THE ELEVENTH CHESAPEAKE SAILING YACHT SYMPOSIUM

A Review on *Il Moro di Venezia* Design

Mario Caponnetto, University of Genoa, Genoa, Italy

Introduction

The design of a boat for the America's Cup has always been a challenging task for any naval architect.

While in the past the success of the boat was mainly a question of sensibility and experience of the boat designer, lately the increasing technologies and economical means usually at the disposal of the syndicates provides great potential.

Both experimental and theoretical tools require a specific technical knowledge of the matter, which leads to the involvement of many specialised people in different fields.

For this reason a big managerial effort is required to organize and collect data and ideas coming from different fields.

This paper summarises the first experience of the "Il Moro di Venezia" syndicate in dealing with the design methodologies from the hydrodynamic point of view. While a great part of the collected data are still of confidential nature, here a brief history of the design work and some peculiar aspects regarding the use of tools like the towing tank, the wind tunnel, the CFD codes and the VPP are presented.

Calm Water Tank

From the beginning of the challenge a big effort has been devoted to the tank testing of hull and appendage models.

All the tests have been accomplished at the Rome water tank INSEAN (Istituto Nazionale per Studi ed Esperienze di Architettura Navale), whose only previous experience in sailboat testing were a limited number of test on a medium size model of the 12 m. "Azzurra" for the 1983 America's Cup.

The big dimensions of the main tank (470 x 13.5 x 6.5 m) and the noticeable technical and human resources present at the INSEAN, were promising for a successful project.

Soon the design and the construction of a very sophisticated test rig, able to tow very large sailing boat models, was started.

Considering the tank dimensions, a big scale ratio seemed to be ideal to minimize the scatter on measurements due to noise, and the scaling error from model to full scale, which are known to be the main sources of uncertainty and error in sailboat testing.

Thanks to the water tank length, up to three tests were performed during one course of the carriage.

Repeatability analysis proved that the performance of the test rig was acceptable, but also showed that extreme care should be devoted to the control of the ambient conditions during the test, expecially the temperature in the tank and the residual flow of the water due to previous tests.

The first factor greatly affects the friction drag of the model but can be easily calculated with simple formulas, while the second factor can cause serious scatter in the measure of the lift and the induced drag and is more difficult to control.

The early work in the towing tank also included a detailed analysis on the way to correctly stimulate turbulence over the hull and the appendage.

The analysis was partly performed with the aid of numerical viscous flow codes, that allowed the calculation of the local thickness of the boundary layer and the pattern of the stream lines.

Both factors allow the correct location of the stimulators and avoid the possible omission of stimulation over certain hull portions.

Special care was devoted to the construction of the carbon fiber models, having in mind the important requirements of stiffness, lightness and accuracy of construction.

The CAD/CAM process started with the design of the hull surface, which was done by the designers with Mac Surf.

Then the hull files were developed with Unigraphics and Catia commercial computer graphics programs, and finally sent to the numerical control machinery for the construction of the mould.

A large number of hull models, plus a certain number of appendages including keels, bulbs, rudders and winglets, were built and tested.

Of these hull models, about an half formed a limited systematic series developed from a parent hull, systematically modified in the main parameters such as displacement, prismatic coefficient, beam to draft ratio and longitudinal center of buoyancy position.

The systematic approach seemed to be the most rational and promising, considering the lack of experience in the new rule and thanks to the time and the means at disposal at the beginning of the challenge.

Indeed at that time it was a hard thing to foresee what characteristics an IACC boat should have. A parametric analysis of the rule was required to clarify many points to the designers.

The standard procedure on each model included a series of runs in the upright condition over the whole range of practical Froude numbers, plus certain other runs for given combinations of speed, heel and yaw.

Also the vertical location of the center of effort was varied in order to simulate different sail sets.

Further refinements included rudder and trim-tab adjustement.

A large amount of work was done by W. Michelini who continuosly improved the regression formula used to join and correlate the experimental points.

This is indeed a critical task for the tank test analysis. While we know that a boat can sail in quite infinite combinations of speed and trim, practical constraints limit the number of combinations simulated in the towing tank.

A deep physical comprehension of each phenomenon is then required to find interpolating functions able to represent correctly the behaviour between the experimental points.

Keeping in mind that the difference of time predicted by the VPP to run the America's Cup course seldom exceeded a couple of minutes even for quite different model shapes, it is clear how much care is required at each step of the data chain.

While the towing tank tests on the models of the systematic series were going on, the first "Il Moro di Venezia" (Moro 1), designed without any previous experimental support, was launched in Venice.

It was essentially a laboratory boat, useful for the education of sailors, sailmakers and designers.

