with the scaled stability characteristics of the prototype.
On the other hand, the semi-captive method allows more easily for the investigative approach, but has the disadvantage that the actual sailing conditions may not have been tested and the designer does not know the nearest sailing condition to the experiment until after the test program is completed. If a VPP is used to predict the sailing performance before the model is tested, the designer has the opportunity to ensure that something close to a realistic sailing condition

is included in the test matrix.

It is our conclusion that a semi-captive model test system, combined with a state-of-the-art VPP represents the optimum combination for a model test system to meet the anticipated need at the IMD St. John's facility.

4. A PROPOSED MODEL TEST FACILITY FOR SAILING YACHTS

It is planned to implement at IMD a semi-captive system generally as shown in Figure 2. Before starting the detail design, the likely test program requirements were reviewed and a sensitivity analysis performed to establish the basic specifications for the test apparatus. A study of the test programs for 12m yachts indicated that the system should be capable of testing models of 1/3 scale at scaled speeds between 3 and 12 knots. Heel angle is required to be varied between 0 and 30 degrees, in steps of 5 degrees and yaw angle adjustable up to 7 degrees in steps of not more than 1 degree. The yaw angle should vary not more than 0.01 degrees, when under load, which represents an error of 0.25% at 4 degrees of leeway and keeps errors in longitudinal forces within 0.1%. An acceptable maximum distortion in the heel angle is 0.05 degrees, which corresponds to an error of 0.2% at 30 degrees of heel.

An essential part of the proposed system will be integration of the numerical prediction methods with the model test program. This requires a computer system on the test carriage with sufficient capacity to handle data acquisition and analysis. IMD is currently using a microVAX II which has 9 megabytes of disk storage, and the additional capability to link with the Institute's main computer system, a VAX 11/750. Graphics capability is available for plotting both time history data from individual transducers, and reduced data in coefficient form. In addition, curves of faired data, calculated from the VPP, or measured from earlier experiments will be included for direct comparison with the results obtained during the current test. This will give the designer and the experimenter immediate feedback on the performance of the test equipment and the hull compared to the design estimates. This analysis scheme is outlined in Figure 4.

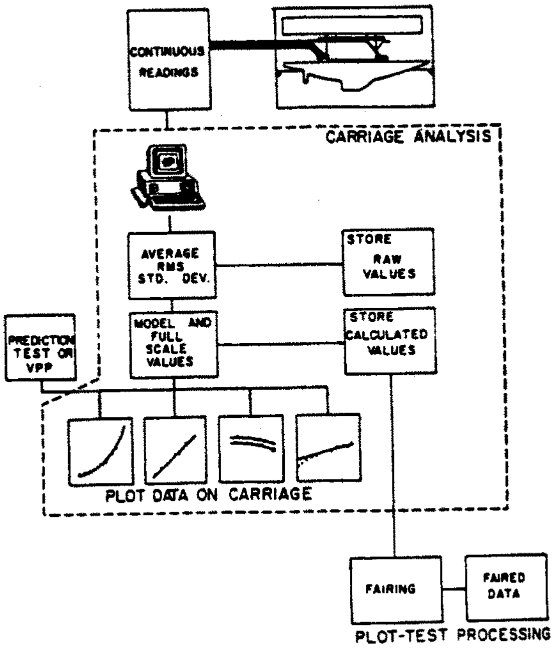

Fig.4: Data Acquisition and Analysis for IMD (St. John's)

The ability to compare the results of

the experiments with the equivalent predictions is a key feature of this scheme. VPP's generate the data required to predict the performance of the yacht on the basis of algorithms for hydrodynamic forces, but they do not give results in a form directly comparable with the data from a model test program. Most VPP's are structured to predict performance for a series of realistic sailing conditions, and not the constrained conditions used in a semi-captive model testing. For this reason a VPP will be restructured to produce lift and drag forces for fixed heel and yaw angles which corresponded to the test program. The output will be a series of points for contours of constant heel and yaw angle. The measured data will be presented in a similar fashion and so the file structure can be identical. These results (or predictions) would then be faired using elastic spline and surface fitting techniques. The actual sailing conditions could then be interpolated from the faired data. This means that a performance prediction could be made at each stage with the most up to date information available at the time.

5. CONCLUSIONS

Despite the developments of mathematical modelling techniques, physical model tests will continue to be an essential part of the process of designing 12m yachts for the foreseeable future. They give the most reliable performance predictions and provide an opportunity to experiment with features which would be difficult to model accurately with analytical techniques, or expensive and time consuming to do full scale.

Both the free sailing and semi-captive systems of model testing have proven to be successful in developing cup winning 12m designs. Each system has its strengths and weaknesses, but the semi-captive system offers information in the most systematic manner, and in a form which can be used more easily to refine numerical modelling techniques. It most conveniently allows the designer to see the effects of modifications to the hull or appendages both in terms of performance around the race course, and in terms of the fundamental hydro-dynamics upon which that performance depends.

6. REFERENCES

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REVIEW OF THE CURRENT STATE-OF-THE-ART FOR SAILING YACHT MODEL TESTS AND FUTURE CHALLENGES FACING TESTING FACILITIES

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ABSTRACT

Since 1983, when the innovative AUSTRALIA II won the America's Cup, there has been a major resurgence in model testing of sailing yachts. Based on work completed in the United States and published descriptions of testing at European facilities, testing in preparation for the 1987 America's Cup indicated that a wide variety of test and performance prediction techniques are in use, and test facilities face a number of challenges in meeting the designers' requirements for future testing. This discussion attempts to provide background on recent developments in yacht testing and the activities associated with the 1987 America's Cup in North America. Existing problems are identified and likely changes in design and sailing conditions are analyzed to define the challenges that will be faced by testing facilities during the next four years. Recommendations are formulated from the standpoint of a test facility, on research and development requirements and the potential role of the ITTC.

1. INTRODUCTION

Testing of model sailing yachts can be traced back to the late 1800's when models were tested for upright and heeled resistance during the design of SHAMROCK III. In the early 1900's tests were conducted with leeway angle as well as heel; however, side force was not measured and upwind performance was therefore not analyzed. A major advance was made by Davidson [1] when the methodology to predict windward performance from model tests was developed. From 1936, when Davidson's work was published, through 1970, no major developments in the science of testing yacht models were made, with the exception of improvements in equipment and techniques typical of standard resistance testing. During this time period, a considerable amount of yacht testing was conducted in North America, primarily at the Davidson Laboratory.

In 1970 and 1974, several America's Cup yachts were developed with the aid of extensive testing programs which exhibited questionable performance. This resulted in wariness on the part of designers and a considerable amount of research into scale effects. The landmark paper by Kirkman and Pedrick [2] came to the conclusion that models with waterline lengths of approximately 4.5m are required to minimize scale effects. Between 1974 and 1983, testing in North America declined to the point where the 1983 America's Cup defender, LIBERTY, was not model tested.

During this period when testing was declining in the US, NRC in Canada developed a new technique for heeled and yawed testing [3] where the model is towed from a mast and assumes equilibirum roll and yaw conditions. This technique was further developed by NSMB [4], and was used for testing of AUSTRALIA II. Throughout this period, the Wolfson Unit at the Southampton University and the Delft Unviersity of Technology remained active in testing and technology development.

2. TESTING IN PREPARATION FOR THE 1987 AMERICA's CUP

In the fall of 1986, 13 challengers and 6 defenders raced in preparation for the 1987 America's Cup. Most of these efforts included design and construction of more than one boat, and most were supported by model testing programs. In North America, all of the 8 challenging syndicates conducted model tests. Participating facilities included ARCTEC Offshore (formerly Offshore Technology Corporation), the David Taylor Naval Ship Research and Development Center, Tracor Hydronautics, and the Davidson Laboratory. As an example of the emphasis placed on model testing, the author's facility tested approximately 75 model variations for 6 syndicates, with individual test programs including as many as 30 model variations. Other facilities known to be active worldwide were MARIN, the Wolfson Unit at Southampton and British Maritime Technology.

Calm water testing included upright resistance tests, tests for heeled and yawed performance prediction, various types of flow visualization, measurement of forces on individual appendages, wave cut measurements and wave profiling, pressure mapping on hulls and appendages, boundary layer profiling, and tests intended to optimize the orientation of appendages. In addition, tests in regular and irregular waves were conducted to evaluate added resistance in head seas and the potential for surfing in following seas. Since most design efforts included integrated model testing, numerical analysis, and full scale testing, a number of specialized tests were also completed specifically to validate various analysis techniques or provide correlation with full scale results.

Based on experience in North America, and published descriptions of model programs in Europe, it is evident that testing and performance prediction techniques vary greatly from facility to facility, and the community has not developed a consensus on the importance of model size, test technique, turbulence stimulation, or the test program required to predict performance. Most tests in preparation for the 1987 races were completed using 1/3 scale models, however the Wolfson Unit tested both 1/10 and 1/4 scale models, and Davidson Laboratory completed tests at 1/8 scale. With the exception of tests conducted at MARIN using the free-running model technique [5], most facilities have adopted the captive model technique pioneered by Davidson. Even in these facilities, differences in dynamometry, measurement reference frames and test programs are significant. Wide variations in methods for turbulence stimulation also exist, ranging from some facilities using various arrangements of studs on canoe bodies and all appendages to others providing no stimulation for the 1/3 scale models. Some facilities move ballast to account for bow down trim caused by sail forces while others ignore this, and the number of tests used to characterize performance varies from as few as 60 to as many as 130 conditions.

Techniques for scaling results and performance prediction are as varied as test techniques. Most facilities assume that induced drag and added drag due to heel scale without viscous corrections. Calculation of the viscous portions of drag is completed by as many different methods as there are active facilities. The original approach of Davidson uses the Schoenherr friction line and calculates Reynolds Number based on a characteristic length of 0.7 times the water length. This approach is still used in some cases, and other facilities have adopted the same approach using the ITTC correlation line. One facility uses the Schoenherr line and a methodology that accounts for laminar flow ahead of stimulators. Piecewise calculation (stripping) of viscous resistance has been completed by a number of organizations, and three dimensional extrapolation using Prohaska's method to derive the form factor is used by various establishments with and without stripping. One establishment applies the total model form factor to the canoe body of the prototype and then calculates individual form factors for the prototype appendages. Previously conducted analysis [6] using model data from a non-winged keel twelve meter indicated that these different scaling methods can result in differences in prototype resistance as large as 8% at a 5 knot speed and 4% at an 8 knot speed.

