

# **“TWELVE METER DESIGN: STATE OF THE ART IN 1986”**

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# 12-Meter Design: State of the Art in 1986

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A number of factors have contributed to renewed efforts in using engineering methods to design 12-Meter yachts. This paper describes the wide range of engineering methods used during the design and development of 12-Meter yachts, and clarifies how the data resulting from the use of these tools can contribute to better performance. The strengths and weaknesses of each tool are identified, and it is shown that, next to hard engineering numbers, an artist's touch and experience are still required for designing an outstanding 12-Meter.

## Introduction

MORE THAN most design disciplines, sailboat design, and in particular 12-Meter (12M) design, is a subtle juggling act of parameters. Within the physical constraints of drag, stability, safety, structural strength and power, there are the added constraints of the Twelve Meter Rule, the America's Cup deed of gift, and Lloyd's scantling requirements. Since the success of a design gets judged only at the finish line, it is often hard to judge the actual merit of a design once unquantifiable factors such as crew work, weather, management, and plain luck come into play. In addition to these difficulties, one has to live with the fact that even a breakthrough design is only fractions of a percent faster than an average design, and that speed is not necessarily the only performance factor that will determine whether a particular yacht crosses the finish line first.

Since it is not presently possible to develop a complete model of a 12M yacht (the term "model" meaning an abstract representation of a physical object), a designer attempts to study small interrelated model sections as accurately as possible and uses his judgment to fit the results into the overall model. Yacht designers, and more particularly 12-Meter designers, try to distribute their efforts among the various subsections using tools like weather predictions, towing tank tests, structural analysis, performance measurements, weight studies and performance predictions. As shown in this paper each of these methods has its weaknesses and peculiarities, and only careful evaluation of results will provide a designer with useful information.

The observations and opinions expressed in this paper are based on Johan Valentijn Inc.'s efforts to design a 12M yacht for the Eagle Challenge of Newport Beach, California, the success of which will soon be determined in the America's Cup races in Perth, Australia.

## Design objective

The objective of a 12-Meter designer is to design an object that can be moved around an America's Cup course such that it will cross the finish line before its opponent, using only propulsion forces provided instantaneously by wind, waves, and oceanic currents, while conforming to the International Twelve Meter Rule, the racing committee's rules, the America's Cup Deed of Gift, and Lloyd's requirements for 12 Metre International Rating Class Yachts. This might appear as a rather

strained definition, but is meant to point out that a 12-Meter yacht is by no stretch of the imagination a powerboat with sails and without an engine. The above objective could suggest a number of different approaches (such as sinking one's opponents), but history, and refinement of the rules mentioned in the objective have dictated approaches which attempt to increase speed and, to a lesser extent, to improve maneuverability, performance in waves, and acceleration. The designer attempts to maximize these performance parameters by carefully applying the knowledge he gains while studying limited aspects of sailboat behavior.

The amount of time and effort spent on performing these studies is wildly out of proportion to the cost (and probably also the profit-potential) of the actual sailboat, but is required, since the performance of a 12M yacht will only improve proportionally to the amount of blood, sweat and tears shed, and one simply has to shed more than the other syndicates. Fortunately 12M design is connected with a matter of national pride, and it is not uncommon that engineering companies approach designers with offers of assistance which enable a designer to study areas which would be too expensive if contracted at normal rates. The syndicate has done extensive performance, stress and structural studies which would not have been possible without donated equipment, labor, and computer time from a variety of sources.

## Description of research and development areas

Rather than concentrating on one aspect of yacht design, the intention of this program was to build a database with input from as many engineering methods as possible which could serve as a check against each other. Figure 1 shows the dependency and interrelation of the various methods used in this design program. From the large variety of studies, it can be seen that there was no exclusive dependence on one engineering method, but rather it was attempted to let each program contribute to the overall database. It was expected that faulty results would come to light when compared with data collected in different programs. It also was expected that certain research programs would enable other programs to be conducted in a more accurate manner, and that certain data would support subsequent programs. It is, for example, impossible to do an accurate performance prediction without accurate meteorological data, and it would be meaningless to perform structural studies if the forces encountered by a 12M under sail are not known. Figure 2 shows a schedule of the various testing programs and studies performed. Although various changes were made since the start of the program in 1984, the basic philosophy has been maintained. Details on each method used are provided below.

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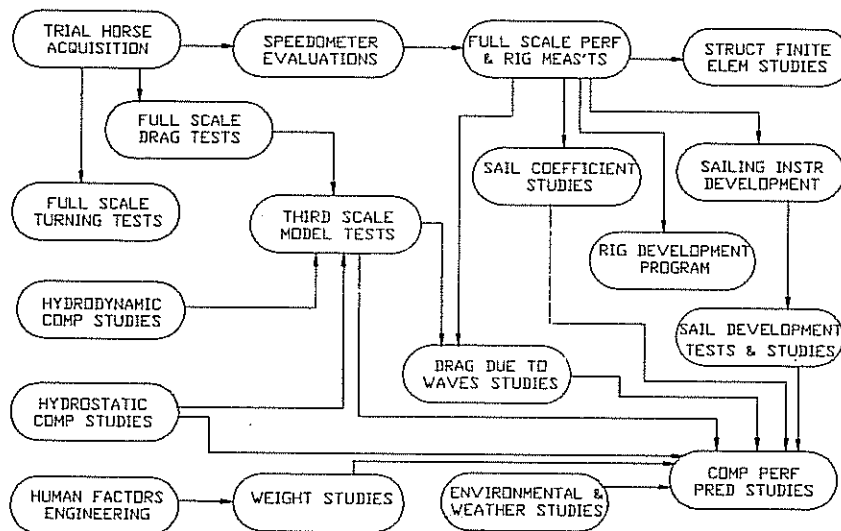


Fig. 1 Flow of design information

### Trial-horse acquisition

A suitable 12M hull for testing is essential to any 12M campaign. The level of usage of such a trial horse varies from syndicate to syndicate, but at the very least it is used for crew training, and as a speed yardstick. At a more sophisticated level it can be used for evaluation of instrumentation, force testing, and equipment testing. From a crew training and speed yardstick standpoint, it is advantageous to buy a relatively new 12-Meter that has been actively campaigned so that a fair amount of information is available about her performance against other boats. In this respect it is advantageous to have access to a successful design, since it becomes easier to determine whether a new design is an improvement over the state of the art. If the trial horse comes complete with the crew that campaigned her successfully—as is the case with Alan Bond, who has *Australia II* and most of his original people available—it becomes relatively easy to evaluate the speed of a new design. In the case of the Eagle Challenge a slightly different route was taken. Rather than purchasing a boat like *Liberty*, or *Freedom*, it was decided to purchase *Magic*, a rather unsuccessful design, built for the 1983 defense. There were a number of factors which contributed to this decision. First there was familiarity with this boat since Johan Valentijn was her designer. Secondly, because of her rather lackluster performance in 1983, the purchase price was very low compared with other 12M's, which can cost up to \$1 million for a fairly new hull in sailing condition. (Although 12M racing is an extremely expensive pastime, economy is still a factor.) Thirdly, Johan Valentijn felt that *Magic* had an efficient hull, and that her lack of performance was due to other factors. And finally it was obvious that all 12M yachts were essentially outdated when compared with *Australia II*, and consequently it would not really be useful to buy an expensive successful boat and be forced to modify it with a winged keel, thereby changing its performance and making it useless as a yardstick. Upon purchase, *Magic* was fitted with a winged keel and raced against *Victory 83*, a 12M very similar in performance to *Liberty*, and also the 1984 World Champion 12M. This enabled the designers to calibrate her as a yardstick for the new designs to come.

### Full-scale drag tests

After the successful campaign of *Australia II*, extraordinary attention has been paid to model testing of sailboats. Since

these model tests are meant to predict the full-scale lift and drag of yachts, it was considered significant to measure the actual drag of a full-scale 12M in order to compare it with the values as predicted in the tank. A secondary objective of this program was to measure the difference in drag between a winged keel and a conventional keel.

Full-scale hull testing has been attempted before, but has met with only limited success due to a number of factors. The factors that enable model testing, accurate drag measurements, accurate speed measurements, and undisturbed flow are also the factors that make full-scale testing hard to accomplish. Nevertheless some very interesting open-water measurements were made with *Magic* at zero heel, with a conventional keel, and with a winged keel. These tests were performed in the early morning on Narragansett Bay near Providence, Rhode Island, when there was no or very little wind. A fair amount of trial and error was required to develop a setup which provided reliable numbers. In the final configuration *Magic* was pushed by the tender using a boom which was attached to *Magic* at her mast location about a foot above deck level. *Magic* was pushed without her rig in order to give her the same aerodynamic profile as a model. Drag was measured by a load cell at the mast, while speed was measured by a variety of speedometers. In addition to drag and speed, wind speed, wind direction, micro-accelerations and trim as recorded by a gyro were recorded on an OPTIM MEGADAC data acquisition system at a rate of 20 samples per second. After reduction, consistent drag curves were developed which were used for model testing comparisons, and winged keel/conventional keel comparisons (Fig. 3).

As is the case with all measurements, a large amount of time was spent on calibrating instruments, most notably the load cell and the speedometers. During the testing it became apparent that even very small waves have a sufficient effect on the drag measurement to make even reduced results questionable. This is mainly due to the out-of-phase motions of the pushboat and the test boat. One interesting variation on full-scale drag testing would be to tow a 12M from a mast near the sail center of effort using a long cable and a helicopter. In this configuration it would be possible to measure sail driving forces in addition to straight drag by making the helicopter tow at angles away from the bow.

### Full-scale turning test

Using the setup developed for the full-scale testing program

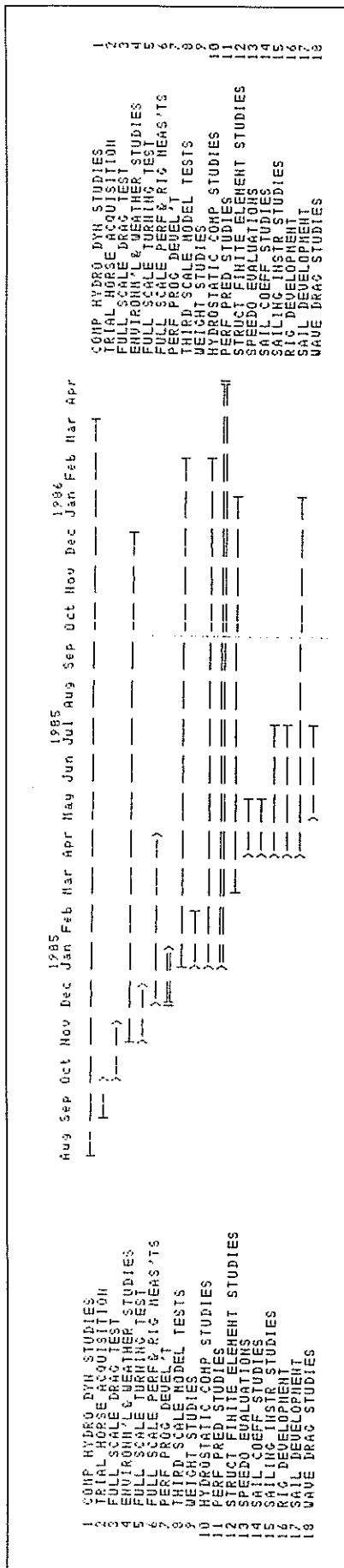


Fig. 2 Design schedule

with the addition of an electronic compass, a transverse speedometer, and a rudder angle indicator, a series of tests was performed measuring the turning performance of *Magic* without her rig.