Then Moro 2 followed, whose parameters, in order to span the IACC rule, were opposite those of Moro 1. Comparative tests between the two boats held in Palma de Mallorca, showed an excellent agreement with the VPP prediction, using the tank results of the systematic series.

This result was encouraging for the engineers working on model testing, and showed that tank results could be successfully used for the optimization of the hull shape.

After a historical analysis of the San Diego statistical weather conditions, the VPP supplied the theoretical "optimal" boat of the systematic series.

Keeping the main parameters of the optimal boat, a further work of refinement and fairing lead to the design of a new model.

The model was tested in the towing tank, showing the expected results, and their lines became that of Moro 3, (that won the 1991 IACC World Championship).

The model also became the parent of a new series of hulls tested in the towing tank, that allowed a further refinement of the shape, which lead to the design and construction of Moro 4, and finally lead to the design of Moro 5 that won the Louis Vuitton Cup and that participated in the America's Cup.

Besides the analysis on hull shape, a further analysis on appendages was performed in the towing tank.

The analysis was obviously related to the knowledge of those phenomena of non-viscous origin, that are essentially the lift, the induced drag and the wave resistance. Viscous phenomena were mainly studied in the wind tunnel.

Between the others, a series of 7 systematically modified bulbs were tested, supplying interesting information on induced and wave resistence.

The influence of the keel chord length was studied too, as well as the shape and position of the rudder and the effect of winglets.

Particularly useful was the analysis of the so called "trim drag", that is the additional induced resistance due to non-optimal distribution of load between keel and rudder, determining the optimal angle of rudder and tab (if any) in the different sailing conditions.

Seakeeping

While calm water tests proceeded until the end of the challenge without special problems, we can't say the same for the seakeeping tests.

These tests had to be executed in the tank number 2 of the INSEAN, which was equipped with a wave maker and having dimensions 200 x 9 x 4 m.

Due to the reduced dimensions of the tank, compared to those of tank number 1, it was decided to build and test a series of models of reduced scale ratio.

Some of these models were the reduced copy of those of the systematic series tested in the calm water tank, while the remaining were special models designed to analyze particular problems, such as the effect of the overhang and different shapes of the bow.

The test rig was built on the skeleton of an existing one used at INSEAN for seakeeping on conventional ships. It slid over two rails fixed to the bottom of the carriage, and during the run was kept in an average equilibrium position by means of a constant thrust equipment.

The model was fixed in yaw, while another mechanism applied a constant vertical force at the end of a lateral arm, then supplying constant heeling moment to the model and allowing it free heeling movement around a mean value.

This kind of test rig gave good results during the upright seakeeping test, but when the model was tested heeled and yawed at the critical wave frequency the rails of the test rig bent significantly, showing the inadequacy of this test rig for sailboat testing

For this unexpected problem, the syndicate asked the Defender for permission to execute the tests outside Italy, not having any other water tank equipped for seakeeping tests at disposal inside Italy.

After a check, the SSPA Swedish tank was selected, mainly because of its experience in the seakeeping field and its equipment including a very efficient test rig for sailboat testing in waves.

When everything was ready for the forwarding of models to Sweden, notice arrived from USA, stating that the Defender denied permission to test models outside Italy.

Without any experimental support, a theoretical approach was investigated utilizing a code written by R. Biscontini and based on the strip theory.

Although this theory gives good results for the analysis of ships in waves, where it is extensively used, the linearities (which are the basis of the method) are seldom justified for a sailing boat even in moderate wave conditions. The method completely neglects major effects like the existence of the overhangs and the shape of the bow.

The lack of an efficient instrument for the knowledge of the additional resistance in waves, made useless an accurate work of analysis of the statistical wave conditions in San Diego.

On the basis of a large collection of daily sea spectra, measured by a wave buoy over a wide range of years, it was possible to find some interesting relationship between sea state and wind speed.

The sea state depends greatly on the weather history over a wide range of water and time, but at the higher frequencies the ocean gains and loses the energy supplied by the local wind faster.

Typical sea spectrum, such as the Pierson-Moskowitz, usually refer to a fully developed sea generated by a wind blowing over a wide fetch.

These hypotheses are usually acceptable for seakeeping analysis of conventional ships travelling in the ocean, but in general they cannot be applied for boats sailing in coastal waters, where the fetch is often limited and the time scale of winds is usually short.

As an example the averaged San Diego spectrum measured with a wind velocity of 10 Kts, and the spectrum predicted by the Pierson-Moskowitz formula for the same wind speed are compared in Fig.1.