Variations in performance prediction techniques, in addition to those described above, are primarily related to prediction of forces generated by the sails. Davidson's sail coefficients derived for GIMCRACK are still in widespread use. These have produced predictions in reasonable agreement with wind tunnel predictions and measured performance [7], but they do not permit prediction of reaching performance. Coefficients derived by MARIN for the complete range of sailing angles have been published [4] and produce windward predictions similar to the GIMCRACK coefficients [6]. Other sail coefficients, including those developed for the IMS handicapping system and proprietary data developed by individual syndicates are also in use.

3. CURRENT PROBLEMS

Based on experience since 1984 testing for six America's Cup syndicates, review of published information on test programs at other facilities, discussions with other experimenters after the 1987 races, and preliminary discussions with potential defenders and challengers for the 1991 America's Cup, the author believes that we, as operators of test facilities, face some very serious problems. The primary problem is that the designers require (would like to have) results that are accurate to a tolerance that may not be within our capabilities, regardless of the test or analysis techniques employed. Very small changes in performance, of the order of 1/2%, are significant on the race course. For a typical sailing speed of 8.5 knots this corresponds to a change in drag of approximately 2%. To the author's knowledge, no test facility has published data showing the repeatability in drag measurements over a period of time of three to four years. Casual conversations with experimenters and designers have resulted in claims ranging from 1-1/2 to 2%, to 4 to 5%. Based on an analysis completed using a 1/3 scale standard model, tested over a 20 month period at ARCTEC Offshore, it appears that the full scale drag can be predicted within 1-1/2% from upright tests, and 3% from heeled and yawed tests. It must be noted that these values were achieved after significant development efforts and experience with test gear and procedures, and during the course of several years of testing, cases existed where experimental errors were larger than these values. Recently, repeat tests of a cruising yacht indicated that both upright and heeled yawed predictions were accurate within 1-1/2% over a two month period. Kirkman [8] claims that faired upright results are repeatable within 10% for 1/13.33 scale models, 5% for 1/8 scale models and that there is "no discernable difference" for 1/3 scale models. In any event, the author has heard designers express dissatisfaction with repeatability in data from most facilities that participated in the 1987 effort, including his own facility.

The reasons for limitations in repeatability include facility calibration and quality assurance techniques, design and understanding of dynamometry, turbulence stimulation techniques, and maintenance of model condition. Given the tolerances desired by the client, every aspect of calibration and quality assurance must be pushed to their limits. Even when this is done, limitations in test equipment can affect accuracy. Measurement of small changes in drag in the presence of very large side forces and roll moments is an extremely difficult dynamometry problem, and interactions can be caused by sensors, deflections in test rig fittings, use of indeterminate structures, and even deflections in the carriage. ARCTEC's approach to solve this problem has been to develop very stiff test gear and complete an elaborate calibration procedure used to define influence coefficients, which are then used when sensor outputs are converted to engineering units. This problem may be eliminated through use of the free-running test technique, however, this technique still requires measurement of orthogonal forces, and in addition requires precise measurement of several angles. One facility [7] addresses the problem by completing tests on both tacks and then averaging the results for each pair of headings. This same facility correctly points out potential errors due to slight misalignments of test gear in the basin, deflections and model assymetries. Even at 1/3 scale, model quality requirements are extremely rigorous. In addition to canoe body accuracy and fairness, accuracy and alignment of multiple appendages are critical to test results. The tendancy among U.S. groups is to provide models to the test facility which are built by a small boat builder. Usually these are sufficiently fair, however numerous problems have been experienced related to appendage alignment and degredation of models during a test session or between test sessions.

The issue of turbulence stimulation really deserves attention, especially since most recent designs include relatively small, thin-sectioned appendages. As stated previously, no standard technique exists and very little information is available on the effects of alternate stimulation schemes and different model sizes on full scale predictions. Inadequate stimulation can cause poor repeatability as well as erroneous prototype predictions. This is aggrevated by the fact that high quality, full scale data is not available in the public domain to check modelling or analysis techniques. Lack of available full scale data also prohibits intelligent assessment of alternate techniques for scaling viscous resistance.

4. FUTURE REQUIREMENTS

Recently, the San Diego Yacht Club and Sail America Foundation announced that the next America's Cup will be held in 1991, near San Diego, California. With the advent of advertising and increased commercial sponsorship, participation is expected to be high and most efforts will include significant hull development projects. A significant amount of model testing is expected, and the venue and rule changes will probably place more stringent demands on test facilities. In addition, the growing acceptance of professional yacht racing should start to generate interest in model testing for different types of racing yachts.

Typical wind conditions in San Diego are much lighter than those for Fremantle. This will result in significant design changes for the participating yachts, and they will be optimized for lower speeds. Test facilities will be required to place greater emphasis on these lower speed ranges and the issues of model size and stimulation techniques will therefore become more critical. In addition, if the boats are operating in an area on the drag curve that is less steep, improved accuracy in drag predictions will be required to maintain accuracy in speed predictions. Since viscous resistance will be a greater percentage of total resistance, scaling techniques will be more critical to accurate performance predictions.

Several expected design changes will also impact test facilities. Several designers from the 1987 cup races have said that the radical USA had the "fastest straight-line speed of any boat in Australia", and further development is therefore expected. This design incorporated very high aspect ratio control surfaces at the bow and stern, and the keel was a body of revolution. In addition, the 12 Meter Rule was recently modified to permit additional movable appendages such as wings with varying angles of attack and leading edge flaps on keels. Test facilities will have to deal with the problems of scaling lift and drag from these small appendages.

Based on the reported problems with USA, several additional test techniques may be required to optimise these radical designs. As the number of control surfaces increase, determination of optimum settings becomes more difficult, but this can be addressed simply by expanding test matrices. However, the area that has not yet been addressed is control surface use during maneuvers such as tacks. Dynamic testing and/or math modelling based on empirical coefficients may therefore be required.

Another area where development is required, is added drag and changes in a seaway. Although this will not be as critical in San Diego as it was in Fremantle, eventually we will have to address this area. Based on the similarity of the boats, and the tolerances desired by designers, determination of differences in added drag for alternate designs may be beyond the current technology. Also, due to the fact that very few facilities exist that can test large models in realistic windward sailing conditions with waves, the affects of waves on lift and lift to drag have been given very little attention. This may be very important for designs similar to USA, and test facilities may be required to develop techniques to address this problem. Previous work at Davidson Laboratory [9] indicated that head sea tests were relevant for conventional designs, however this may or may not be the case for unconventiona designs.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on a review of model testing completed for the 1987 America's Cup races and expectations for the next event, it appears that participating test facilities must address a number of basic problems if model testing is to improve as a valuable design tool for these efforts. Since very little data (especially full scale) exists in the public domain, and currently active facilities are using such diverse techniques for testing and analysis, the required research and development efforts may be beyond the resources of any individual facility. The author therefore believes that it would be in the best interest of participating facilities to begin to work together to address some of these basic problems.

The stated aim of the ITTC is to "stimulate progress in solving technical problems of interest to tank Directors and Superintendents who are regularly responsible for giving designers, builders and operators of ship and marine installations advice based on the results of experiments with models". It is therefore recommended that the ITTC establish a forum for addressing the problems that currently exist related to sailing yacht model testing and performance prediction. This forum could take the form of a new committee on Sailing Yacht Performance, or it could be addressed by forming a special working group under an existing committee such as Resistance and Flow. If such a forum is established, the following areas should be addressed.

1. Assemble high quality full scale and/or comparitive model data that can be used by facilities to evaluate their testing and performance prediction techniques. Under the auspices of ITTC, it is likely that full scale data could be made available for one or more "second string" 12 meters which were sailed in Fremantle. In addition, testing of a standard design by various facilities would be of great value.

2. Stay abreast of developments and encourage research in the area of turbulence stimulation. It should be noted here that stimulation requirements for yachts are different than those for ships due to operation with an angle of attack and the presence of various sized lifting surfaces.

3. Stay abreast of developments and encourage research in the area of scaling viscous resistance. Again, requirements are different than those for ships.

4. Review performance prediction procedures and consider developing standard procedures.

5. Encourage research into seakeeping and the effects of waves on drag, lift, and appendage performance.

To date, a great deal of effort has been expended by individual facilities and their clients addressing problems associated with performance prediction for sailing yachts. These efforts have led to the wide variety of techniques currently in use, and the resulting lack of information which can be used by a facility to measure its capabilities and intelligently address clients' needs. Cooperative efforts in the areas described above should improve the capabilities of all participating organizations and, more importantly, should improve our collective credibility with the industry.

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18TH ITTC
Contribution to Group Discussion
in Yacht Testing

"SOME CORRELATIONS OF 12 METER MODEL TEST RESULTS"

by
P. Ward Brown*
and
Daniel Savitsky*

INTRODUCTION

Within the past several years most of the 12 Meter yacht design community has been favoring the use of 1/3 scale models in developing their designs. While the expense of such large 20 ft models and their associated towing tank costs appear to be affordable in 12 Meter campaigns, such costly model tests cannot be tolerated in the design of the average yacht. It would be unfortunate if economic considerations were to deprive innovative yacht designers of a valuable tool to develop new concepts and to expand the hydrodynamic technology of sailing yachts.

Fortunately, some laboratories, particularly those in Universities, have continued to test models smaller than 1/3 scale. With meticulous attention to test technique, dynamometry design, and scaling procedures, it has been shown that smaller models are indeed credible and can be a great asset in economically and rapidly developing new hull concepts.

It is the purpose of this brief contribution to the ITTC "Group Discussion on Yachts" to summarize recent published and unpublished test results using model scales from 1/10 to 1/3 as obtained at the Davidson Laboratory; University of Southampton; DTNSRDC; and MIT. This is not the forum to discuss the nebulous term "scale effect" which seems to mean different things to different people. Every model, regardless of size, has some scale effect which must be accounted for in developing full scale performance predictions. Since tank testing is but one of many tools used in design, providing the designer with some options in selecting model size would be most useful.