*Magic* was pushed up to speed after which she was released and made to turn at a constant rudder angle. Data were recorded until she stopped turning. While these tests were performed, almost as an afterthought to the full-scale drag program, it turned out that the tests were extraordinary both in their elegant method and in the insight in turning performance they provided. In one morning of testing, it was possible to determine optimum rudder angle for minimum drag turning, and optimum rudder angle for maximum turning rate for any speed. Incorporating instrumentation as described above in a 12M sailing instrumentation package will enable the designer to immediately evaluate the effect of changing rudders on a boat by duplicating the turning test.

### Full-scale performance and rig measurements

*Magic* was fitted with strain gages at all rig/hull intersections, and instrumentation that recorded all sailboat performance parameters, including such usually ignored parameters as trim and leeway, and sailed by Rod Davis, the Eagle Syndicate's skipper during the fall of 1984 in Newport, R.I. All this information was simultaneously recorded on the MEGADAC, providing a complete picture of the interrelationship of performance and rig forces. A total of 55 channels (Fig. 4) were used simultaneously for this test, and relationships like change in trim during tack and trim versus heel were investigated. All this information is stored on the computer in Newport, R.I. and can be recalled when required for further investigation. While the original intent of the program was to provide data for the drag-to-waves studies, performance prediction studies, and structural studies, the completeness of the data, the easy access to the data, and the power of the OPTIM Corporation's OPUS program has enabled use of the data to verify a variety of information on a case-by-case basis. For example, when a certain performance prediction method indicates that a certain tacking speed is required to take advantages of a highly maneuverable design, we can verify whether such a tacking speed is feasible for varying wind and wave conditions.

### Speedometer evaluations

Speedometers are the single most important instrument used during testing and racing, and have to be able to measure very small changes in speed for them to be useful. A speedometer is supposed to measure the speed along the longitudinal axis of the boat moving through the water, which is not to be confused with measuring the speed across the ground, which can be accomplished relatively easily with Loran or SATNAV-type equipment. There is a variety of ways of measuring boat speed, none of which are perfect due to the inherent weaknesses of sensors. Table 1 lists a number of different boat speed sensors currently in use or proposed for use on 12M yachts, giving some of their advantages and disadvantages. As can be seen, none of these sensors are perfect, although the Brookes and Gatehouse sonic speed sensor appears to have the fewest drawbacks. The laser Doppler sensor is the only sensor that actually measures the speed of the boat through the water, rather than measuring the speed difference between the boat and a body of water that moves at a certain speed due to the presence of the boat. This means that the laser Doppler speedometer would be the only speedometer that does not need calibration once installed on the boat (a very important advantage since speedometer calibration is a tedious and time-consuming process).

As far as speed is concerned the designer's requirements for a

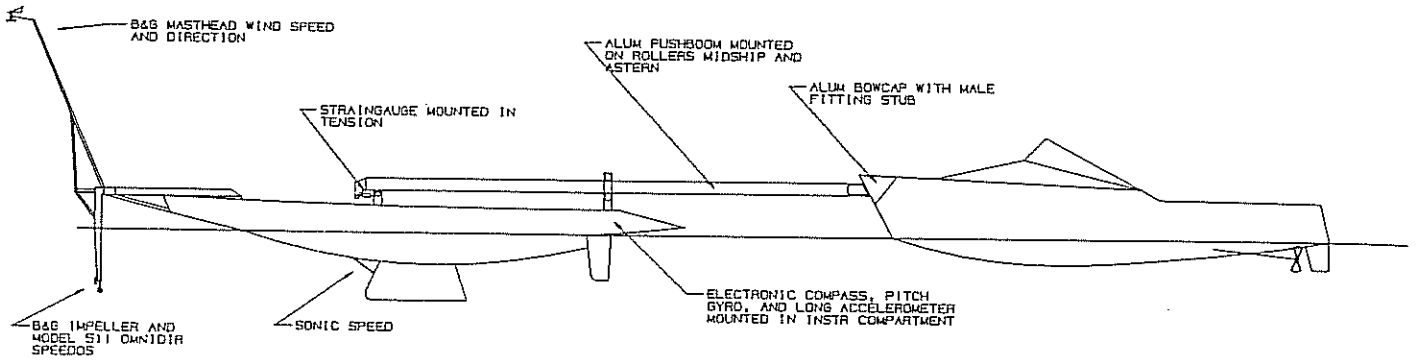


Fig. 3 Full-scale drag and turning test setup

speedometer are different from those of the boat's crew. The boat's crew uses the speedometer to check whether their boat is performing as expected. This is accomplished by comparing the present boat speed to boat speeds recorded under similar conditions during earlier sailing sessions. This means that their speedometer has to have 100 percent repeatability and zero hysteresis. As long as the crew knows that they are measuring the same thing today as they were measuring the day before, or the week before, it makes no difference to them whether they

are measuring knots, apples, or nonlinear oranges, provided they measure the same nonlinear oranges every day. The designer, on the other hand, is interested in actual boat speed, that is, feet per second, or knots, to the greatest accuracy possible, since he uses these boat speed values to calibrate performance prediction programs, and an error of 1 percent will make any performance prediction meaningless.

Figure 5 shows the variation in readings of three different sensors during actual sailing. It is clear from this plot that speed

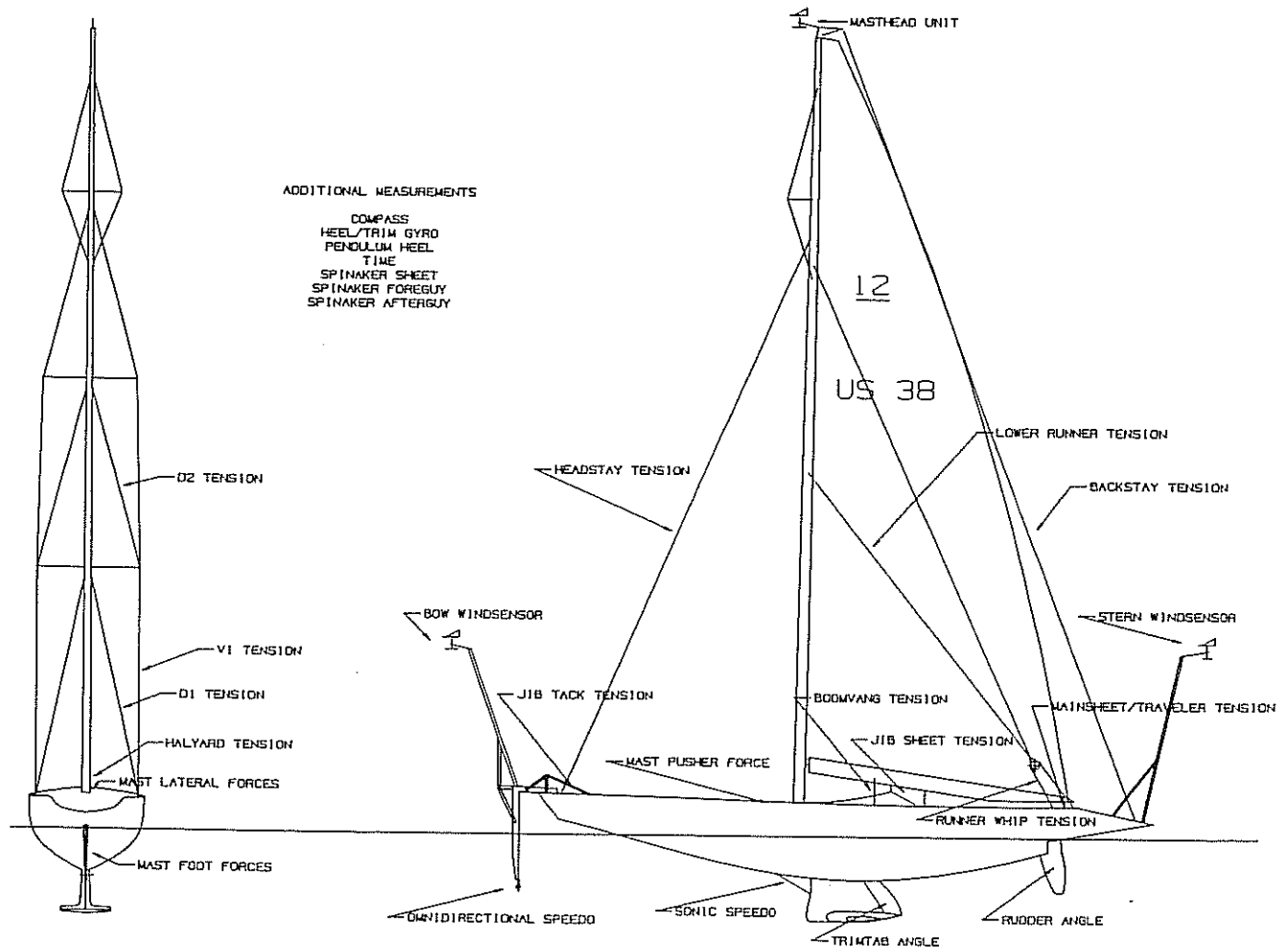


Fig. 4 Full-scale measurement program

Table 1 Speedometer comparisons

	Impeller	Paddlewheel	Sonic	Electromagnetic	Laser Doppler
Alignment	hard	not sensitive	easy	easy	easy
Linearity	poor	poor	excellent	needs careful design	excellent
Repeatability	poor	poor	excellent	temp. sensitive	not known
Availability	widely available	widely available	one manuf'r	one manuf'r	under development
Op. experience	large amount	large amount	growing amount	small amount	none
Accuracy	poor	poor	excellent	good	not known
Cost	low	low	average	higher	highest
Disturbs flow	yes	yes	small amount	yes	no
Sensor weight	low	low	low	average	very high
Leeway measur't	no	no	with add'l sensor	yes, inherent	yes, with more power
Calibration	continually	continually	once	occasionally	never (high power) once (low power)
Power req'ts	low	low	low	low	high to very high

as recorded by one sensor is not the same thing as speed recorded by another sensor.