While the agreement is good at the higher frequencies, at the lower frequencies the San Diego spectrum shows much more energy, which can be considered as the residual of the previous history of that sea.

A similar comparison done for 25 Kts shows that, although the two spectra are similar, the San Diego sea is less developed then the Pierson-Moskowitz spectrum.

The San Diego spectrum showed in general the presence of three different bands of energy: a long swell, whose energy is not directly correlated with the actual wind, and having a modal period of about 14 sec.; another uncorrelated higher frequency band and a third band directly correlated with actual wind, but in a manner different from that predicted by Pierson-Moskowitz spectrum.

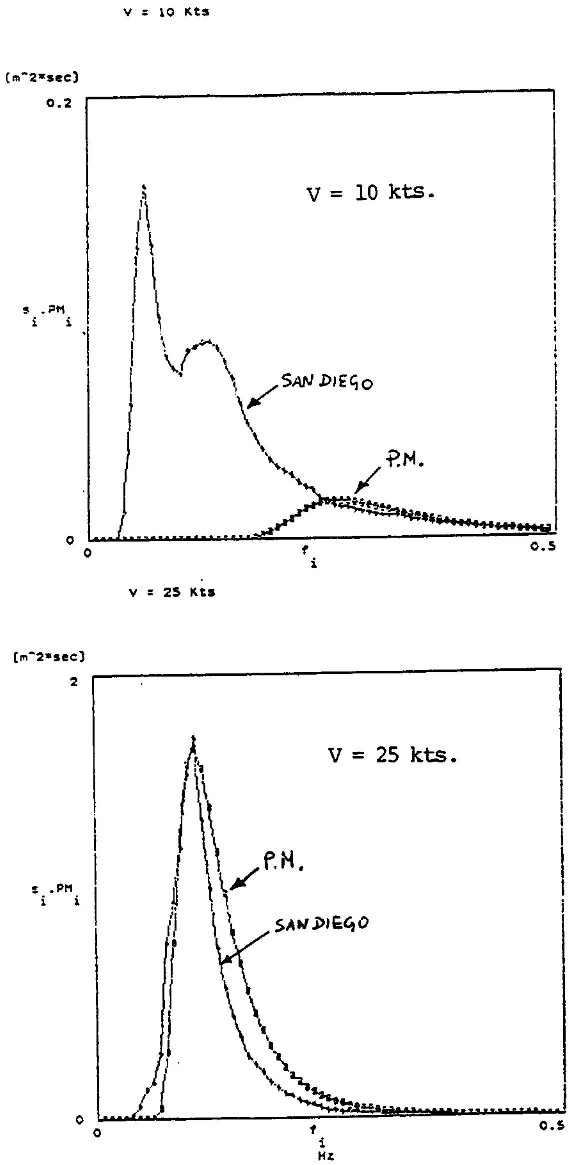

Fig. 1

On this basis a monoparametric relationship between wind speed and sea spectra was found, as the sum of two spectra due to dead waves, plus a wind correlated high frequency spectrum.

Having at disposal response operators for additional resistance in waves, a VPP could supply, for each real wind speed, polar plots of the boat velocity calculated for the mean statistical sea state.

Wind Tunnel

Most of the experimental studies on appendages have been accomplished at the wind tunnel of the Aermacchi aeronautical industry.

Due to tunnel dimensions, the 1:3 scaled appendages were not mounted on the scaled model of the true hull, but on a dummy model of reduced dimensions.

The dummy model (put on the floor of the tunnel to simulate a "rigid" sea surface) was dynamically disconnected from the appendages to allow the evaluation of forces on the appendages alone, but taking care to avoid any gap between hull and appendages.

No simulation of heeling was attempted.

Despite these limitations the technical and practical advantages of testing appendages in the wind tunnel are noticeable, and are due to a closer approach to the full scale Reynolds number, to the possibility of executing detailed flow visualization on the model surface and on its wake, and to an easier access and manipulation of the model.

R. Marazzi, who devoted particular attention to the improvement of laminar flow extention over the appendages, designed the keel and rudder sections with the aid of two-dimensional codes and then verified the results in the wind tunnel, both in terms of resistance and in terms of extention of laminar flow.

A similar approach was adopted for the bulb design.

Apart from the transition between laminar and turbulent flow, flow visualization also allows the detection of flow separation in the critical parts of the appendages, as at the junction of the keel with the bulb and with the hull, where a sharp pressure gradient can produce flow separation, increasing resistance (the so called "interference drag").

While this phenomenon can hardly be studied theoretically for the practical cases, flow visualization in the wind tunnel can give reliable information on the shape of the fairing needed at the junctions.