HISTORICAL RECORD

The defense of the America's Cup has had a profound influence on sailboat test techniques because the success of Ranger in 1937 was accepted as validation of Dr Davidson's model testing technique (Reference 1). For nearly 40 years after, eight successful cup defenders were designed using 1/13 scale models tested at the Davidson Laboratory. In 1973 both "Mariner" and "Courageous" were developed in the same Davidson Laboratory tank using small size models. Yet, over the years, one has been referred to as a terrible experience brought on by the use of a small model and the other as the ultimate hull form of its time. At the time of the tests, the Davidson Laboratory knew of the relative merits of the two designs which, for ethical reasons were not made available to either designer, but the comparison has now been published (Reference 2). The relative performance of the two yachts is shown in Figure 1. In view of this

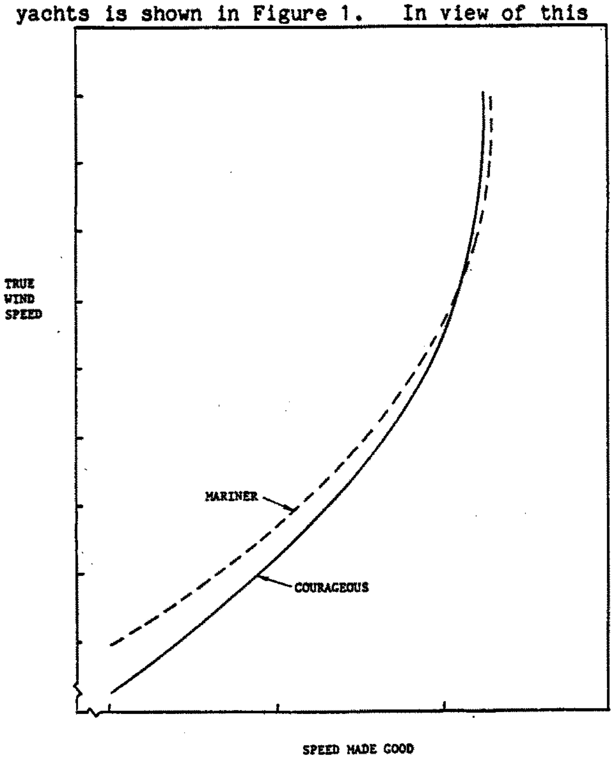

FIGURE 1 SMALL MODEL PREDICTION OF THE PERFORMANCE OF 12 METERS "MARINER" AND "COURAGEOUS"

evidence of the superior performance of "Courageous" which was also demonstrated in full scale, it is impossible to conclude that the small scale "Mariner" tests were misleading.

COMPARISON OF 1/10 and 1/4 SCALE RESISTANCE VALUES FOR VICTORY 83

Campbell and Claughton, at the University of Southampton U.K. made extensive use of 1/10 scale models in the development of 12 Meter hull forms for the 1987 New Zealand America's Cup entry. (Reference 3). However, in keeping with the trend in 12 Meter yacht development, they also conducted some tests on 1/4 scale models using the Number 1 tank at the Admiralty Research Establishment (ARE). This experience provided the authors with the opportunity to examine the validity of their scaling procedures by comparing results from tests at two model scales. A comparison of

*Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ USA

predicted full scale upright resistance values for Victory '83 is given in Figure 2 (taken from Figure 11 of Reference 3) and shows excellent agreement between both model scales.

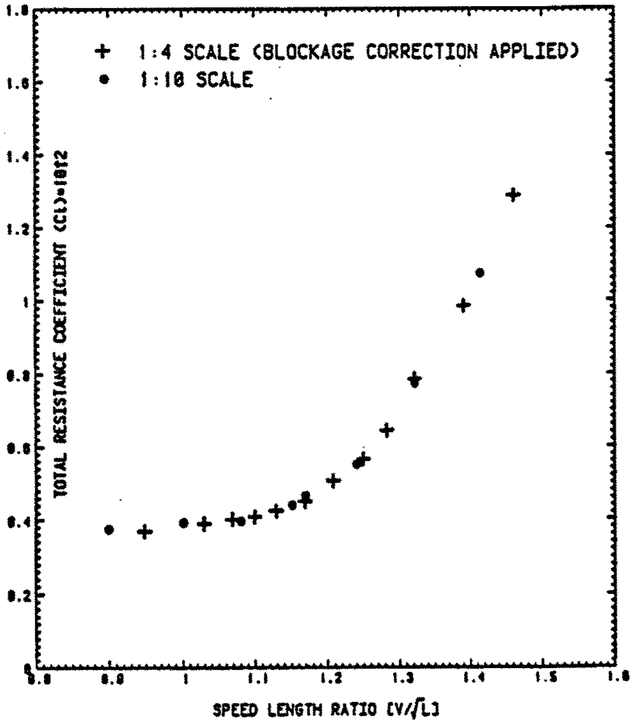

Fig. 2 Comparison of resistance values for Victory 83 from 1:10&1:4 scale tests

Campbell and Claughton conclude that tests of 1/10 scale models will provide results of use in tackling many design problems.

COMPARISON OF 1/8 and 1/3 SCALE RESISTANCE VALUES FOR WINGED-KEEL HULL FORM

In a recent development of a winged-keel hull 1/8 scale model tests were conducted at the Davidson Laboratory in their 12 ft wide tank, and 1/3 scale tests were conducted at DTNSRDC. These tests were of course, conducted by different test crews but all the results were analyzed by the sponsoring syndicate. Figure 3 presents previously unpublished data relating the drag to side force squared for three heel angles at a full scale speed of 8 knots. This plot clearly shows that, when extrapolated to full scale, the agreement between the 1/3 and 1/8 scale model is quite good.

APPENDAGE TESTS AT LOW REYNOLDS NUMBERS

In a recent experimental study, unrelated to 12 Meter yachts, Professor Kerwin at Massachusettes Institute of Technology conducted tests on symetrical air foil sections over a Reynolds number range of 1×10^5 to 5×10^5. In these tests, the fin was

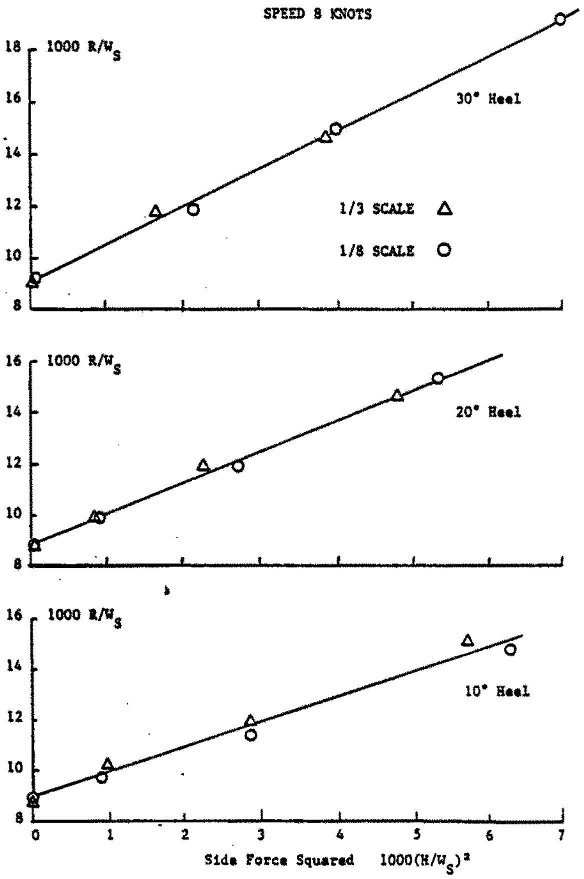

FIGURE 3 COMPARISON OF HEELED RESISTANCE OF 12 METER YACHT FROM 1/3 AND 1/8 SCALE TESTS

mounted on a body of revolution and measurements made of the fin normal force at angles of attack varying from 0 to 14 degrees. These previously unpublished results are shown in Figure 4.

It is seen that, at all angles of attack the normal force coefficient is essentially independent of speed, when the Reynolds number is greater than 1.25×10^5. Included on this plot are the Reynolds number for the winglet and keel of an 1/8 scale model of a typical 12 Meter yacht running at an equivalent full scale speed of 6 knots. It is clear that, for an 1/8 scale model, the normal force coefficient for these yacht appendages will be independent of Reynolds number over the test speed range of major interest.

CONCLUSIONS

There is accumulating evidence that models smaller than 1/3 scale can be useful in yacht development programs. Especially when budgets or the availability of large facilities are restricted, tests on smaller models will provide the means for rapid evaluations of various design options.

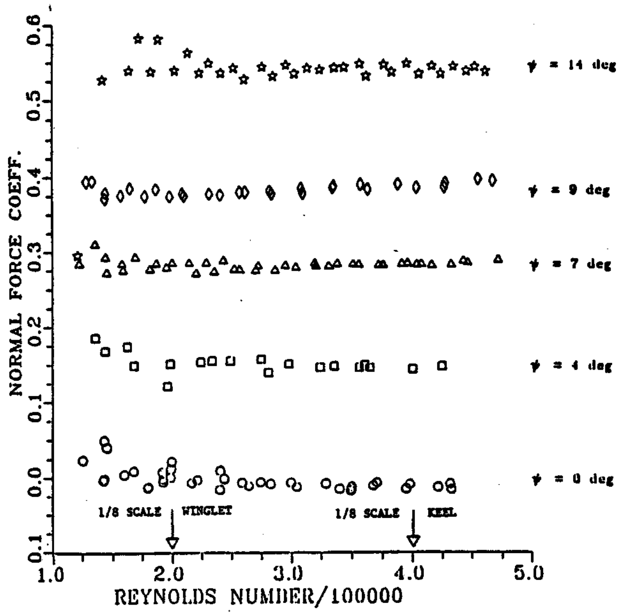

FIGURE 4 EFFECT OF REYNOLDS NUMBER ON FIN NORMAL FORCE

It is strongly recommended that the ITTC undertake a study of model scale options and establish a standard model prototype extrapolation procedure. It would appear that computational fluid dynamic models which are extensively used in 12 meter development programs, and which are Reynolds number dependent, can be most useful in guiding and analyzing the results of such a study. We offer this challenge to the ITTC community in the hope that their efforts will again provide the low budget yacht designer with an essential design tool.

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MODEL TEST OF A SAIL TRAINING SHIP

by

N. Takarada, J. Obokata

1. Introduction

The role of model test and kinds of test in the development of structure of sail training ship are not so different from those of the merchant vessel as far as the underwater factors are concerned. This paper relates to the water tank test which is peculiar to the sail ship and the wind tunnel test using the sail model. The principal particulars and the completion photograph of the Nippon Maru, which was the object of the present development, are shown in Table 1 and Fig. 1, respectively. The model ship used in the water tank test was reduced to a scale of about 1/22, and that of the wind tunnel test, about 1/75.