### Third-scale model tests

Rather than testing with small models, third-scale models were used to minimize scaling effects. To date, five series of tests constituting a total of about seven weeks of tank time, and more than 1500 test runs, have been made at Offshore Technology Corp. in Escondido. Some of these runs were made evaluating actual 12-Meter configurations, while others were used for evaluating new concepts, or for obtaining more knowledge on bodies moving through water. In order to provide a baseline, models were made of *Liberty* as she sailed in 1983, *Magic* with her original keel, and *Magic* with her present keel. In addition, a total of six new 12M designs have been evaluated in the tank. Using modular parts for various bow and stern sections, and various keels, a total of about twenty 12M designs were evaluated. As far as new concepts are concerned, tests with bulbous bows, hull wings, and unusual bustles have been performed. In order to gain more understanding of hulls moving through water, models with varying centers of buoyancy and bare hulls without keels have been tested. Some models were also evaluated in waves, or were fitted with dye injectors for flow visualization.

Historically the towing tank has always received the most publicity in yacht design, and it has either been the reason for the success of a design (*Intrepid*, *Australia II*), or the reason for the failure of a design (*Mariner*, *Valiant*). At the moment, due

to the success of *Australia II*, the model basin appears to be the magical potion for developing faster 12M yachts, and by the author's estimate about \$10 million must have been spent in model basins around the world on developing faster 12M yachts. Remarkably enough it does not appear that this \$10 million has produced any advances in the state of the art of 12M design. Time after time syndicate leaders, yacht designers, and even directors of model basins have announced that a new design is significantly faster than the state of the art, while in actuality it turns out that the new design had a hard time keeping up with trial horses.

All this money has not gone entirely to waste, however, and the use of a towing basin is still essential in the design of 12M yachts for a number of reasons, as long as the designer is aware of its significant limitations. Model testing large models enables the designer to quickly and definitively eliminate concepts which would have produced disasters. A very bad concept will always show up bad in a model tank, and several hulls and configurations were tested which originally appeared promising but turned out to be full-fledged disasters in the model basin. Without the use of the model basin these concepts might have actually been built. On the other hand, the model basin will also give the designer sufficient confidence to continue work on a radical concept that appears to be competitive with baseline hulls. Once a designer has something that appears to be competitive with baseline hulls, he should check the equipment, check his numbers, retest the concept on a different model—ideally retest the concept in a different model basin—and then make a judgment whether he is willing to risk building that concept. Next he should sit down and ask himself whether what he is seeing actually makes physical sense. If he expected more lift but is actually getting less drag, the concept will still appear to be promising, but it probably means that the drag gage is busted. If something “does not look quite right” at 1/3 scale it will look three times as much “not quite right” full scale.

If after all of this effort the concept still appears promising, he can take his numbers to the syndicate and convince them that it might actually be worthwhile taking the risk. It is obvious that tank testing is not an easy process, and the “blood, sweat and tears” principle counts double in the model basin. As an engineering tool a model basin is not an ideal tool for sailboat design; there is too much ground to be covered, and consequently too much room for error to be able to use model data for accurate performance prediction. The model basin measures only model lift and drag; once these are recorded for a number of heel angles and yaw angles the data get converted to full-scale lift and drag values (a conversion which by itself has never been proven to be possible). Then estimates for sail lift and drag forces, estimates for drag due to ocean waves, estimates of lift and drag due to trim tab and rudder settings, estimates for expected wind conditions during the race, estimates for the

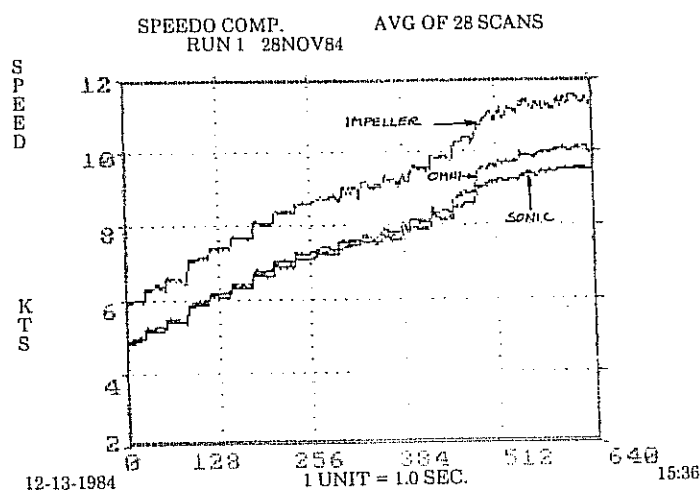


Fig. 5 Variations in speedometer readings during full-scale drag tests

number of tacks during the race, and estimates for the stability of the boat get added, and after all this one then is supposed to be able to know whether one boat is 1 percent faster than another boat. In other words, anybody who expects to get the type of performance that the tank indicates is going to be in for a surprise.

As an artist's tool, however, the model basin can be very helpful; just as carving a half model can be an important help to designing a fast boat, actually seeing the hull move through the water can be an even more important help to designing a fast boat. Especially if some type of flow visualization is being used, and if good visual records are made by still or video camera, an experienced yacht designer will know by seeing, and comparing wakes and flow patterns, what is working and what is not working, and often does not even have to consult the measured data to know whether he is working in the right direction or not.

### Hydrodynamic computer studies

The 1987 America's Cup and computers are generally being mentioned in one breath. Although computers in various capacities have played important roles in the America's Cup since the early sixties, this is probably the first campaign where the computer has actually moved into the designer's office on a day-to-day basis. The designers have become familiar with what a computer can and cannot do, they feel comfortable with questioning the worth of certain programs, and they have accumulated a certain amount of practical experience with the results of computer studies. Furthermore, and probably most importantly, central processor unit (CPU) time has become a measure of the amount of calculations performed rather than a measure of the amount of money spent. This is the first campaign where the yacht designer is not in the unenviable position of needing a computer more than any other design engineer, and being unable to afford it. All the American syndicates have access to virtually unlimited computer capacity, and computers are contributing in all aspects of yacht design.

The most spectacular computer application in 12M design is the determination of hydrodynamic flow on sailboat hulls using vortex panel methods. Although this method is not new in aerospace applications, it was first applied successfully in sailboat design by Joop Slooff of the Netherlands Aerospace Laboratory during the design of *Australia II*. Mr. Slooff's work was probably more significant in the development of the winged keel than any other factor, since it saved a significant amount of time over towing basin model testing. The computer program used by him divides the hull and keel into small imaginary flow panels, which combined model the flow of water around the hull. By simultaneously solving these individual flow equations, the drag and lift of the entire hull can be calculated at various heel and yaw angles.

The most significant difference between Slooff's program and earlier vortex panel programs was the ability of the Slooff program to model the wake created by a hull moving through the water. Since the drag of a sailboat at high speed is mostly due to its wavemaking, and since keel lift is effected by the shape of the wake, such a capability is essential for studying the hydrodynamics of a sailboat using a computer.

The Slooff program was very helpful in optimizing concepts and in eliminating bad concepts; however, it could not provide the accuracy required by a yacht designer to determine whether a boat was a breakthrough or merely an average boat. A vortex panel program is by nature very good at determining lift, but is not so good at determining drag because it does not take into account hard-to-quantify effects like flow separation, which is often a major contributor to the overall drag of a sailboat. Furthermore the free surface, or wake, is calculated by superimposing pressures as induced by the hull on the free surface, but the effect of the resulting wake on the hull above the original

waterline is not considered. Consequently the effect of overhangs is not taken into account by these programs.

It is the author's experience that these programs are extremely helpful in evaluating and optimizing unusual and complex keel shapes, but useless in the development of sailboat hulls. When comparing the lift and drag of keels as generated by the computer, and as measured in the model basin, an improved keel in the computer has also been an improved keel in the model basin, although the degree of improvement has not always been the same. Based on this, the majority of keel evaluation now takes place on the computer, and the author's company was still refining keel designs up to the moment of pattern building for the actual keel. Figure 6 shows some pictures of various keel arrangements, and pressure distributions at various heel angles, as performed by Arvel Gentry for the Eagle syndicate.

### Hydrostatic computer studies

While hydrodynamic calculations constitute the upper part of the computer applications spectrum, hydrostatic calculations are probably the simplest computer application for a yacht designer and can easily be performed on a personal computer. However, the simplicity of hydrostatic calculations should not be confused with their importance. The efficiency, behavior, and effectiveness of a 12M hull are based to a very large extent on the hull's hydrostatic characteristics. Comparisons between hydrostatic characteristics of different hulls can be a major indication of their performance.

Before the rise of personal computers, the hydrostatic characteristics of a 12M hull were determined by hand calculations of hull volume, center of buoyancy, and surface area. Performing a thorough hydrodynamic analysis of a sailboat hull by hand could take a week—which very often was the reason for cutting corners at this very important aspect of sailboat design. Now it is possible to enter a hull shape into a personal computer, using a digitizer, and to calculate all its hydrostatic characteristics in about two hours. Once the hull is in the computer it is a matter of minutes to change its trim, or displacement, and obtain all the hydrostatic data for the new conditions. With a large number of 12M hulls on file, both existing hulls and concept hulls, it is possible to get a good feel for the performance of a new hull once its hydrostatic characteristics have been determined.

Table 2 gives the hydrostatic characteristics of a number of 12M hulls. The most notable point of these numbers is their large variation, which is especially unusual when considering the fact that the boats don't vary much in speed in absolute terms. Apparently there are a lot of roads that lead to Perth. Closer examination will show which boats excel in light air, and which boats excel in heavy air. Generally boats with low wetted surface area, lower prismatic coefficients, and high sail area to displacement ratios excel in light air. For heavier air it pays to design a boat with a higher prismatic coefficient, higher stability, and a longer waterline. Naturally the choice gets much harder in moderate or variable conditions. Is it more important to have a high prismatic or a low wetted surface area at 15 knots true wind speed? The best way to determine this is to evaluate how existing boats performed in certain conditions, which is a very important reason for building the largest possible database for 12M hulls. Once the designer gets a feel for the general hydrostatic characteristics he is shooting for, he can draw a new hull, or modify an existing one. The final hull will be, as always, a compromise, but at least the designer has a very good idea of what he can attain, and what he will get.

A number of usable line fairing/hull development programs have recently become available. The use of a line fairing program in conjunction with a hydrostatics program enables the designer to rapidly evaluate a large number of hulls.