Wake surveys, performed with a system of Pitot tubes, supplied extremely useful informations on vortex characteristics in the wake field.

CFD

Besides the experimental work, a noticeable effort has been devoted to the developement and the aquisition of a certain number of computational tools for fluid flow analysis (CFD).

It is well known that the mathematical solution of nearly every engineering problem involving fluid flow, always requires some simplifing hypothesis at its basis (as an example the assumption of potential flow or the neglection of free surface effect), so that much care and experience is needed in the interpretation of the numerical results.

Differently classified physical behaviours always have some connection between each other (for example viscosity affects the wave resistance in some way and vice versa), and then the neglect of one term certainly disturbs the remaining one.

The hope is that, if the connection is weak, the error committed with the approximation of the phenomenon should be always in the same "direction", then allowing comparative analysis between different cases.

However, sometimes the possibility to analyze separately single parts of a complicated phenomenon , can be useful for a better understanding.

A good coherence between theoretical and experimental results was achieved using "Shipflow" [1], a program based on a development of Dawson and Hess methods, that allowes the calculation of potential flow around piercing bodies developing lift, such as sailboats.

The program was written by Prof. L. Larsson of Flowtech and managed in the syndicate by M. Downey.

In many previous CFD calculations on sailboats, free surface effects and lifting effects were kept disconnected, considering the boat like a conventional ship where free surface effects were concerned, while considering it like "half" an airplane where the lift and the induced resistance were concerned [2].

On the other hand it was known, at least in a qualitative way, that in some cases the connection between lift and free surface could be strong, affecting in some way appendage design [3].

The theoretical capabilities of the program were extremely interesting for a better comprehension of this interference in a quantitative way.

Then a systematic series was developed from an existing set of appendages, systematically modifying some main parameters such as the bulb volume, the taper ratio, the sweep angle and the chord length of the keel, but keeping the same hull displacement.

The mathematical models were tested over a wide range of Froude numbers and trim conditions, with and without yaw in order to separate the effects due to lift from those due to volume displacement.

The trend of the results were as expected from the qualitative knowledge of the phenomena, showing that the optimal shape of the appendages, among those tested, could vary significantly with the Froude number, but also that below a given speed free surface effects can be neglected for the appendage design without appreciable errors.

Fig.2 shows examples of the models of the series developed by modifying the taper ratio, while Fig. 3 shows how much the taper ratio required for minimal resistance (without viscous effects) changes as Froude number increases.

These results are in good agreement with the fact noticed in [3] that a nearly elliptical spanwise lift distribution is optimal at the lower boat speed, while at higher Froude numbers a lift distribution more loaded at the tip could give better performance.

While keel taper ratio cannot change during a race, a tapered trim-tab could allows the change of the spanwise lift distribution at different boat speeds.

The other series based on bulb volume showed that bulb dimensions affect both wave resistance and induced resistance, although some doubt arises from the

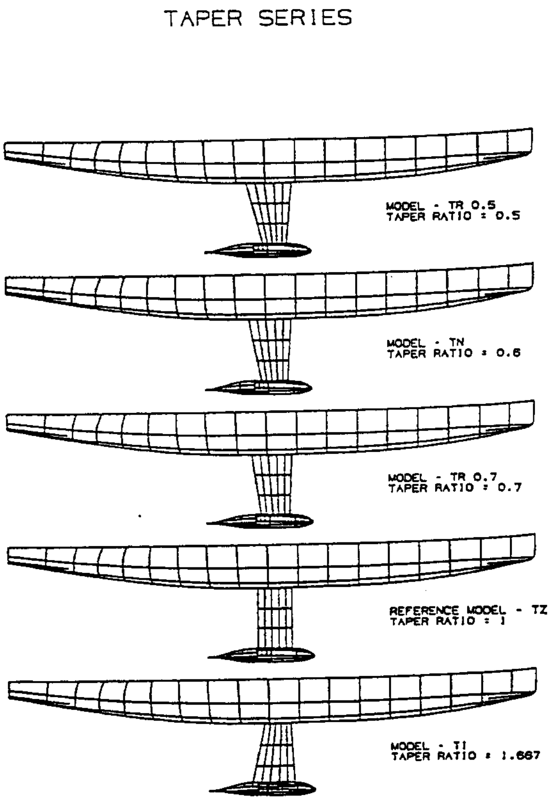

Fig. 2

uncertainty of the treatment of Kutta condition on poor lifting bodies like bulbs .

Anyway, when tested in the towing tank, the new appendages born on this basis showed results in line with the calculations.

While free surface calculation is based on the potential flow theory, viscous flow codes [1] were used to calculate viscous resistance of the models tested in the water tank.