Table 1 Principal particulars of the Nippon Maru

Length (overall)	110.09m
Length (b.p.)	86.00m
Breadth (moulded)	13.80m
Depth (moulded)	10.70m
Draft	6.29m
Gross Tonnage	2,570 T
Sail Area (total)	2,760m^2
Main Engine	Daihatsu 60 SMB27NS x 2 1,500 PS x 2 at 234 rpm
Speed	13.2 knots
Number of Crew	70
Number of cadets	120
Owner	THE MINISTRY OF TRANSPORT OF JAPAN
Delivery	September 1984

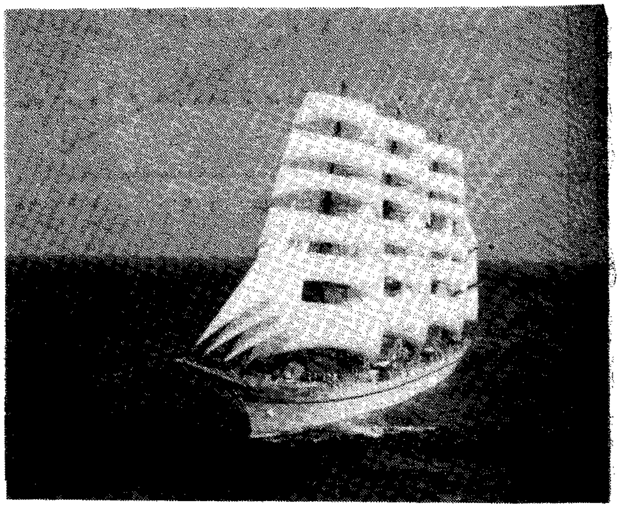

Fig.1 Nippon Maru in completed full sail condition

2. Resistance Test with Free Rotating Propeller

While sailing, the resistance of the propulsion system is a cause to lower the speed, and this countermeasures have been traditionally considered. Already in the middle of the nineteenth century, the hoisting screw was used, and in the modern ocean-cruising yacht, the feathering propeller which has collapsible propeller blades is widely used. The resistance test of the propeller which freely rotates while sailing is stated in this report.

(1) Test procedure

This is basically same as the ordinary self-propulsion test, and the rotating speed is variously changed near the propeller free rotating region, that is, near the propeller thrust is zero, and the towing force F, propeller thrust T and torque Q at various speeds are measured.

(2) Test results

An example of measurement is shown in Fig. 2. The result of resistance test without propeller is also shown. It is known that the towing force with propeller at zero thrust is nearly equal to the resistance without propeller.

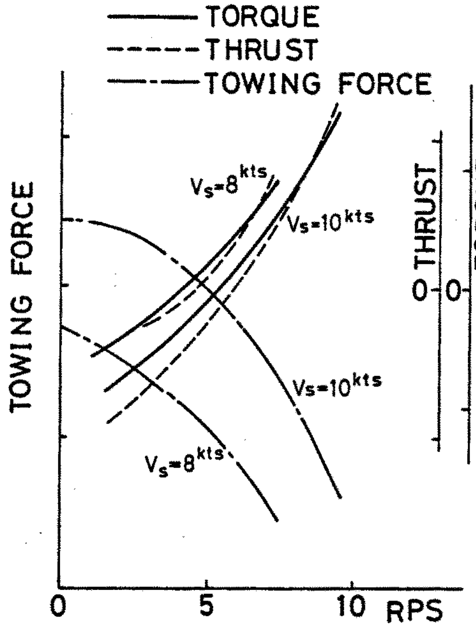

Fig.2 A result of resistance test with free rotating propeller

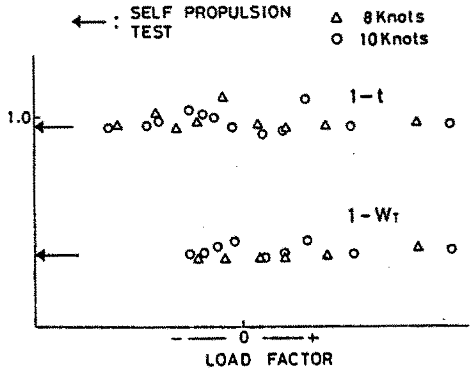

Fig.3 Self-propulsion factors

The self-propulsion factors determined by using the open characteristic of the model propeller used in the test is shown in Fig. 3, which shows that it is all right to use an ordinary values for the self-propulsion factors in the vicinity of the propeller free rotating region.

(3) Estimation of free rotating resistance in actual ship

Supposing the propeller free rotating resistance to be ΔR_T, the dimensionless ΔC_T is expressed in equation (1).

$$\Delta C_T = \Delta R_T / \tfrac{1}{2} \rho s \, S V_s^2 = -(1-t) / \tfrac{1}{2} \rho s \, S V_s^2 \qquad (1)$$

where ρs: density of sea water
S: wetted surface area of full scale
V_s: actual ship velocity

Rewriting equation (1) by using the wake ratio Ws of full scale and the propeller diameter D of actual ship, equation (2) is obtained.

$$\Delta C_T = -(2D^2/S)\,(1-t)\,(1-Ws)^2\,(K_T/J^2) \qquad (2)$$

Between the frictional loss ΔP_S of the shafting in the propeller free rotating state and K_q/J^3 of the actual ship, the following relation is established.

$$K_q/J^3 = 0.8389\,\Delta P_S / V_a^3 D^2 \qquad (3)$$

where $V_a = V_S\,(1-W_S)$.

If the ΔP_S of the shafting of the actual ship can be estimated, the K_q/J^3 is determined from equation (3), and by reading J, K_T in the propeller characteristic curve of actual ship and when the self-propulsion factor in the vicinity of free rotating region is known, the value of ΔC_T will be determined from equation (2).

Fig. 4 shows an effective horsepower curve including the propeller free rotating resistance calculated by using the self-propulsion factors obtained from the model test, by estimating the ΔP_S from the literature on this subject.

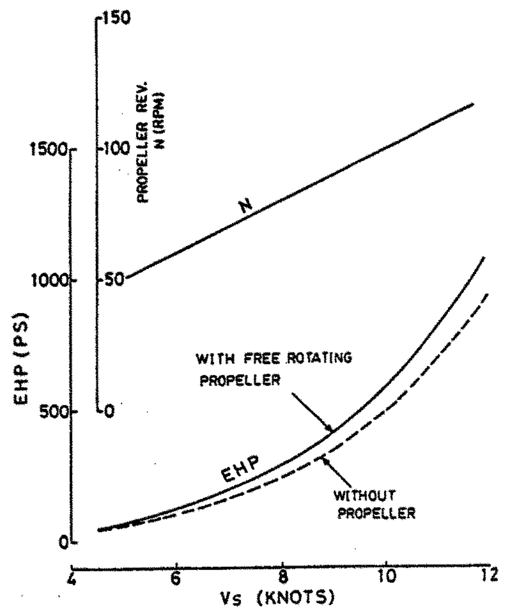

Fig.4 Effective horse power including the resistance of free rotating propeller

3. Oblique Towing Test in the Sailing Condition

When evaluating the navigation performance of a sail ship, in the first place, the stationary straightforward cruising in various wind directions and velocities must be basically considered. Its handling is considerably different from the powering technique of an ordinary merchant vessel because not only the thrust and hull resistance, but also heeling moment, turning moment and lateral force act on the hull. Since it is hard to investigate the sailing state directly in the model test, it is general to determine the hydrodynamic force by oblique towing test, and estimate the performance by numerical simulation by using that value. In the sail ship, however, since the hull is heeled except when sailing with following wind, the hydrodynamic force in heeling state must be measured.

As one of the structural features of a wooden sail ship, a large bar keel is noted. In the modern merchant vessels, bar keel is rarely used, and it is generally replaced by the bilge keel, which was, on the other hand, not used in the wooden sail ship. In the case of a sail ship, the role of bar keel is important, not only from the viewpoint of the strength, but also in the light of increasing the lateral resistance, and the bar keel or box keel is used on the modern sail ship in steel structure. Therefore, in the sail ship, it is indispensable to measure the hydrodynamic force of the structure with bar keel.

(1) Oblique towing test with heel

Changing the drift angle β and the heel angle ϕ in a maximum range that could occur during sailing, the model ship is towed. The model ship is attached to the towing carriage by way of a force detecting system as shown in Fig. 5, so that the hydrodynamic forces X, Y, N, K acting on the ship can be measured. In this test, the rudder angle δ is 0°, that is, the rudder is located in the middle, but during the oblique towing, some fluid inlet angle is caused in the rudder, and as a result a rudder normal force (F_N) is generated. This is the so-called rudder sway damping force, and this force can be measured by the load cell mounted on the rudder stock. The mode of oblique towing test with heel is shown in Fig. 6.

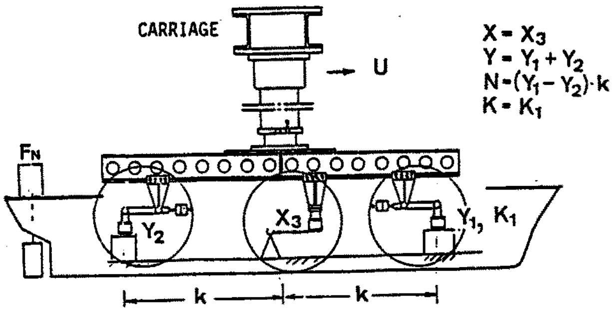

Fig.5 Force detecting system for the oblique towing test

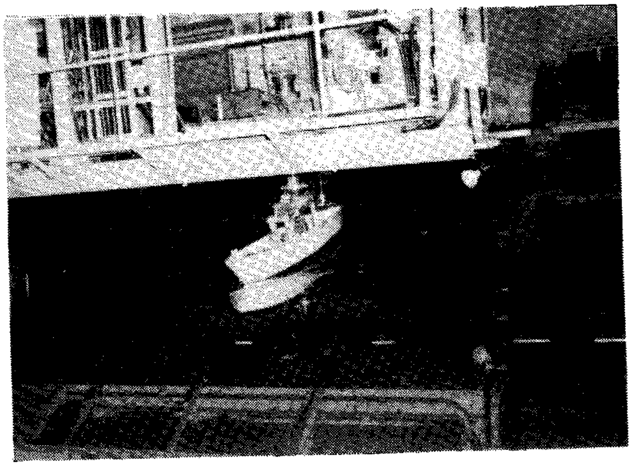

Fig.6 Oblique towing test with heel

(2) Test results

As an example of the test results, the effect of the heel is shown in Fig. 7. The test was conducted in a wide range of combinations of β and ϕ, but due to the definition of the coordinate system, the state in which β and ϕ have the same sign in stationary sailing does not actually exist.