It will become even more interesting when the computer

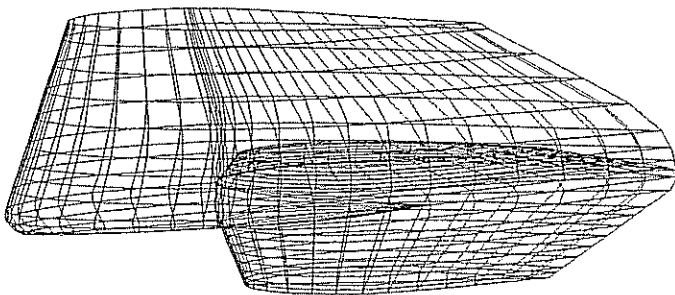
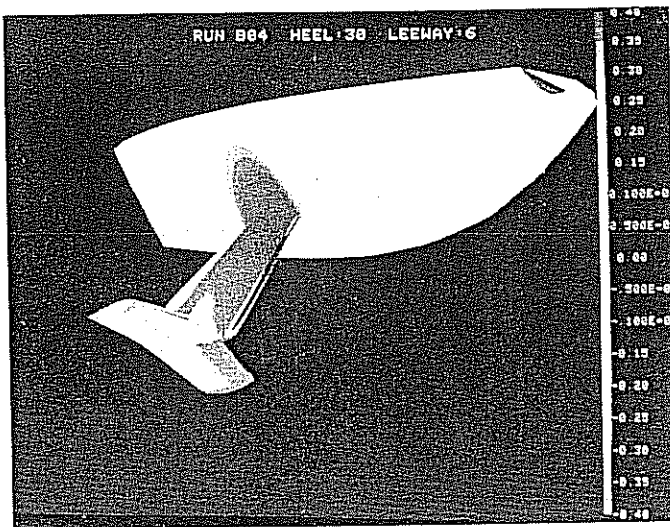
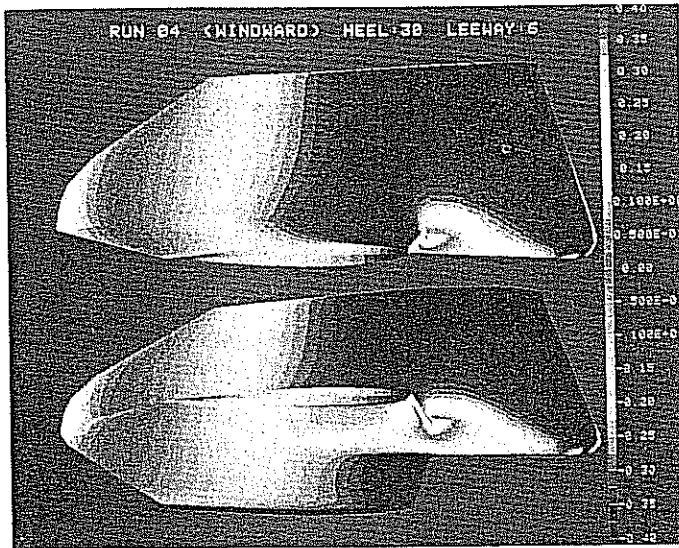
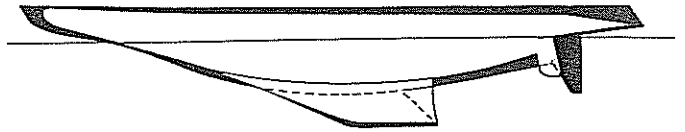


Fig. 6 Keel panel arrangement and pressure distributions from computer hydrodynamic analysis

develops a hull using the designer's constraints. Johan Valentijn Inc. is presently developing a computer program which takes a semi-intelligent approach to hull generation. It basically mimics our approach in drawing lines plans, but can draw a hull constrained by certain parameters such as prismatic coefficients, wetted surface area, or displacement penalty, or can draw a standard Johan Valentijn 12M to a certain waterline length, and then will allow refinements of the designer's choice. This program runs interactively on our computer-aided design (CAD) system, and produces faired lines automatically.

Table 2 Hydrostatic comparison

	Model No					
	1	2	3	4	5	6
LWL 0 deg	46.30	46.60	47.62	48.00	49.21	49.50
LWL 30 deg	48.90	48.85	49.90	51.10	52.53	49.80
WSA 0 deg	470.00	495.00	520.00	509.00	546.00	580.00
WSA 30 deg	484.00	525.00	530.00	520.00	574.00	604.00
PC 0 deg	0.55	0.58	0.56	0.59	0.58	0.55
PC 30 deg	0.55	0.55	0.53	0.55	0.54	0.53
Trim 30 deg	0.44	0.34	0.35	0.64	0.73	0.25
Displ.	49 000	56 000	58 000	56 000	66 000	71 500
RM 30 deg	102 000	131 000	135 000	129 000	155 000	145 000



Size comparison: Southern Cross vs. Australia (white overlay)

### Weather and environmental studies

During the winter of 1984/1985 a wave buoy and a weather station were deployed on the America's Cup course in Perth to obtain accurate wind, weather and wave data during the Australian America's Cup summer. This information is stored on the computer and can be reduced as required. In addition, historical information has been obtained from the Australian weather bureau, and additional data will be recorded in 1986. This meteorological information was used to develop a computer model of the Australian conditions, which in turn were used for performance prediction studies. The wave studies were also used for the structural analysis and the drag-due-to-wave studies. In addition, a study was performed to analyze where the Australian conditions varied from the Newport, R.I. conditions. It was interesting to note that Australian wind and wave conditions occur frequently off Newport during the fall.

### Structural finite-element analysis

While the 1983 America's Cup series was held under the specter of the winged keel (Every America's Cup series has something special: 1980 had *Lionheart's* bendy mast and 1977 had Ted Turner.), it could very well be possible that the 1987 America's Cup series will be held under the specter of the fiberglass hull. Since glass reinforced plastic (GRP) hulls were officially allowed by the International Yacht Racing Union (IYRU), at least four syndicates have performed research in the design of GRP 12M yachts, and one syndicate (the New Zealand Syndicate) is presently sailing GRP 12M yachts. It will be interesting to see how a GRP 12M performs compared with aluminum hulls. In the 12M design game, structural optimization in aluminum and GRP is a very complex engineering and tactical process which has no equal in yacht design due to the requirements of Lloyd's Rules and the original intention of the 12M rule.

Before going into a description of structural design procedures, it will be necessary to outline the structural requirements for a 12M hull. Generally, a yacht designer would like to design a hull which is stiffer, lighter, has a shorter radius of gyration and a lower center of gravity than the competition. When using the term "hull" in a structural context, it means the structural shell, without ballast, rig, equipment, or control surfaces. Since any weight taken out of the structure can be reintroduced into the yacht in the form of ballast under the 12M rule, it pays to keep structural weight to an absolute minimum. Of course the original developers of the 12M rule (which was written in the

very early 1900's) were aware of this trend, and required that all 12M yachts be certified under Lloyd's scantling rules. Lloyd's approval would at least ensure that the yachts would be relatively safe, relatively durable, and roughly equal in structural weight. Lloyd's approval was intended to stabilize 12M yacht design, and to increase the popularity of the rule as a relatively inexpensive coastal racing/cruising class. Ironically, the 12M rule did not really become popular until after 12M's developed into an expensive racing class in the mid-fifties. After a while, Lloyd's developed a set of rules for wooden 12M yachts, and later for aluminum 12M yachts. Since the aluminum rules will produce a hull that is roughly 20 percent lighter [2000 lb (907 kg)] than a wooden hull, everybody is now building aluminum 12M yachts.

Lloyd's Rules for Alloy 12 Metre International Rule Yachts is a relatively straightforward document which allows the designer a certain amount of freedom as far as the structural arrangement of the hull is concerned. The plating thickness of the hull is very strictly defined, and the designer can vary the internal structure depending on certain restrictions for frame, web frame spacing, and sizing. In addition, the designer can propose an alternative internal structure arrangement that might be approved if it does not lower the hull center of gravity or reduce the hull radius of gyration, weight, or basic strength. (The alternate structure rule, incidentally, is defined in the 12M class rules, rather than in the Lloyd's Rules.)

While it will never result in a quantum leap in performance, a yacht designer might use these rules to design a structure which is stiffer than the competition. However, for unspecified reasons, Lloyd's has assumed that they should not allow a structure which is within the rules but more efficient than the norm, and has developed rather stricter unpublished rules. Since the 12M rule allows yachts in a very wide variety of sizes and shapes, Lloyd's is now faced with applying their arbitrary unpublished methods to a wide variety of designs, which can result in amendments that are completely mystifying to the designer who has made an effort to design his yacht to the Alloy Rules. Although the designer can attempt to compromise with Lloyd's on these amendments, he is generally faced with having to build his boat Lloyd's way, although this can often result in a weaker or more flexible structure.

Due to pressure from a variety of sources, the International Yacht Racing Union has allowed GRP as a legal material for 12M construction. In order to keep developments in the 12M class evolutionary, rather than revolutionary, a GRP yacht has to have the same center of gravity, longitudinal inertia, and weight as an equivalent aluminum hull, and should have equivalent stiffness. Whether intentional or not, a standard GRP design (with standard glass/epoxy ratios) which has equivalent weight, vertical center of gravity (VCG), and radius of gyration will be less stiff than an aluminum design. In other words, in order to design a GRP hull in accordance with the IYRU requirement, one has to design a glass hull using ply optimization, and advanced glass fiber composites (prepregs, and vacuum technology). It is only to be expected that Lloyd's has not been very eager to accept advanced composites for 12M structures, and the designer is faced with an expensive and time-consuming fight in order to get approval for a GRP hull.

Since durability and resale value are no longer of overriding concern to the 12M community, it is the author's opinion that the requirement for Lloyd's approval should be dropped from the 12M rules. Such a change will strengthen the 12M class by allowing experimentation in advanced structures which can be passed on to other types of sailboats and to the engineering community at large. Lloyd's approval is frustrating to both Lloyd's and the designers and owners. There is no question that Lloyd's tries to be fair in the application of the rules, but since it is hard to maintain a set of rigid rules for a wide variety of designs, Lloyd's has to spend an extraordinary amount of time jus-

tifying their decisions, while the designers and owners are being frustrated in their efforts to improve on the state of the art.

While designing a sailboat hull, a designer generally tries to minimize the weight while providing sufficient strength and maximum fore-and-aft stiffness. The reasoning for minimizing weight and providing adequate strength is obvious. Increased fore-and-aft stiffness increases boat speed by allowing better sail control, primarily by reducing headstay sag. Although it is hard to quantify, a stiffer boat tends to be faster to windward than a more flexible design.

In the 12M design game, the minimum weight is generally defined by Lloyd's Rules, and sufficient strength is inherently provided because Lloyd's Rules are very conservative from a strength standpoint. Consequently, in order to design a better boat, the designer is faced with designing a stiffer boat, either by rearranging structure with Lloyd's approval, or by adding excess material.

In order to discover the most efficient way to optimize a 12M hull from a structural aspect, Todd Shipyards Corp. developed a complete finite-element model of a 12M hull (Fig. 7). Todd's assistance was greatly appreciated not only for their knowledge in modeling naval structures but also for their actual work in developing the model. Developing a finite-element model from a construction plan can be compared to describing every detail of the structure in words to a person who has never seen a sailboat in his life. The listener cannot tell the modeler that he doesn't understand him, because he doesn't know what there is to understand.

The model was loaded as if sailing upwind, in waves as found off Freemantle at 30-deg heel. All forces were balanced, so that the model could be restrained at the bottom of the keel with very small resultant reactions at the restraining points. Since the stresses due to the hull structure's weight are very small compared with the stresses from the keel weight and rigging loads, the weight of the hull was not included in the loading. This enabled us to vary the hull structure without disrupting the balance of forces.