Indeed a knowledge of the friction drag more precise than that supplied from the ITTC '57 model-ship correlation line, reduces the error on drag scaling from model to full scale, and allows the evaluation of the "form factor" influence between different hull shapes.

Also sail shape can be studied with CFD codes, as was extensively done by the sail makers for the design of their sailplans.

Apart from sails performance differences due to manufacturing, boat design requires a deep knowledge of sail forces, as different boats need different sailplans conforming to the rating rules, whose performance must be properly known in order to correctly evaluate the equilibrium point of the boat.

Moreover IACC rules allowed new unconventional kinds of sails, with extremely roached and efficient mains, whose performance couldn't be studied on the basis of the existing public domain data on sail coefficients.

A Vortex Lattice Method (VLM), based on a previous work [4], was developed and applied to calculate the polar plot of the sail plan of each model to be tested with the VPP.

Each sail plan was tested in a wide combination of boom and lead angle, twist, camber ratio, heel and apparent wind angle, always inside the field of applicability of the potential flow theory. A correction for viscous drag and flow separation was applied at each sail section on the basis of experimental data on cambered plates, and finally the force coefficients and sail center positions found were used as input in the VPP code.

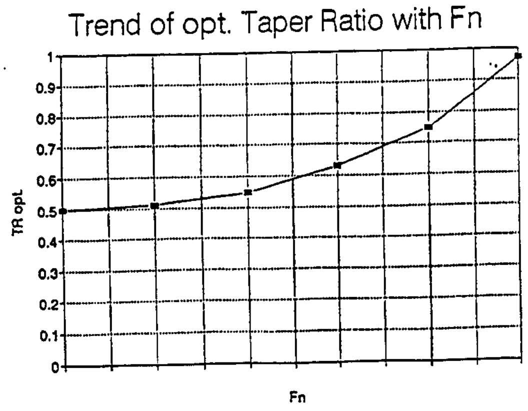

Fig. 3

VPP

The Velocity Prediction Program (VPP) is the computational tool that allows the evaluation of the equilibrium condition of the boat in any combination of wind speed and angle, calculates the velocity polar plots and finally predicts the time taken over a given course.

At present it is the only instrument that allows a quantitative comparison between boats with different characteristics, provided that the input data arise from the same sources (computational or experimental).

Although the algorithm which solves for equilibrium is quite robust, attention must always be paid to the correct physical representation of the phenomena being analised.

For example, during the improvement of the VPP with sail coefficients supplied from the VLM calculation, the importance of the leeway angle on boat performances was noticed, in the sense that it reduces the angle of attack of the wind on the sail, then decreasing lift and thrust for the same sail trim.

While this effect is neglected in some VPP's [5], as can be reasonably done for comparison between boats having similar appendages, this is not the case when studying the effects of different appendages.

If we want to analyze keel chord length when beating without considering the leeway in the VPP, as we reduce the chord length the resistance of the boat decreases and the leeway angle increases, but the sail thrust is considered unchanged for the same boat course.

As a consequence, the optimum chord is found for the minimal keel drag, usually above stall.

On the other hand, if the leeway is properly taken into account, a trade off is found between the reduction of resistance due to a shorter chord length and the reduction of sail thrust due to a proportional increase of the leeway angle.

Conclusion

In this paper the effort accomplished by the "Il Moro di Venezia" syndicate in the hydrodynamic design field is presented. Within the limits of confidentiality of the great part of the matter involved, it has been focused how both experimental and theoretical approaches have been followed during the development of the design. In particular it has been noticed how water tank and wind tunnel are still the best instruments for the design of, respectively, hull and appendages, while CFD capabilities are greatly useful in the early stage of the design, as well as for the comprehension of special phenomena.

References

1. Larsson, L., Broberg, L., Keun-Jae, K., Dao-Hua, Z.,"A method for Resistance and Flow Presdiction in Ship Design", SNAME Transactions, Vol. 98, 1990,pp. 495-535.

2. Oliver, J. C., Letcher, J. S. Jr., Salvesen, N.,"Performance Prediction for Stars & Stripes", SNAME Transactions, Vol. 95, 1987, pp. 239-261.

3. Sloof, J. W., "On Wings and Keels", 15th AIAA Symposium on Aero/Hydronautics of saling, 1985.

4. Boote, D., Caponnetto, M., "A numerical approach to the design of sailing yacht mast", Annapolis, 10 th. CSYS 1991, pp.59-81.

5. Kerwin, J. E., "A Velocity Prediction Program for Ocean Racing Yacht", M.I.T. Ocean Engineering Report N° 78-11, Cambridge, Mass., 1978.