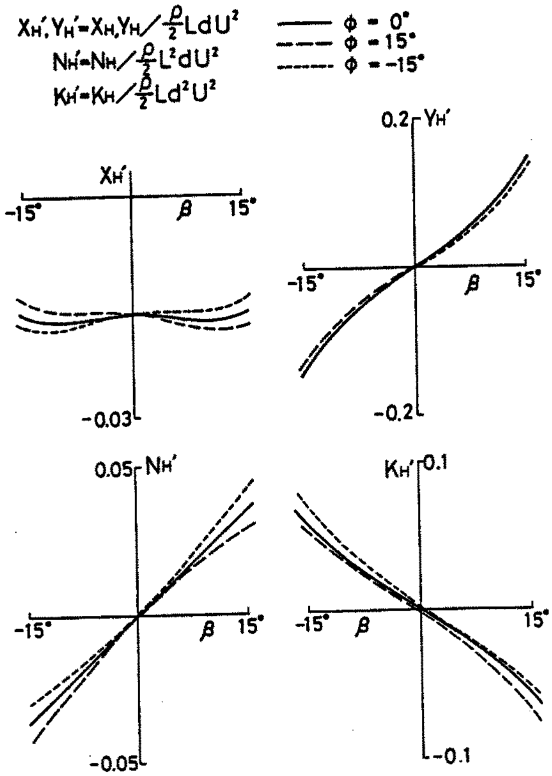

Fig.7 Effect of the heel on hydrodymanic coefficients

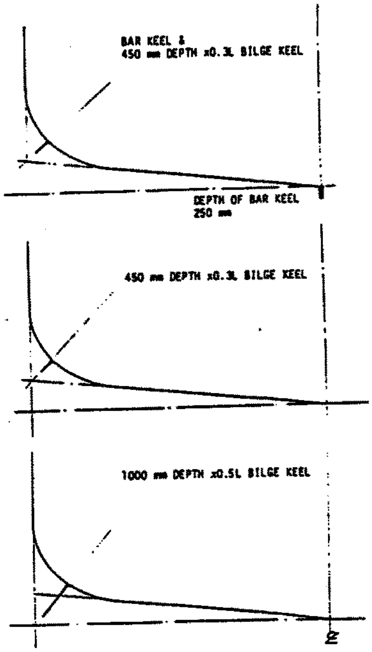

Fig.8 Model sections for the study of bar keel effect

(3) Effect of bar keel
To study the effect of bar keel, a model having only the bilge keel by removing the bar keel as shown in Fig. 8, and a model having a deeper bilge keel were compared in the oblique towing test, and the results are shown in Fig. 9.

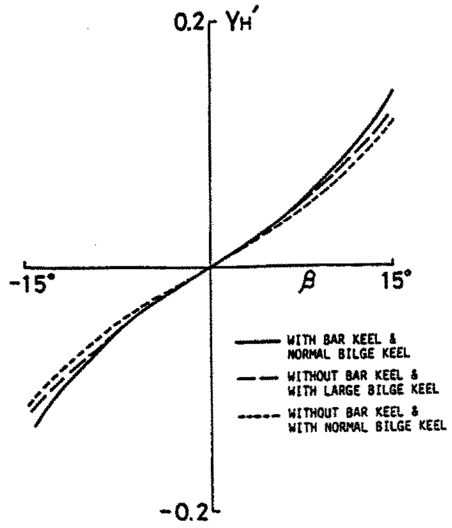

Fig.9 Effect of the bar keel on hydrodynamic coefficients

The effect of the bar keel on the lateral hydrodynamic force is significant, and in the case of bilge keel alone, even if the depth is considerably increased, the effect is not manifest unless the hull is heeled greatly.

4. Wind Tunnel Test of Model Sail Ship

To calculate the sailing performance, it is necessary to understand not only the underwater hydrodynamic force, but also the above-water aerodynamic force, that is, the force acting on the sail. Accordingly, using a model of the upper part above the sea level, a wind tunnel test was conducted. Although the model should be as large and as close to the shape of actual ship as possible, it is impossible to use a large model as used in the water tank test because of the limited size of the wind tunnel. In this case, the scale factor must be considered, but it generally seems that the scale rarely affects the lift force.

(1) Test procedure
As shown in Fig. 10, the sail ship model including the sea surface board is installed in the wind tunnel, and the wind direction and sail trim angle are varied at a constant wind velocity, and the wind force acting on the sail and the hull, and its moment are measured by using a 6-component load cell. In the usual sailing state, the heel is generally 10° or less, and in the wind tunnel test, this heel was ignored, and the test was conducted in an upright state. The model photograph is shown in Fig. 11.

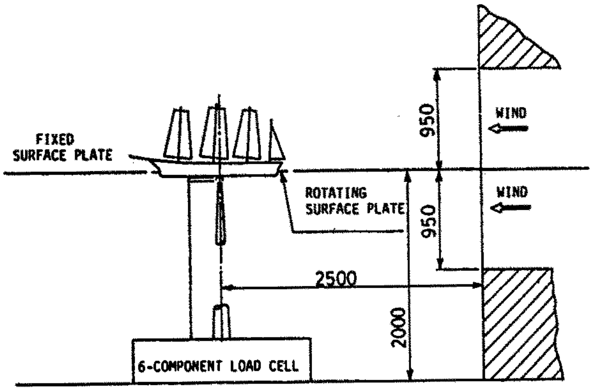

Fig.10 Set up of the wind tunnel test

(2) Test result
In the model test, it is next to impossible to match with the Reynolds number (Rn) of the actual ship. Therefore, in order to see the effects of the wind velocity on the wind force coefficient, the wind velocity was varied while keep-

ing the sail trim angle and the relative wind direction constant. An example of measurement is given in Fig. 12. As far as this result is concerned, the wind force coefficient remains constant if the wind velocity alters.

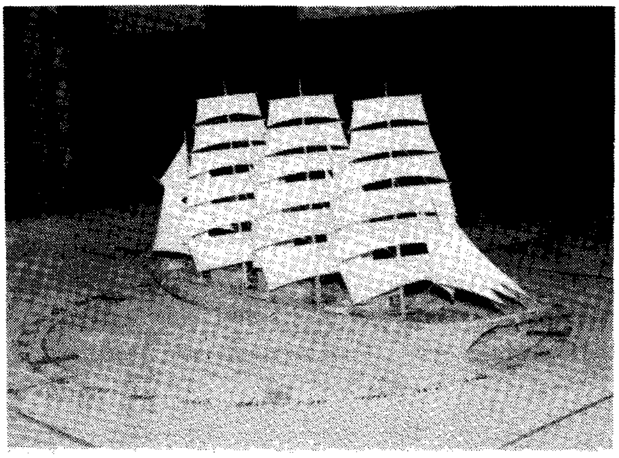

Fig.11 Model for the wind tunnel test

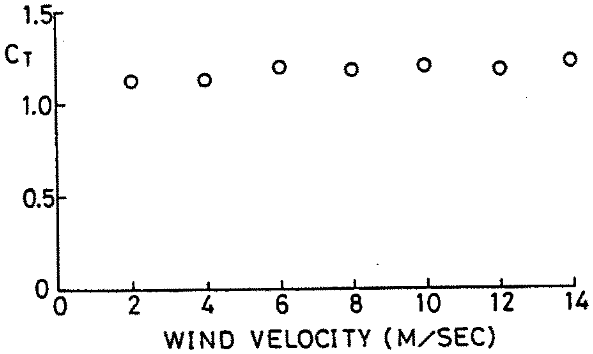

Fig.12 Effect of wind velocity on the wind force coefficient

The wind force coefficient in the full rigged condition is shown in Fig. 13. The maximum forwarding force is obtained when the relative wind direction is 120°.

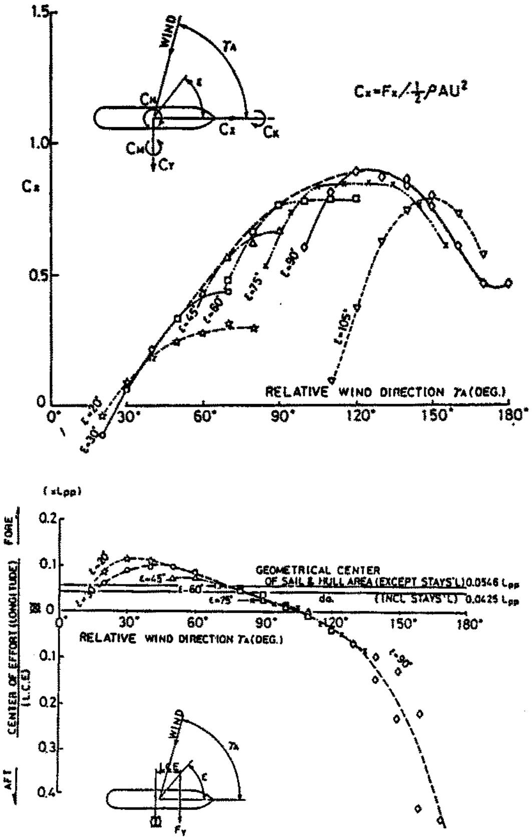

Fig.13 Wind force coefficients in the full rigged condition

5. Roll Motion Test

In the sail ship, since the effect of its sail by the wind force is significant, its rolling characteristic is estimated to be drastically different from that of the general merchant vessel. It is therefore important to perform the stability test including the oscillation in waves under wind force, and to precisely estimate the lateral accelerating relating to the mast stay strength. Accordingly it is necessary to measure the rolling angle and the lateral acceleration while the hull is stopped in the beam wave and wind which seems to be the severest condition for the ship.

(1) Test procedure
The model ship is supported by the jig using thin wires and chain weights as shown in Fig. 14 to prevent the heading angle from being changed by wave or wind, and, at the same time, the drift is arrested. In the beam wind, the sail angle of the square sail in the full sail condition is set in three points (33.75° from the center line), and the spanker is set 45° lee side.

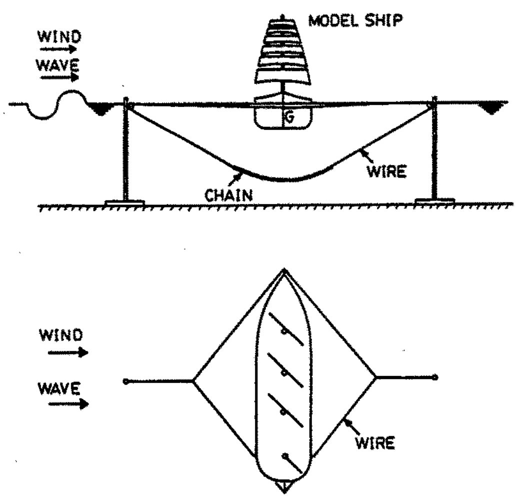

Fig.14 Setup of the roll motion test

(2) Test result
The rolling amplitude when the wind velocity is changed is shown in Fig. 15, and the sail damping effect comparing with bare pole condition is displayed together. The ship motion in waves can be calculated precisely by the strip method, but as for the rolling, theoretical method to estimate the damping coefficient precisely has not been established yet, and it is general to determine the damping coefficient by model test, and apply the result in the equation of motion. The calculated values in the figures are the results of solving by the strip method using the extinction coefficient (N coefficient) obtained by free rolling test. When the wind velocity is about 20 m/s, as compared with the windless state, the peak of rolling amplitude is known to be decreased to about 40% by the aerodynamic damping effect.