As mentioned earlier, the cost of using a computer is a rather vague issue. Todd Shipyards at that time did not run their structural analysis in house, and the computer time required for this analysis was provided by the company which provided them with computer support. However, a relatively large model, like the one in this study, quickly uses a large amount of computer time both to sort out the inevitable bugs and to actually run it, and it soon became somewhat of a problem in terms of computer cost. Furthermore, it is customary to run large programs like this during the evenings in order to take advantage of the lower evening rates, which means that it becomes hard to run more than about three structural arrangements a week. Fortunately for this particular program, an offer from the Chrysler Corp. was extended to all the American syndicates for unlimited computer time on their in-house computers. Performing a structural analysis using Chrysler's facilities is different from using somewhat more common facilities, due to the capacity of Chrysler's computers. Since Chrysler does not charge for computer time, one does not have to worry about how often a program runs, or have to wait until the evening to run it. Consequently a finite-element analysis run is used more as a tool than as a major project, and it is possible to prepare one run and have the next run ready by the time the first run is completed. Turnaround times of 15 minutes were achieved on runs which would have taken a day on other systems. In one week it was possible to investigate as many structural options as would take eight weeks when timesharing a computer. Once methods of improving the performance of an aluminum 12M structure were identified, they had to get approved by Lloyd's. While the design proposed by this syndicate did get more or less accepted by Lloyd's, other syndicates have

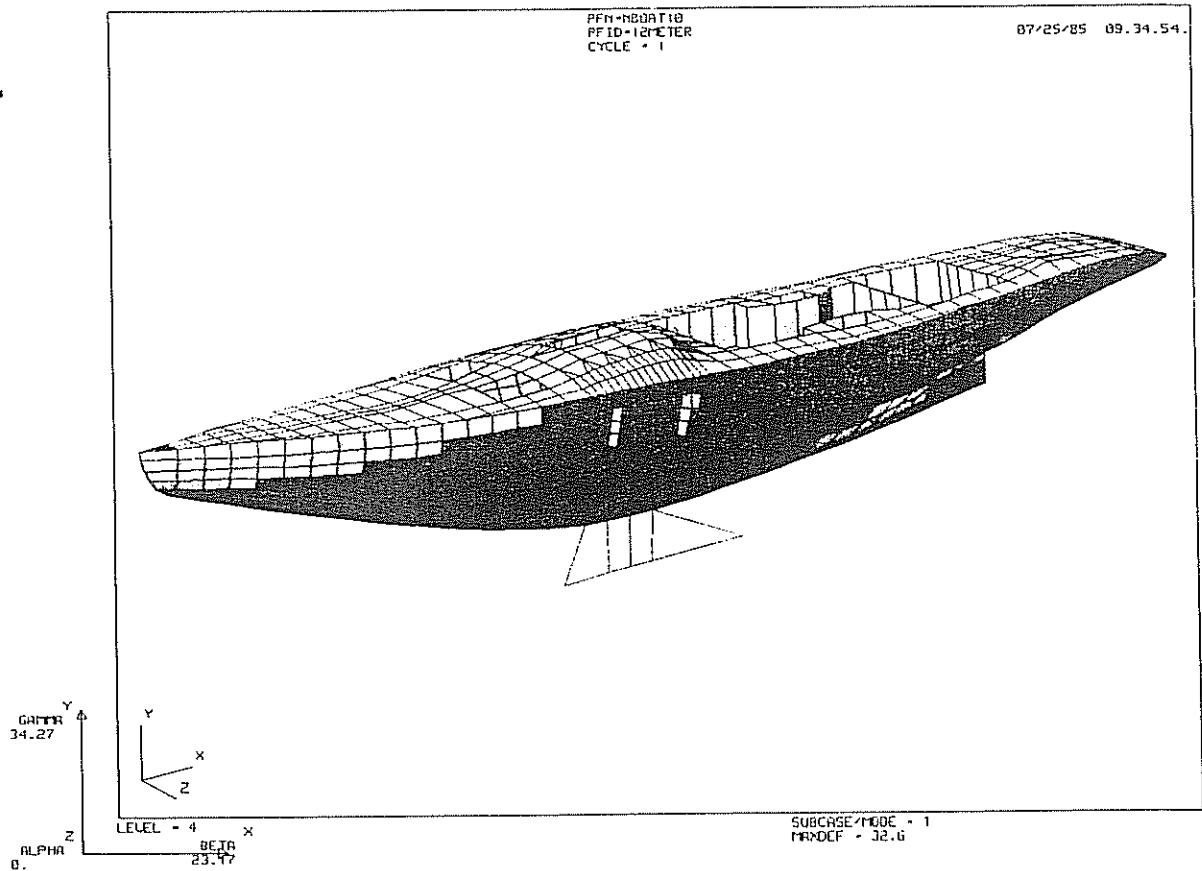


Fig. 7 Hull deflections due to sailing loads

been faced with making major modifications due to Lloyd's amendments.

Once it was felt that improvements on the aluminum structure started to level out, the model was converted to fiberglass in order to be able to determine whether a GRP hull would be an improvement over an aluminum hull. Although the number of variations of structural arrangements for an aluminum hull is large, the number of variations possible for a GRP hull automatically increases by about a factor of 10 since GRP is an anisotropic material. In other words, next to specifying the dimensional properties of each element of the model, one also has to specify the orientation of each fiberglass ply in each element.

While the early runs did not look very impressive, it later became apparent that there were a number of ways to improve the stiffness of a GRP hull, and the final arrangement indicated that a 20 percent increase in overall longitudinal stiffness is not unrealistic. Bearing in mind that the first GRP arrangement was 15 percent less stiff longitudinally, this is a rather drastic improvement—especially considering the fact that the first arrangement was similar to the arrangement found in what are considered advanced composite sailboats. This stiffness increase was mostly due to fiber orientation, and did not increase the weight of the structure. In addition to being 20 percent stiffer longitudinally, the natural frequencies of the final GRP hull were also 30 percent higher, indicating that the increase in stiffness was also exhibited in other areas. It should be noted that the GRP material properties used in this study were representative of a unidirectional R-glass preimpregnated with epoxy resins. This material was developed by SP Systems for the boating industry and can be considered the state of the art as far as GRP is concerned. It is impossible to build a GRP 12M of stiffness equivalent to an aluminum 12M using hand lay-up

mat and woven roving. Upon completion, the GRP design was submitted to Lloyd's for approval, but the amendments made to the design reduced the overall structural stiffness to such an extent that an aluminum hull, as approved by Lloyd's, turned out to be more efficient.

### Weight studies

One of the most important and also one of the most tedious aspects of 12M design is weight control. While every 12M designer would rather play in the model basin, or do some performance tests in Southern California, sooner or later he is faced with having to make a detailed weight estimate of the yacht he is designing. The most obvious reason for making a weight estimate is to make sure that his design will float on the measurement lines. But there are other reasons for performing a weight estimate which are at least as important; for example, classification, performance prediction, and selection of areas of improvement.

Weight studies is one more area where computer technology has changed the life of the naval architect. By using one of the relatively inexpensive spreadsheet programs available, it takes only one big push to get a detailed weight estimate of a 12M hull. Once the first weight estimate is completed it takes only a few hours to do the next estimate, by changing the appropriate variables, or by changing the location of various pieces of equipment. The computer does all the calculating, including totaling the weights, calculating the centers of gravity, and the radii of gyration of the design.

By performing detailed weight estimates of a number of existing hulls, it became possible to make plots of center of gravity and weight of 12M hulls versus waterline length and freeboard.

These plots enabled input of the center of gravity of an arbitrarily sized 12M into the performance prediction program automatically and consistently. Since vertical center of gravity is probably the most important factor influencing sailboat performance, a detailed weight estimate greatly contributes to the relative accuracy of performance prediction.

### Wave-induced drag computer analysis

Since 12M yachts rarely sail in absolutely smooth water, it is rather important to be able to predict the drag added to a 12M due to the effect of surface waves. One method for predicting drag in waves is to tow a model in waves, but this method has a number of disadvantages, cost being the most important. For a number of years the maritime industry has had remarkable success with motion prediction programs. These computer programs predict the motion of vessels in a seaway, and have done this with surprising accuracy. In addition to predicting a vessel's motion they also calculate the increase in drag due to waves, which is exactly what would be required to be able to predict performance of 12M hulls in a seaway, provided it is assumed that the lift produced by the hull is not reduced.

A number of attempts have been made to use these programs but they have not been very successful in obtaining reliable drag numbers, for a number of reasons. The offsets and weight characteristics of a typical 12M hull were entered into one of the programs, and the drag numbers obtained closely approximated the drag numbers anticipated by performing simulations in performance prediction programs. However, the drag numbers obtained were calculated using a standard ocean wave spectrum. Calculations of drag due to waves using a spectrum that more closely approximated coastal conditions (both for Newport and for Australia) were much lower than those anticipated both from performance prediction simulations and from model tests. There are a number of possible explanations for this discrepancy. The added drag derived from motion prediction programs is due solely to the energy absorbed from the hull's movement through waves and it is possible that a sailboat experiences an increase in drag, or a decrease in lift, from other factors. The program used did not take into account heel (most wave motion programs do not), lift in unsteady conditions, the damping effect of sails, changes in driving force due to rig deformations, or the motion of the sails due to waves. In addition to this the program was also not particularly reliable at heading angles more than 45 deg away from head seas. Any of these factors, or a combination, can be the cause of the decrease in performance of sailboats in waves. It will take a considerable amount of research until a reasonably accurate estimate of relative performance of sailboats in waves can be made. Until then a designer will have to compare various designs on their merits in flat water, while hoping that waves will not too severely disturb their relative performance.

### Sailing instrumentation development

Yacht designers and their associates (sailmakers, rigging and hardware manufacturers, etc.) are always looking for ways to incorporate any type of new technology in their designs. This is mostly due to the fact that yacht owners are gluttons for gadgets, and that winning has no price tag. It is unlikely that most people outside the aerospace industry have ever seen titanium, while this expensive material is commonly used in racing sailboats (although sometimes for dubious reasons). This attitude can also be attributed to the fact that boat electronics is probably one of the most competitive and exciting businesses around. One only has to go to a boat show and stop at the electronics stands to realize that computers in cars is old hat. A number of companies manufacture sensors and computers that provide a sailor with such vital data as boat speed, wind speed, wind

direction, compass heading, heel angle, rudder angle, and global position, and that automatically compute and display functions such as velocity made good and time to lay line. Furthermore these systems can be interfaced with a personal computer which will record, store and process all these data. For an additional couple of thousand dollars the systems will even radio-transmit the data to shore or to the sailboat's tender for further reduction and analysis.

These systems are very good, but there is still a lot of space for improvement, and manufacturers of these systems come out with new features almost daily. As can be seen from the section on speedometers, there are very different requirements for instrumentation depending on the needs of the user, and the 12M branch of sailboat racing is the cutting edge of this technology.

Basically there are four areas where a designer tries to gain an edge on the competition: sensor technology, display technology, artificial intelligence, and data storage and retrieval.

As mentioned earlier in the speedometer section, accuracy is very important in sensors, since a winning edge tends to be less than the error in sensors. Once various readings are combined to display a computed function, the accuracy of the function is the product of each sensor used. Consequently a function which uses the speedometer reading, the wind speed indicator reading, the wind direction indicator reading, and the compass is not sufficiently accurate, although the average of a large number of readings can cautiously be used to identify certain trends. Any sensor that can be made more accurate increases greatly the reliability of the system, and thereby increases the performance of the boat by providing the designer and skipper with more meaningful information. In addition to this the system also has to provide information as completely as possible. It is meaningless to develop a certain target speed for a certain point of sail at a certain wind speed if nothing is known about the wave conditions. And this is exactly what is required in order to make significant gains in the ability to predict the added drag due to waves.

The following measurements are required to actually be able to record the conditions influencing the performance of a sailboat: speed, heading, wind speed anywhere along the sails and rigging, wind direction anywhere along the sails and rigging, heel, trim, wave conditions, sail shape, rigging forces, weight, center-of-gravity location, air temperature, water temperature, rudder angle, trim tab angle, global position, leeway, current, time and accelerations. While some of these measurements are easy to make, although barely accurate enough, some are next to impossible to make. In addition, the following measurements would greatly increase the possibility of winning: all the data mentioned above for the opponent, current all over the race course at any time, wind speed and wind direction all over the race course at any time, and wave conditions all over the course at any time. The last measurements can also be translated as intelligence gathering, tide table interpretation, weather forecasting, and eyesight. The only problem with such a translation is that the results are not very reliable, and are hard to store in a computer. As mentioned earlier, improvements are slowly being made in all these areas. For example, rig strain gages and accelerometers are starting to become standard equipment, and some day soon somebody will be able to adapt aircraft or missile-tracking radar into a radar that will track the opponent.

Display technology today consists of numbers being displayed on computer monitors, or liquid crystal displays; behind these displays there is a large amount of computation which actually results in these numbers being displayed. One of the most frustrating of these computational routines is damping. Since conditions are never steady on a sailboat, a decision has to be made as to how often displays should be updated, and how this should be accomplished. The display both has to be readable and to display information as quickly and accurately as possible. A slow update rate provides a relatively steady and

easy-to-read display, but does not provide the crew with up-to-date information; a display might indicate a boat is still accelerating while actually it has already started to decelerate. On the other hand, a high update rate might make the display too jumpy and hence hard to read for the crew. Some tricky juggling of numbers combined with knowledge about the actual dynamics of measurements, sensors and sailboats is required to obtain accurate, and fast displays.

Artificial intelligence is a rather vague term, for any thinking a computer does. In this case it is meant as a support in decision-making. At the risk of being attacked by proponents of other sports, this author would suggest that sailing is probably the most complex sport there is, both as far as preparation and as far as the actual racing is concerned, and decision-making occurs on all levels. A properly designed instrumentation system can aid the crew in deciding what sails to select, in finding the fastest side of the course, in finding the proper trim, and in finding an opponent's weaknesses. Some of these decisions are extremely complex, and the best a computer will likely be able to do is to provide assistance in decision-making, but just as chess programs keep getting better, sailboat computers will also continue to improve.

The last category, data storage and retrieval, is probably most applicable to the designer, since a designer is listened to only when things aren't going right, and then he has to be able to determine where things started going wrong. Data storage and retrieval is an eternal tug-of-war; store a lot of data, and it is hard to retrieve, store a little data, and it is easier to retrieve, but the data needed might not have been stored. There are only three things a designer can do to alleviate this problem: properly store the data, obtain the best possible data processing programs, and obtain the fastest possible computer.

### Sail development

While sail development is generally being handled by the sailmaker, sail technology has to be incorporated into the design by the designer. Sail development consists of four areas: structural as related to sail design, aerodynamic optimization, structural as related to loads on the boat, and sail coefficient generation. The first and second categories are almost entirely handled by the sailmaker, and consequently cannot be considered an area of expertise of a yacht designer. Nevertheless, it is interesting to note that the same factors that have changed the yacht design business—new materials and computers—have also revolutionized the sailmaker's business. Sailmakers have made impressive advances with materials like Kevlar and Mylar, the structural arrangement of panels, aerodynamic shapes, and the dynamic stability of sails. Computers are used by sailmakers for design, analysis, and construction of 12M sails. Very advanced technology in terms of cloth development, computerized design and manufacturing, and computerized databases has become so important that only the largest sailmakers can afford to be in the 12M game.

The last two categories—loads induced by various sails and sail coefficients—are of immediate importance to yacht designers. When a sailmaker designs a sail that changes the loads induced on the hull, either the magnitude or location of lift and drag forces, or localized loads like sheet or tack loads, the yacht designer might have to make adjustments in the hull or rig. These adjustments can vary from increasing the strength of a shackle, to moving or changing lifting surfaces such as the keel or the rudder.

Sail coefficients are parameters which define the heeling and driving force of sails. Depending on the shape of sails, there is a range of sailing coefficients which can be physically achieved and, depending on the characteristics of the sailboat and the conditions in which it will be sailing, there is a set of optimum sailing coefficients which can then be converted into an opti-

mum sail shape for that particular boat. Designers and sailmakers alike are now starting to get a hold on sail coefficients, and in the future it might be possible to greatly reduce the amount of time needed for optimizing sails to a particular design. Just like yacht design, sail coefficient development is a juggling act, and sail coefficients get developed by investigation of performance predictions, wind tunnel tests, and full-scale performance tests.

### Rig and hardware development

While probably less glamorous than model testing and computers, hardware and rigging is probably the most important factor in winning sailboat races that a designer can contribute to. Racing history is filled with incidents where major races were won or lost due to rigging failure. The 1983 America's Cup is probably the most revealing example. In three out of seven races the outcome was heavily influenced by hardware or rigging failures. *Australia II* had a steering gear failure in the first race and a headboard failure in the second race, while *Liberty* had a jumper strut failure in the fifth race. If not for these failures, the history of the America's Cup would have taken a dramatically different course. If not for *Liberty's* jumper strut failure the Australians could have gone home 1-to-4, no better than in 1980, and foreign interest in the America's Cup could have died right there.

The designer has to make a decision between reliability and minimizing excess weight. Weight high up, in the form of heavy halyards, heavy headboards, and spreaders, significantly raises the center of gravity, thereby reducing the performance of the boat, but a failure in any of these items will contribute significantly to a loss. *Australia II* was an example where weight was saved, while *Liberty* was a more conservative approach.

The rougher conditions in Perth are going to cause a lot of failures, and preventing failures will probably be the single most important contribution to the success of a challenge. It is the designer's task to equip the boat with rigging and hardware that is as light and simple as possible, with the lowest center of gravity and the highest reliability. Then it is the crew's task to test the hardware and rigging to its limit, before the racing starts. Finally, it is the boat manager's task to ensure that the hardware and rigging do not deteriorate.

### Human factors design

While yacht designers (and, sadly enough, engineers in general) rarely address it directly, human factors design is an area which constantly enters in the overall performance characteristics of a sailboat. Human factors design is most prominent in three areas of yacht design: deck layout, hardware, and something which might be called "psychological design."

A 12M yacht has 11 crew members, and each has a highly defined task. In order to make the boat perform, each crew member has to be as comfortable as possible and has to be able to perform his tasks as efficiently as possible. Each crew member's position, and his access to controls, is defined in the deck layout. Deck layouts are the most personalized area in 12M design, and inspection of the deck layout of a 12M yacht will reveal the crew's personal preferences. An efficient layout is based on the characteristics of the crew and on the conditions in which the boat will be sailed. In Australia, watertight integrity will be a major factor, while this was not as important in Newport. A boat that has a navigator who also assists in foredeck work needs a layout that allows the navigator to move forward, while other navigators on other boats might be much better located below deck. Generally, designing the deck layout is an iterative process where the designer gets input from the crew, and where modifications get made while the boat is actually sailing.

Human factors have to be taken into account in all hardware design in order to eliminate as many distractions as possible. Winches have to run light, have to have the right reduction ratios, and have to be easy to operate. Hydraulic panels have to have valves which are easy to open and close. Computer displays have to be easy to operate and read. And all equipment has to be easy to service and maintain. It is imperative that the designer observe the crew functioning, and that the crew keep making suggestions for improved human design.

The final area of human factors design—psychological design—is worthy of a paper by itself. Sailing is a mind sport, and the outcome of a race can be heavily dependent on psychological factors. 12M skippers are keenly aware of this and often prepare themselves for races with the help of psychologists, coaches, and major behavioral changes. The skipper ultimately is in command, and has to use every trick in the book to force his opponent into making mistakes and to motivate his crew. In certain ways the designer can contribute in this psychological game. Every syndicate has its own image. Some syndicates are the frontrunners from the beginning, others play the underdog, while others come to prominence from nowhere. America's Cup history has examples of all these types, and generally the designer will try to reinforce this image by releasing certain information, or by making certain statements. Furthermore, a front-running syndicate always needs to be up front; in other words, the boat constantly has to be up to speed, and consequently the designer has to take a rather conservative approach. The other types allow the designer to take risks, and fail at times. Depending on the image of the syndicate the stage at which to use a certain gadget or innovation might differ. Whatever happens, it is important for a syndicate to stick to its image in order to maintain momentum.

Within the syndicate, psychological design becomes important in designing the boat to fit the skipper. A very aggressive starting skipper might benefit from a boat with good acceleration and maneuverability, while other skippers would prefer a boat with good straightline speed. It is also important to convince the skipper that he is getting what he wants. For the skipper to be able to perform, he has to believe in the boat. A radical design can work, but only if the skipper believes in the design. If he does not believe in the radical feature, the boat will never perform to its potential. Some skippers might even intentionally slow the boat down in order to avoid having to admit he was wrong. Naturally the same comments apply to a lesser extent to the rest of the crew. At the same time the designer also has to be honest and admit that a certain feature did not work. If the designer notices that the boat is not performing, for whatever reason, he has to make a change in order to maintain the momentum. Whether this change actually alters the boat or is merely cosmetic is not always important, because speed differences cannot be measured anyway. The designer merely has to make everybody feel that development is continuing.

Another psychological design method is to make the opponent think that he has to catch up. It is very frustrating for opponents to know that they can't get a certain piece of equipment, or that they have to play catch-up in a certain area of design. For example, a designer might have spent a lot of time developing a certain piece of equipment, only to find from testing that it does not really work. The obvious thing would be to remove it from the boat and to forget about it. However, if it is possible to make one's opponents believe that the piece of equipment is working, they will be wasting their time trying to copy it rather than concentrating on their own design.

### Computer performance predictions

To determine whether a certain design change actually contributes to the performance of a 12M, one has to have a method that will predict the performance of a sailboat. Such means

have been around since the 1930's when Dr. Davidson started applying the results of his studies in sailboat performance. He basically tried to learn as much as possible about sailboat loads (lift, drag, and hydrostatic loads) in general. For each particular design he tried to pick the correct loads, for which he would then calculate the optimum resultant and its associated velocity. Although the calculations were tedious, they were not particularly sophisticated. Dr. Davidson obtained his hull lift and drag numbers from the model basin, his sail driving and heeling coefficients from full-scale tests; the hydrostatic values could be either calculated or measured.