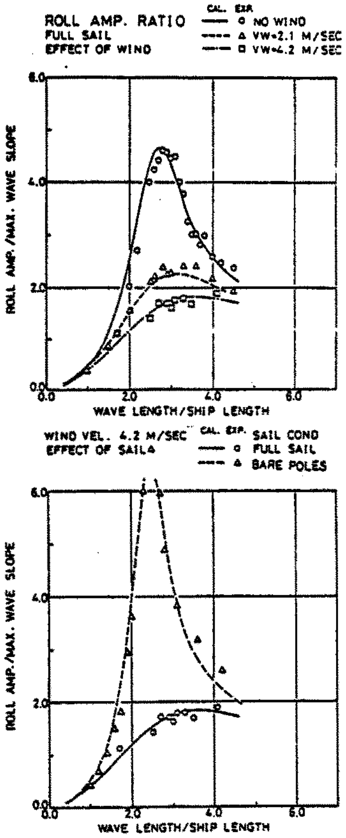

Fig.15 Effect of sail damping

6. Conclusion

The outline of the model test of sail training ship is reported in this paper although another important problem of interference between sails, and between sail and structure which is omitted is existing. Recently, many merchant sail assisted ships are used for the purpose of saving energy, and the leisure yachts are becoming popular and popular these days. The old and new ship, the sail ship, is expected to be further enhance in performance, gathering up the achievements of the latest technologies.

SLAMMING ON RACE SAILING YACHTS IN HIGH WAVES

V. FERDINANDE, State University Ghent, Belgium

According to their skippers, sailing yachts can "fall" into the wave trough. This would happen in high bow waves under 35−45 deg. heading, upon crossing the wave crest. The yacht is heeling to the lee side, hence, the impact of the hull does not occur in the keel line area, but at a location somewhere midway keel and deck line, between midship and stem.
On yachts built of composite materials, damage to the sandwich hull (delamination and crushing of the core) has often been observed midway the foreship part.

In view of determining at the design stage the necessary local strength of the hull, an upper limit of the vertical relative velocity with respect to the wave surface at the instant of impact is sought for.

A fairly realistic representation of the steep waves concerned is assumed to be given by the 2nd order Stokes wave. In severe weather conditions, the speed of the sailing yacht is expected not to exceed 10 knots.

For a given wave length, wave breaking begins at a wave height for which the vertical acceleration at the top exceeds 0.5g (Longuet-Higgins' criterium). For the present calculations, it seems reasonable adopting a wave height between the latter and the theoretical maximum 0.14 L_W.

The yacht cannot be considered at a displacement vessel when crossing a breaking crest, but rather as partly planing on the rear side.

The kinematics and dynamics involved are those of a beam rotating under the effect of gravity about a point C on the hull, a quarter length from the APP, which follows the wave profile (with a heading μ = 155−145 deg.) at forward speed V = 10 knots, but having a certain depth d at the moment the hull hits the wave surface in a point of the foreship, located on a diagonal corresponding to the heel angle (up to 45 deg.). That diagonal line shows an angle of inclination γ with respect to the tangent parallel to the logitudinal plane of symmetry. In C, this angle γ_0 is considered as a pitch-up angle when C is on the wave crest. Presumably, the highest impact pressure will be noted at the point where at the instant of contact this diagonal is parallel to the wave slope at that location. A general configuration is given in Fig. 1a.

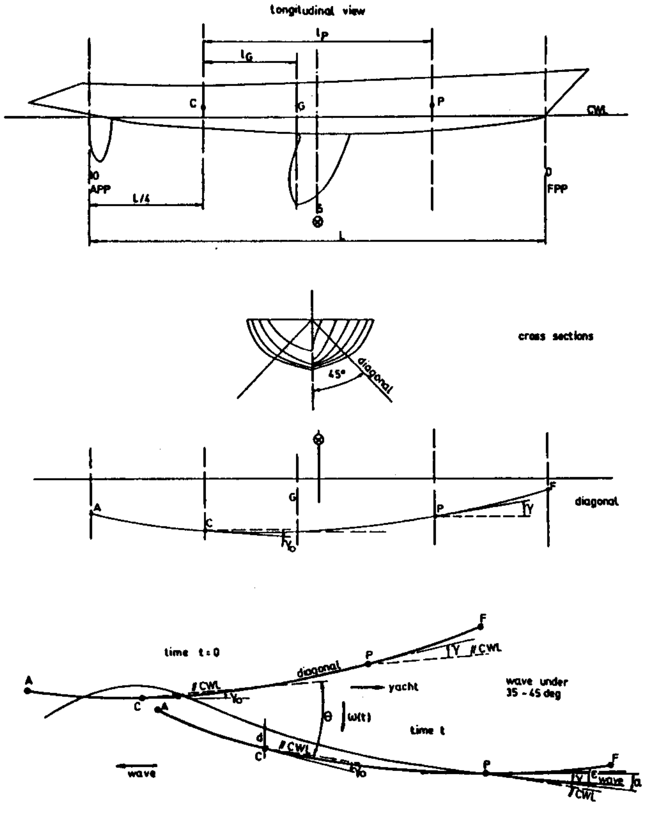

Fig. 1a.

The gravitational and inertial forces in the center of gravity G, resp. mg and ma, makes the hull rotate about C with a rotational velocity ω (t). The longitudinal moment of inertia I_C of the hull about C can be approximated by

$$I_C \cong (1.35\ \ell_G)^2 m \qquad (1)$$

where ℓ_G is the length CG (according to analysis of existing maxi–race sailing yachts).
The equation of rotational motion is

$$I_C\frac{d\omega}{dt}+m\,\ell_G a+m\,\ell_G g=0 \tag{2}$$

The instant t of contact of a point P (ℓ_P from C) with the wave surface can be found by means of the following relations

$$h_P=\zeta(0;t)-\zeta(\ell_P;t)=\zeta_A\cos\omega_e t+\frac{\pi}{\lambda}\zeta_A^2\cos 2\omega_e t$$
$$-\zeta_A\cos\left(\frac{360}{\lambda}\mid\cos\mu\mid\ell_P+\omega_e t\right)$$
$$-\frac{\pi}{\lambda}\zeta_A^2\cos 2\left(\frac{360}{\lambda}\mid\cos\mu\mid\ell_P+\omega_e t\right) \tag{3}$$

$$h_P-d+\frac{\theta_0\,\ell_G}{57.3}(\ell_P/\ell_G)\cong(\theta\,\ell_G)\times\frac{\ell_P}{\ell_G} \tag{4}$$

where

$$\theta\,\ell_G=\frac{1}{2}\left(\frac{g}{1.82}\right)t^2$$
$$-\frac{\zeta_A}{1.81}\left(1+\frac{\pi}{\lambda}\zeta_A-\cos\omega_e t-\frac{\pi}{\lambda}\zeta_A\cos 2\omega_e t\right) \tag{5}$$

(ζ = wave surface elevation, ζ_A = wave amplitude, ω_e = circular frequency of encounter).
The situation at the moment of contact in P is given in Fig. 1b.

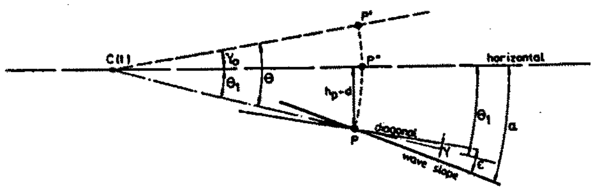

Fig. 1b

The vertical relative impact velocity in P is determined by the velocity derived from the relations above, and the vertical velocity difference between C and P:

$$v_{rP}=-\mid v_P\mid\frac{d\zeta(x_C,t)}{dt}-\frac{d\zeta(x_P,t)}{dt} \tag{6}$$

Also the longitudinal location from the wave crest is determined. Of particular interest is the inclination angle of the diagonal with respect to the wave slope α

$$\varepsilon=\mid\theta_1\mid+\alpha-\gamma \tag{7}$$

Computations have been executed for an existing maxi–race yacht of L_{WL} = 18m(Desperado), in waves of different lengths (20 to 80 m) and heights at which crest breaking is expected (resp. 2.2 to 8m).
For example, at P on 0.75 L from APP, the relative vertical velocity goes up to 10m/s, (L_W = 50 and 60 m), but the longitudinal inclination angle ε has a lowest value of -9 deg (neg.ε = position in Fig. 1b). In all cases considered this ε had a negative value (lowest value 7 deg. for L_W = 20m, but then V_r = 5.5 m/s).

The impact pressure is represented by

$$P=k\frac{1}{2}\rho V^2_{rP} \tag{8}$$

where k will be determined experimentally.