Since those days a lot of refinements have been applied to his methods although no great leaps in accuracy have been made. The best-liked improvement to the original method is the incorporation of the computer in the performance prediction process. Rather than having to perform the calculations by hand, it is now possible to do them in seconds once the inputs have been generated. Loads are also being determined in different ways: sail loads from the wind tunnel, loads using vortex panel methods, and drag and lift using shape coefficients. In addition, some work has been done in solving the dynamic equations of a sailboat, rather than the static equations, and in predicting the performance in waves. The bottom line now is that for a couple of hundred dollars anyone can take a design to a variety of places, have a performance prediction performed, and get a good idea of the speed of a particular design as long as it is not too unusual and as long as the accuracy does not have to be within 1 percent. These programs are quite good for studying the effects of variations in design, but they are very poor in evaluating absolute performance. The only reason that such programs show results representative of real life is that they are tuned against actual full-scale performance. One basically enters hull parameters into the program and then adjusts the sail coefficients until they produce velocities which are representative of the type of boat that is being studied. For comparison studies the sail coefficients are kept constant while the different hull designs and sail areas are evaluated.

Performance prediction is tricky, and a designer cannot rely on the calculations unless he is intimately familiar with the restrictions and assumptions of the program. A performance prediction program was developed by the author's company which can be considered a hybrid. It predicts performance using model basin data, but can also perform parametric studies using flow equations and certain shape coefficients. With this particular program, input files were developed for every model tested. Once the performance of the tested model was calculated, the program could also evaluate changes to the model without additional model tests. Among features that were added to the program was the ability to change the scale factor of the model while adjusting the sail area according to the 12-Meter rule. This feature was used to find the optimum size (waterline length) for each model and for a specified wind speed. It also served to detect measurement inconsistencies. In addition, the program could increase or decrease the planform area or the thickness ratio of the keel of the tested model, enabling a study of the optimum keel size with respect to minimum wetted surface area, minimum drag, and the lowest possible center of gravity. Other features were a rough analysis of the effect of waves on various hulls, and the effect of mainsail roach as allowed by the 12M rule with respect to boom length. Since the program was developed in-house it was possible to make changes once new information became available. The large amount of testing data available made it possible to cross-check new features, and full-scale performance testing on *Magic* enabled us to calibrate the program.

While the program was very useful in parametric studies, it could not perform accurate absolute performance predictions, for a number of reasons. Assuming that model tests are accurate (which is not necessarily true), the most frustrating weakness in

performance prediction programs is the sail coefficients. The sail coefficients inherently reflect the sail configuration and sail shape. Once a set of sail coefficients has been developed, these are used to compare all the different designs. In real life, however, every boat has a set of sails that is optimum for certain conditions, and those sails will differ from boat to boat in shape and size. Some boats will perform better with flat sails, while others will perform better with fuller sails. These differences are due mainly to variations in stability, drag, and keel area. Since the same sail coefficients are used for every boat compared, it is possible for a weak design with optimum sail coefficient to be compared against a good design with sail coefficients that are unsuitable for that particular design. It is the author's opinion that although some work has taken place in this area, greater advances can be made. Once the sail coefficients are straightened out, it will be possible to optimize the sails for a particular design before the cutting takes place, and to perform more accurate optimizations with regard to optimum center of gravity, stability, and planform areas.

### Conclusion

The foregoing is a description of the type of engineering and research methods used by a typical 12M design group. As was shown, the designer depends on a wide variety of methods in order to optimize his design. While certain methods can be more useful than others, it is important for the designer to continually remind himself that a sailboat is a very complex system, and that an improvement identified by one method can turn out to be a disadvantage when studied using other methods. In this regard the success of a design effort can be judged only by the sum of the entire effort rather than the success of one method.

It is hoped that this paper will stimulate interest in 12M design, and its wide variety of related engineering methods. The

America's Cup is a matter of national pride, and is one of the few peaceful competitive activities between nations where engineering plays a significant role. As can be seen from the above, the design of a 12M represents a very large investment, and anybody who feels he can contribute in any capacity to developing the fastest 12M for his country should not hesitate to contact one of the syndicates. Any and all assistance will be sincerely appreciated.

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## Discussion

### Daniel Savitsky, Member

The author is to be congratulated on his overview of the numerous factors which influence the design of a 12-Meter hull. Although many of his conclusions may be debatable, I think that the design community would agree that the performance difference between serious contenders is of the order of only 1 percent.

I would like to limit my discussion to the author's comments on the value of model testing of 12M designs. He rightly states that the hull drag, lift and moments obtained from model tests must be combined with many other factors to predict total performance. I would like to add, however, that the hull and keel drag dominate the total resistance equation and that the towing tank provides the best means for evaluating a new hull design if total performance differences of the order of 1 percent are to be obtained.

The author states that "a very bad concept will always show up bad in a model tank." This is the philosophy of the Davidson Laboratory and indeed represented Dr. Davidson's views some 50 years ago when he developed sailing yacht test techniques. The author contradicts this statement in the section "Third-scale model tests" where he implies that the towing-tank was responsible for the failure of *Mariner* in 1974. This undocumented impression has been repeated over and over again for years until now the yachting community considers this to be gospel. I think it is time that the yachting community stop perpetuating this myth and, as the man said, "let's look at the facts."

The model tests of *Mariner* and *Courageous*, potential de-

fenders for the 1974 campaign, were both conducted here at the Davidson Laboratory. Because of the confidential nature of 12M testing, each yacht designer is aware of only his own test results. Most importantly, the test facility itself is committed to protect the proprietary rights of each designer. It is a responsibility that the Davidson Laboratory takes very seriously.

For over ten years now we have been pained by more and more frequent references to undocumented accounts, such as given again in the paper, that the towing tank was responsible for the failure of *Mariner*. It is time that we put an end to this irresponsible hearsay and present the model test results for *Mariner* and *Courageous* while still respecting the proprietary nature of the data for both yachts.

Figure 8 accompanying this discussion shows a comparison of speed made good to windward versus wind speed based on model test results for both *Mariner* and *Courageous*. Scales are not provided in order to preserve the confidentiality of the test data. It is obvious that the tank results show *Courageous* to be the better boat, which is in total agreement with the full-scale trials.

Subsequent to the 1974 campaign, the Society of Naval Architects and Marine Engineers sponsored a model study to compare two models differing only in that one had a normal afterbody form while the other had a fuller afterbody terminating in an underwater transom similar to that of *Mariner*. Tests were made with both  $1/8$  and  $1/12$  scales covering the normal windward sailing conditions at 10, 20 and 30-deg heel.

In all cases the *Mariner*-style afterbody was inferior to the normal form. The difference was small at the 8.5-knot speed

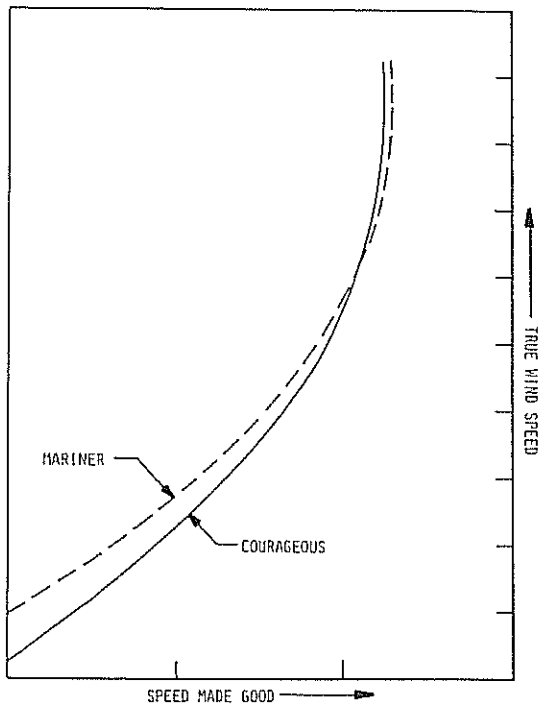


Fig. 8 Predicted windward performance based on 1/13.33 scale model tests

through the water, appropriate to the stronger wind conditions, and the difference increased in lighter winds. These results will be presented in a forthcoming Davidson Laboratory report.

The unfortunate end result of the *Mariner* myth was that it contributed to the extensive use of expensive  $\frac{1}{3}$ -scale models, which are mainly affordable in 12-Meter campaigns. Such costly model tests cannot be tolerated by the average yacht designer so that he is left without a valuable tool to develop new concepts and expand the technology of yacht design. Smaller yacht models are credible and should be used in yacht development.

#### Alfred I. L. Pagan, Member

I have to thank Mr. Van Hemmen for an interesting treatise on the complicated and sometimes passionate subject of design of 12-Meter yachts. I found the paper extremely comprehensive and informative and, I am sure, it will be used as a reference document by other designers in the future.

However, the author has made a number of statements in the section "Structural finite element analysis" upon which I feel bound to comment. I would like first to explain some general considerations from the classification society's point of view before specifically addressing some of his comments.

The 12-Meter class was decreed by the International Yacht Racing Union in November 1980 to be a "developing" class. Therefore, since the dictionary's definition of developing is "the gradual unfolding of" or "laying open by degrees," the implication should be, as stated by Mr. Van Hemmen, "evolution" and not "revolution."

With regard to structural design, in order to maintain this gradual development, some control is required if the "quantum leap" is to be avoided, and from discussions with other syndicates, it would appear that if Lloyd's involvement were dropped, as suggested by the author, the complexity and cost of a 12M project would escalate and become prohibitive to most countries. The existing control, in the form of scantling requirements, is in turn controlled by the regulatory body, IYRU, and it is considered that any relaxation in the requirements could

lead to the results which we have all seen in recent months in the Sydney to Hobart, last year's Fastnet and the present Whitbread Round the World races where in some cases, scantling weight has been sacrificed at the expense of strength.

Indeed, this point has now been recognized and the Offshore Racing Council has seen fit to adopt the American Bureau of Shipping (ABS) requirements for Offshore Racing Yachts for Categories 0 and 1 races from January 1986 and for Category 2 races from January 1987. Although it is not anticipated that 12M's will race in these conditions, a similar analogy can be applied.

All 12-Meter yachts are controlled by the rules of the IYRU, which closely monitors and regulates developments of the class, including developments in the structural design. The annual November meetings of the Keel Boat Technical Committee have become the designers' forum to promote new ideas and thoughts, and certainly a review of their handbooks over the last few years reveals numerous advances in this area such as wing keels, the advent of GRP for hull and deck construction and, very recently, the use of carbon/aramid fibers for rudder and rudderstock construction.

The current America's Cup series has seen a tremendous increase in the number of participating countries, some of which have more than one syndicate producing multiple designs of yachts, and to date Lloyd's Register of Shipping has been involved with the plan approval, building, and subsequent classification of well over 30 new 12M yachts constructed in accordance with the existing aluminum alloy and GRP scantling requirements. To service a project of this magnitude it is essential to have a worldwide organization which respects the impartial and security aspects of these yachts and is capable of supplying surveyors in the field at very short notice. It is also essential that this impartial approach be extended to *all* designers for the structural design aspects and to this end a more comprehensive, metricated set of requirements for the construction of aluminum alloy 12M's was introduced in 1984. This was followed in 1985 with the advent of the draft requirements for the construction of GRP 12M's and in 1986 the draft requirements for rudders and stocks built of carbon fiber or carbon/fiberglass composites.