The existence of a longitudinal inclination angle ε at the time of contact in P with respect to the water surface has an important influence on the impact pressure on the corresponding hull section. The largest part of the hydrodynamic pressure built up during the entrance into the water is due to the rapid growth with time of the velocity potential. When ε = 0, the flow around the cross–section at P could be considered as two–dimensional; when $\varepsilon \neq 0$ the flow is three–dimensional, and at the same entrance velocity the pressure P will be lower than in the case ε = 0; but its theoretical computation is more intractable.
An experimental device has recently been constructed in Belgium. It consists of a derrick on four floating pontoons (Fig. 2), from the top of which a properly ballasted panel of $2m^2$ surface, a full scale sample of the local hull shape around the diagonal at 0.75 L, can be released and dropped from an exactly predetermined height above the water surface, the vertical contact velocity be-

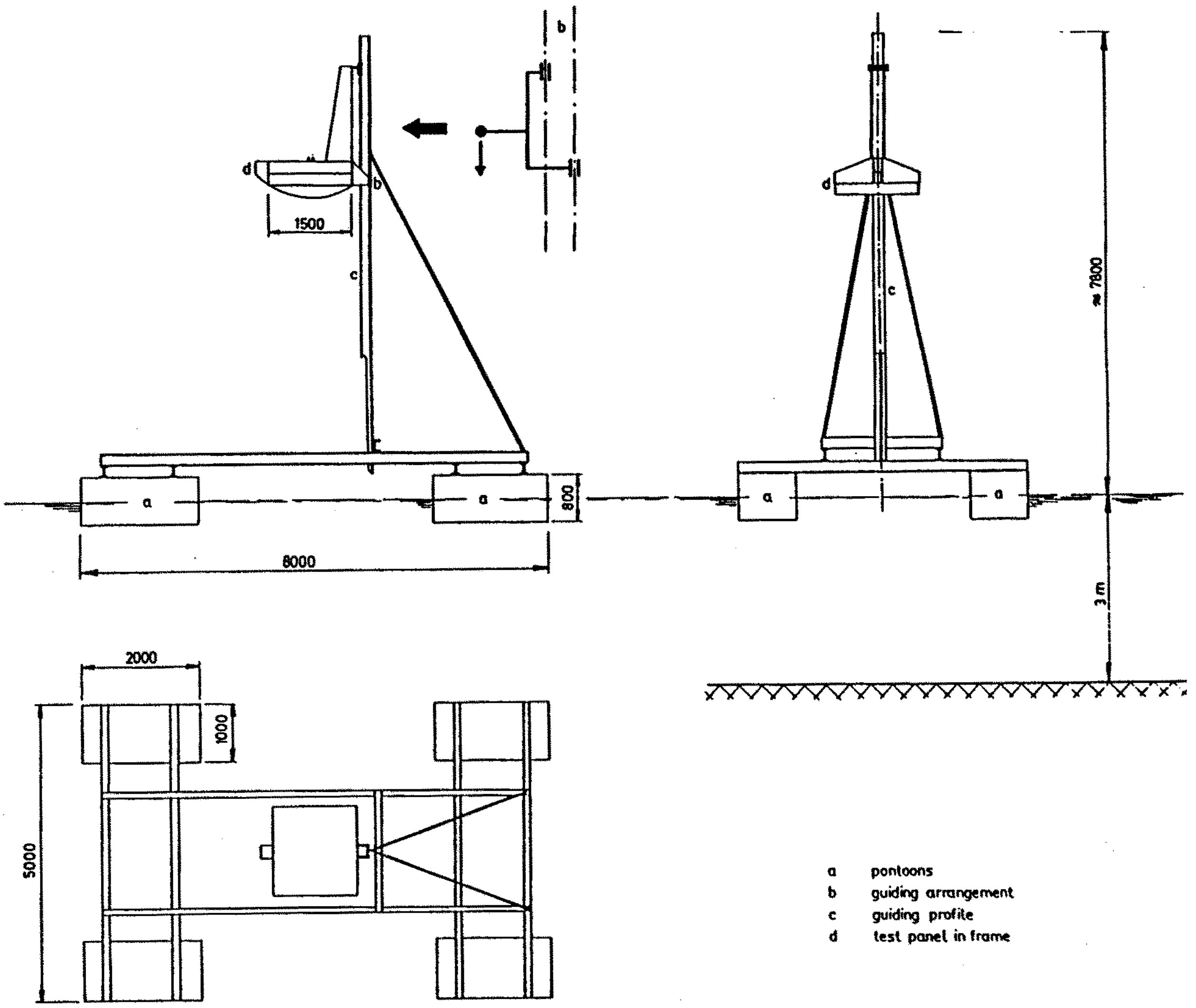

Fig. 2

ing known accordingly (max. height $5m \sim V_r \cong 10m/s$). According to (1) the equivalent impact mass at P is

$$m_{e(p)} = 1.82\ (\ell_G / \ell p)^2 m \tag{9}$$

m = ship's mass.

The panels, with given curvature, are fitted with pressure and strain gauges at appropriate locations, and a time history of high resolution of pressures and strains during the surface piercing process (of a few milliseconds duration) will be recorded by means of the synchronised electronic apparatus. The visual physical phenomena will be filmed by means of a high-speed camera.

From the time histories of pressure gauge signals from different locations, impact force-time diagrams will be derived, and the impulse evaluated.

The local water depth has to be sufficient in order to record the pressure and strain signals before the bottom reflected acoustic wave reaches the sensors and disturbs the signals.

The device is shown sketchily in Fig. 2. The

ballasted panel is held in the top by an independent crane, provided with a trigger. After release, the panel, properly fixed in a frame at the desired angle ε , falls freely between the specially arranged and strictly vertical guiding profiles, as indicated in the Fig. 2, without external friction.
From the knowledge of the hydrodynamic slam forces and force impulses, the value of equivalent static forces will be derived, being uniformly applied to some panels, while giving the same structural response, viz. the same degree of damage, going to extremes. The static experimental device consists of a bag of particular texture material placed upon the panel, brought under controllable pressure which is transmitted uniformly to the panel, where strains and deflections are measured.

The drop testing device has been designed by prof. R. Dechaene (State University Ghent) and built by the yacht−building yard AMTEC at Klein Willebroek, Belgium, with the financial aid of the Institute of Scientific Research in Industry and Agriculture.

READY FOR THE NEW CHALLENGE; MARIN extends facilities for 12−metre design studies

H. C. RAVEN and G. KAPSENBERG, MARIN, The Netherlands

The first signs of the coming America's Cup contest have already been perceived. While most syndicates have not yet started the technical part of the job, MARIN has completed an important stage in its own preparations for the new contest: the further development of the testing facilities and computer programs needed for this application.

In the September, 1986 issue of MARIN Report the large amount of work concerning the 1987 America's Cup races has been described. Eight different 12−metre syndicates used MARIN's services in their preparations for the races, both for towing tests and for flow calculations.

Eventually the finals resulted in the America's Cup returning to the United States: the yacht "Stars & Stripes" defeated the Australian defender "Kookaburra III". Many new syndicates have now been formed, and existing ones revived, for the next America's Cup challenge.

The optimization of a new yacht's performance on the race course in the conditions expected entails a complicated trade−off between many factors, which can only be made rationally if quantitative data are available. Developments in 12−metre design practice go towards an ever more extensive use of model tests and, particularly, of computational hydrodynamics tools to furnish these data. To meet this demand new experimental and computational facilities have been created.

PERFORMANCE IN WAVES

Besides the well−known sailing dynamometer in use at MARIN to test sailing yacht models in still water, a similar test set−up for assessing their behaviour in a seaway has now been developed. This system leaves the yacht complete freedom for all motions.

Similar to the still−water system the model is towed in the centre of effort of the sail forces. This assures that each test is a realistic sailing situation; a realistic combination of speed, heeling angle and leeway angle. For the tests in calm water, the mast is directly connected to the towing carriage; in waves there is a towing wire which connects the model to the carriage via a constant tension winch. This system allows the yacht to move dynamically with six degrees of freedom.

Instrumentation for the yacht consists of a roll and pitch gyroscope to measure these two angles. The position of the yacht is then determined by continuously measuring the position of two lightbulbs on the model. Furthermore, the force components on the towing wire are measured in a coordinate frame fixed to the model.

The experiments showed that tests in waves for a sailing yacht in realistic sailing attitudes are possible, and that measurements of motions with six degrees of freedom and of added resistance in waves can be performed. One more aspect of the yacht's performance entering the optimization!

DAWSON EXTENDED

In the September, 1986 issue of this magazine mention has already been made of the computer program DAWSON, which calculates the potential flow, wave pattern and wave resistance of a ship. Much experience with its use in commercial projects has been gained since, leading to a number of extensions and refinements still enhancing its usefulness and applicability.

This program has now been extended to accomodate lifting surfaces such as a keel, a rudder and winglets. These are represented by source panels on their surface and a vortex distribution on the camberplane and in the wake. From the set of boundary conditions on the configuration and the free surface, together with the Kutta conditions, all source and vortex strengths are found, and thus the complete velocity and pressure field. The forces and moments on the hull can be derived by pressure integration; in addition a number of other resistance calculations has been implemented having a greater numerical accuracy.

Further postprocessing programs have been created to support the analysis of the results. The calculation thus provides the wave and induced resistance, the side force on all components and its vertical distribution; the wave pattern, and the pressure distribution and streamline direction along the hull.

A crucial aspect for using this program as a design tool is the flexibility of the input process. Sailing yachts with wing keels are particularly complicated to represent by a panel distribution. The considerable time needed in the past for generating an adequate hull and keel paneling has now been drastically reduced by exploiting the capabilities of the geometry manipulation package PATRAN. This allows an easy orientation of the hull in the correct sailing attitude, automatic generation of the panel distribution and determination of the intersection lines between curved surfaces such as the keel and the hull. A special program then checks the smoothness of the panel and vortex distributions in order to maximize the numerical accuracy of DAWSON.

A new validation study has been made recently by recalculating the flow about the Australia II in typical sailing conditions and comparing the results with those of model tests. The diagram shows the calculated wave resistance with zero heel and leeway and the experimental residual resistance. The accordance is generally good except at the highest speed where possibly the favourable interaction between the stern wave and the large stern overhang (not included in the calculations) reduces the resistance.

The conditions typical for windward sailing, with heeling angles up to 33 degrees and the associated leeway angles, formed a severe test for the method because of the lift generated on the hull, keel, winglets and rudder and the asymmetry of the geometry and the flow pattern. Nevertheless the predictions turned out to be surprisingly accurate. The prediction of the side force is within 8% of the experimental value, and so is the total resistance. Indeed the side force/resistance ratio, one of the primary factors in windward performance, coincides exactly with the experimental result!

The pressure plots and wave patterns further illustrate some of the results. Much information can be gained from this kind of calculations, providing keys for further improvements and giving a sound basis for the designer's decisions. Owing to the extensive set of pre— and post—processing software and the remarkable accuracy DAWSON is a design tool with a large potential in the America's Cup racing world.

NEW SAILING YACHT DYNAMOMETER

J. M. GONZALEZ, El Pardo Model Basin, Spain

On the Spring of 1986, El Pardo Model Basin started the design and construction of a new rig for sailing yachts tests.
With the very useful advices from Frank DeBord, it was decided to design the rig for semi—captive models with lengths between four and five meters.
Specifications for the system were stated and they were very similar to those explained by Doctor Murdey in his contribution to this Group.
The initial System consisted in two towing posts linked to the ship model trough a rigid structure.
The final system had only a towing post forward and a very stiff guiding system at the after part of the model.
I have some photographs of the testing rig that I can show to interested people.
The testing period of the rig itself lasted several months and all the problems explained by Frank DeBord in his written contribution to this Group were detected.
I believe that this little history proves that the problems in testing sailing boats are, up to some amount, identified and therefore a Group of experts puting together their experiences in this area can find valid solutions in a short period of time.
Some subjects related with testing sailing boats, as well as with some problems of others Technical Committees, are identified as Instrumentation problems.
Therefore, if this Group would be created in the future, some help from Experts on Dynamometry and/or Instrumentation would be very useful.

ON TESTING METHOD OF SAILING YACHT

M. ABE, Akishima Laboratories (Mitsui Zosen) Inc., Japan

I highly appreciate that Dr. Murdey has finely categorized the modern testing technique of Sailing yacht.
My point is that the rudder effect is to be coupled with both in the captive and free sailing systems in order to attain more realistic conditions of full scale sailing.
In case of the free sailing system, the towing point, namely C.E. moves by compensating both the axial force and yaw moment, when leeway is given at a selected speed. This indicates in practise that a rudder should be effected to reduce the excess of leeway and/or heel.
My conclusion is that a rudder should not be constrained, but it should be adjusted to obtain the equilibrium of C.E. In this point of view, the free sailing system will be applicable as a realistic and economical method of testing.

CHALLENGING THE AMERICA'S CUP 1991

H. TANAKA, Ship Research Institute, Japan

This is an announcement of our challenging the next America's Cup Yacht Race. Japanese two parties, namely, we "Nippon Challenge America's Cup Committee" and the Bengal Bay Yacht Club conducted by Mr. Kobayashi have made the application for 28th America's Cup held at San Diego in 1991.

The Committee has organized in April, 1987 fully endorsed by the Nippon Ocean Race Club. The President Mr. Yamazaki has begun operations in technical development, construction and training of crews. It has been sponsored financially by thirty companies and has been assisted by several suppliers.

Design and technical research with the challenging yacht have just started in the sub−committee organized by excellent designers and hydro− and aero−dynamists. Dr. Tanaka, SRI is the chairman of it, and Prof. Maruo, Yokohama National Univ. and Prof. Fujino, Tokyo Univ. have joined it, and Prof. Nomoto from next year. Moreover, SRI, IHI Technical Research Institute and Akishima Laboratories have been expected to conduct model tank test and numerical analysis.

At present we have little technical product to be discussed, but we are heartily grateful that the excellent works developed by the participants at this meeting and others have extended big benefit to us.
The Committee highly appreciate in advance if you all pay kind attention to our challenging the America's Cup.

J. GERRITSMA and J.A. KEUNING, Delft University of Technology, The Netherlands

The Delft Shiphydromechanics Laboratory is presently extending their systematic yacht hull experiments with seven hull forms to include larger length−displacement ratio's up to $L/\nabla^{1/3} = 8$, larger beam−draught ratio's of the canoe body and larger length−beam ratio's.
This addition to our series will be made to cope with modern trends in yacht design and yacht design: a decrease in the weight of displacement and an increase in size, leading for instance to larger length−beam ratio's.

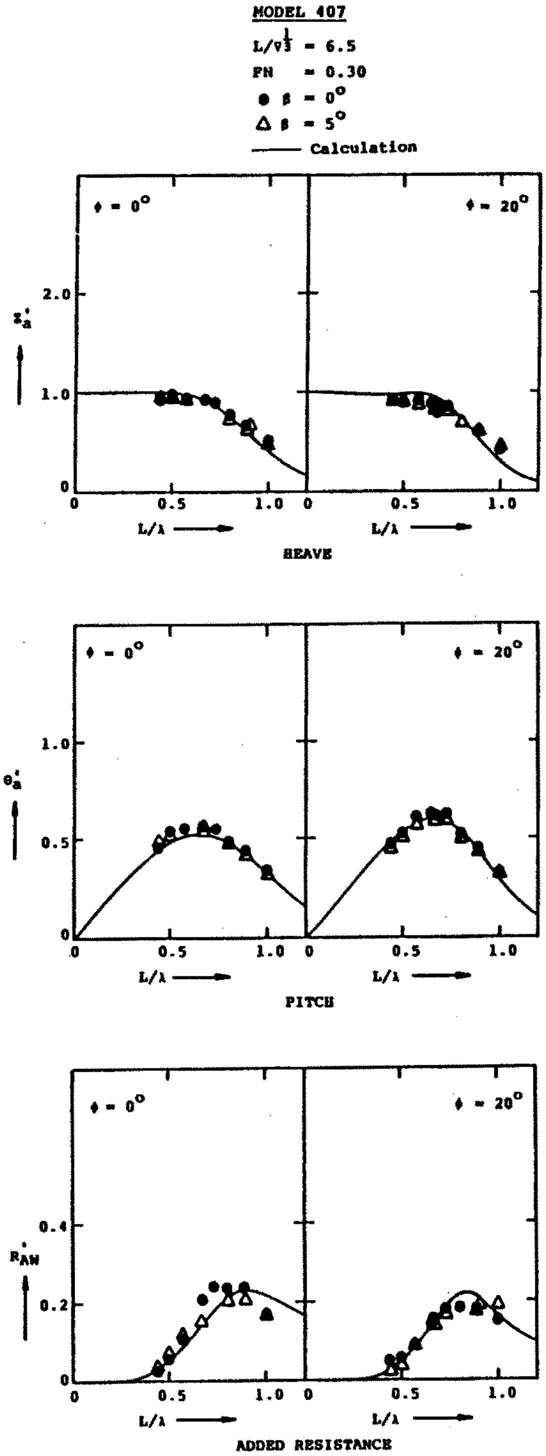

Fig. 1

Two models of the new series have been tested in waves: nr. 407 has a length−displacement ratio $L/\nabla^{1/3} = 6.5$ and nr. 455 is a heavy displacement hull with $L/\nabla^{1/3} = 6.5$.

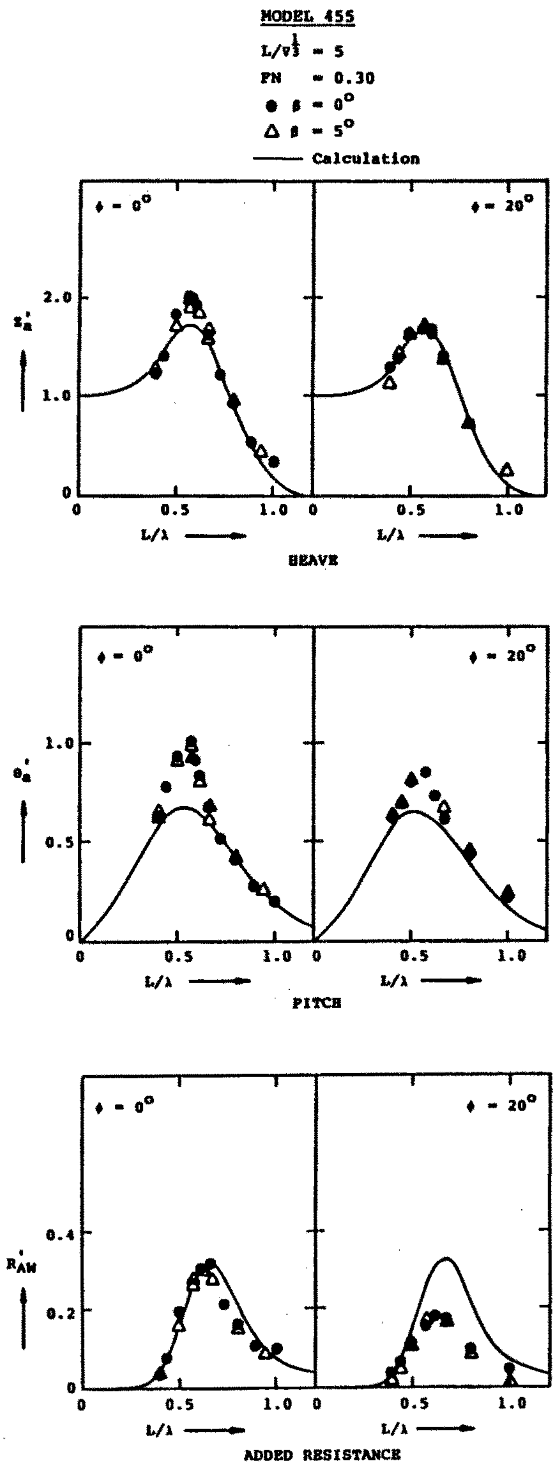

Fig. 2

The model experiments were carried out in regular head waves in wave lengths up to λ/L = 2.2 and wave heights up to $2\zeta_a/L$ = 1/40. The model was free to pitch and heave, but restrained in all other modes of motion. The test conditions included zero heel angle 20 degrees heel angle, zero leeway and 5 degrees leeway angle and one forward speed: Fn = 0.30.

The experimental results are shown in Figs. 1 and 2, where

$z'_a = z_a/\zeta_a$, $\theta'_a = \theta_a L/2\pi\zeta_a$ and $R'_{AW} = R_{AW}/\rho g L \zeta_a^2$.

The influence of a leeway angle on the motions and the added resistance is negligible. Also the differences between the conditions with and without heel angle is small, in particular for the light displacement hull form.

In this respect there is one exception: the added resistance for the heavy displacement hull is smaller when the yacht is heeled compared with the upright condition.

The experimental results are compared with calculations for the zero leeway case and the computed values for pitch, heave and added resistance are depicted in Figs. 1 and 2.

In general the correlation between the computations and the measurements is satisfactory except for the added resistance with heel of the light displacement hull. For this hull the motions at resonance are somewhat under estimated at resonance.

B. MÜLLER−GRAF, Berlin Model Basin, Federal Republic of Germany

I am mainly involved in tank tests of high speed engine driven hulls, but not in yacht testing. But I am sailing since more than forty years all kinds and sizes of keel and centreboard boats. From this point of view, I like to draw your attention to the necessity of additional measurements of the keel and rudder forces. All the presented and discussed measurement devices are only suitable to determine hydrodynamic overall forces and moments. But in developing a new keel form the keel−hull interactions and the ef-

fect of the keel as well on the total resistance as on heel and yaw must be thoroughly known.
The effectivness of the keel depends not only on shape, profile and position relative to the hull but also on the interplay with the hull body and its flow. Therefore it is necessary to measure the forces and moments of keel and rudder separately but together with the overall hull forces. In this respect a special dynamometer has been developed some years ago at the Technical High School in Kiel which allows to measure simultaneously the overall forces but also as the rudder and keel lift and dr y means of special load cells. I like to ask the authors of the papers dealing with the equipment of yacht testing, why they did not account for the keel and rudder forces and the keel—hull interactions?
Thank you for your attention.