Within the scope of the above-published requirements the designer now has the freedom to design either a longitudinally or transversely framed yacht in either aluminum alloy or GRP. It is Lloyd's experience that many designers do not optimize their structures and select materials to give the maximum fore-and-aft stiffness, so desirable for better sail control, as stressed by the author. Lloyd's has the facilities to assist in the optimization and structural analysis processes and does provide an efficient service when furnished with the necessary information.

I would stress that often the general information published in the nautical press relates to public relations material provided as an effective red herring to discourage other syndicates from pursuing the same structural design course.

Now to some specific aspects:

Mr. Van Hemmen has made a number of statements which imply that Lloyd's is restricting the development of the 12-Meter class and is rejecting designs that are, in his opinion, within the published requirements. I would therefore draw attention to the following points.

- (a) It is possible to design a GRP 12-Meter yacht with a stiffness of not less than that of the basic transversely framed aluminum yacht, using conventional glass reinforcements and epoxy resin at the standard fiber/resin ratios, and this aspect has been *demonstrated* from both theoretical and practical considerations.
- (b) As indicated by the author, "the plating thicknesses of the hull are very strictly defined"; therefore, proposals indicating reductions in the local weight per unit area, for

side and bottom structure, so as to redistribute the weight into zones where it would improve the overall stiffness characteristics of the hull, are *unacceptable* and result in Lloyd's modifying the design to indicate the minimum weight acceptable for equivalence of the rule requirements.

In the opening paragraph of the section "Structural finite-element analysis" Mr. Van Hemmen states, "In the 12M design game, structural optimization in aluminum and GRP is a very complex engineering and tactical process which has no equal in yacht design due to the requirements of Lloyd's Rules and the original intention of the 12M rule."

Here I would say that it is the intention of the IYRU and Lloyd's Register scantling requirements for 12-Meter racing yachts to produce a structure with a minimum weight relative to the size of the yacht and therefore the scope for optimization of the structure is more restrictive than for those racing yachts where no control on structural design is applicable.

In the next paragraph he states that "Lloyd's approval was intended to stabilize 12M yacht design, and to increase the popularity of the rule as a relatively inexpensive coastal racing/cruising class."

This is probably true and in this respect Lloyd's involvement has been successful in contributing to the stabilization of design.

The present series has seen a dramatic escalation in costs brought about by the comprehensive tank testing programs, electronic equipment, sails, masts, training, etc., now required by the designers and campaign/syndicate managers in order to keep one step ahead of the opposition. One of the few static costs, taking inflation into account, is the initial cost of the hull and deck construction.

The author goes on to say, "However, for unspecified reasons, Lloyd's has assumed that they should not allow a structure which is within the rules but more efficient than the norm, and has developed rather stricter unpublished rules."

I have checked with our Lloyd's Yacht Design Approval Department in Southampton, England and can state with authority that Lloyd's does *not* have "stricter unpublished rules," only standardized interpretations of the rules which are adopted to ensure that all designs are considered equally. This standardization in turn avoids the designers having to submit extensive calculations to indicate compliance with the strength, stiffness, and weight distribution equivalence clause in the rules.

Later in the same section (finite-element analysis) Mr. Van Hemmen states, "It is only to be expected that Lloyd's has not been very eager to accept advanced composites for 12M structures, and the designer is faced with an expensive and time-consuming fight in order to get approval for a GRP hull."

As I have already stated, we *have* draft rules for the construction of GRP 12M yachts with some draft requirements for rudders and stocks of carbon fiber or carbon/fiberglass composites. Lloyd's has already approved structures for other yachts and small craft incorporating various glass, Kevlar and carbon fiber reinforcements and is perfectly willing to approve GRP 12M yachts. It should be noted, however, that the cost of GRP approval and construction is considerably greater than for a "conventional" transversely framed aluminum alloy yacht. The actual percentage increase is dependent on the complexity of the combinations of actual reinforcements being selected, with the degree of detail given in the initial presentation, and the survey fees for continuous attendance during the molding cycle.

The author calls for the requirement for Lloyd's approval to be *dropped* from the 12M rules, stating that "Such a change will strengthen the 12M class by allowing experimentation in advanced structures which can be passed on to other types of sailboats and to the engineering community at large." As he has

already indicated, the 12M yachts are a "developing class" and his proposal to drop Lloyd's involvement would appear *contradictory*, as this would result in revolutionary structural designs, the complexity and cost of which would escalate to such an extent that they could be prohibitive to most of the present participating syndicates.

To quote Mr. Van Hemmen again from the same section: "Consequently, in order to design a better boat, the designer is faced with designing a stiffer boat, either by rearranging structure with Lloyd's approval, or by adding excess material."

I am not quite sure what he means by "adding excess material," but can only state that it is considered that certain aspects within the 12M aluminum alloy scantling requirements for the transversely framed yachts are already minimal and therefore Lloyd's would strongly recommend optimization to improve the overall structural integrity within the permissible weight control incorporated in these requirements.

Further along it is stated: "While the design proposed by this syndicate did get more or less accepted by Lloyd's, other syndicates have been faced with making major modifications due to Lloyd's amendments."

My response is that we have no degrees of accepting a design—a design is either acceptable or it is unacceptable. As to what other syndicates have been faced with, I can only state that as the plan approval requirements for well over 30 yachts have resulted in only two designs requiring repositioning of three web frames or less, it is considered that no major modifications have been requested by Lloyd's. In this respect it should be noted that a very good working relationship has been engendered over a number of years with the majority of 12M designers to the extent that many request our comments and advice on structural design aspects which would not always be covered by the classification requirements.

I am grateful for the opportunity to state our point of view and reiterate my thanks to Mr. Van Hemmen for a very interesting paper.

**Pierre DeSaix, Member**

The extent to which the author's design group devoted time to basic yacht research, such as sailing trials and full-scale towing tests, testifies to the lack of confidence today's yacht designer has in the technology of those preceding him. The loss of the America's Cup was truly a catastrophic event for American yacht design; however, this lack of confidence began 10 years earlier with the loss of *Mariner*. The disastrous loss of *Mariner* was attributed to the use of small models—the same small models that were used to develop an equally outstanding yacht, *Courageous*.

Designers then shunned the use of small models. Large models were introduced but were not widely used because of the inherent high cost. Designers and their syndicates chose to use computer studies and to try out their concepts by building full-scale yachts, returning, in effect, to the state of the art of some 50 years earlier . . . only to lose the Cup 10 years later to a thoroughly model-tested hull. Now in attempting to regain the Cup, the American design teams (Mr. Van Hemmen's is not alone) have set up research and development programs identical to that of the Australian winner. I doubt if such an event has occurred elsewhere in the annals of engineering history.

By the author's own admission, full-scale trials produce crude results. He need only consult the published trials of the late Kenneth S. M. Davidson, Paul Spens and Pierre DeSaix, J. Gerritsma, J. E. Kerwin, and G. Moeyes—work spanning several decades—to learn that his trials would be too scattered to develop better methods for interpreting model test data than those which already exist. My questions to the author are:

- Did he significantly alter his method of expanding model data to full-size from those of Froude or Davidson as a result of these trials?

- Similarly, did the sailing trials lead to different sail coefficients that would lead to choosing different hulls?
- Or, was this effort primarily a learning experience for his own design team?

Several times the author says that computer studies were not useful in developing hulls with lower resistance. Such is my own experience. That brings us to the use of the towing tank, which in 1986 is still the best tool the designer has for yacht development. It appears also to be a tool that the yacht designer is fearful of.

#### RATIONAL USE OF MODEL TESTS IN YACHT DESIGN

The author points to the necessity of first determining the size and stability of the yacht for the anticipated wind speeds. He is absolutely correct. For this task, our group found the computer a useful tool, confirmed by model tests. Once the size and power of the yacht is decided, the focus must be made on *reduction of resistance*. Simple? No. This is the most difficult task, but a designer's success will be determined on how well he has addressed this task.

The concept of wetted surface contributing significantly to resistance is archaic; yet because of its simplicity it has persisted. Wavemaking, the induced drag of the hull-keel configuration as well as interference drag of appendages, is most easily evaluated in the towing tank, thus freeing the designer to explore innovative ways to reduce drag.

Based on my 30 years' experience model testing 12M yachts, I find that designers frequently get into trouble using the towing tank. Some of these pitfalls are:

- *Bad data*—This is an unnerving experience. One is more apt to question high resistance readings than low readings. All data should be questioned equally. A good tank will provide tolerance to their measurements. This does not mean all data will fall within these statistical limits and, if a test cannot be repeated within the limits, something is wrong. To insure a test is good, plot data and make repeat runs often during the test. This may run the cost up somewhat, but is much more economical than going back later to check a suspicious run. With modern techniques, a lot of data come at you quickly, and it is all too easy to achieve a state I refer to as "information overload." I monitored the quality of all tests as well as the performance of the models with one simple plot, made tankside.
- *Control model*—To check the health of the test procedure, a control model should frequently be tested. Some tanks provide one. All programs start with a base boat. Lacking a control provided by the tank, this base makes a logical choice for a control, yet designers often yield to the temptation to modify the control, thereby losing a valuable tool.
- *Limits of measurement*—The author is correct in stating that a 1 percent (0.08 knot) improvement in speed is significant. Yacht designers must be aware that the change in resistance to cause a 1 percent change in speed is near the limits of measurement in the yacht test. This test is the most difficult a tank can perform. A four-component balance is used, increasing the probability of cross-coupling and other troubles. A procedure for calibrating the balance with the model in place is a strong plus for the tank. When questionable data appeared, I frequently stopped the test, waited for the tank to steady out and applied known forces to the model to satisfy myself that the test was okay.
- *Design of test program*—Make one change at a time to a model. Since most of your changes will fall close to or even within the limits of measurement, make your changes systematically, in stages, and greater than you feel you should. Look for trends in changes. Several models, each serving as a bed for testing a particular variable, provide an efficient approach.
- *Trap*—It frequently happens as the designer makes his

changes—the model is no longer a 12-Meter! "I can add the displacement or stability later" is a common comment. When time has run out is not the time to be looking for a place to "hide" displacement. Always keep the models within the Rule.

- *Final boat*—At the end of the program, two things often happen:

1. The amount of data to define the performance of the final boat is less than the amount obtained for the base at the start of the program. The credibility of the results is a function of the amount of data, calibrations and reruns. Be just as sure of your final results as the first results.

2. It seems incredible but, in far too many cases, the lines get modified one more time from the final model to the loft floor! What did you spend all that money testing for? A model testing program does not instill the designer with clairvoyance. You simply learned what works and what does not work. Any later concepts have to be tested equally as the earlier ones.

I have come out very strongly for the use of the towing tank. Some designers use it more effectively than others. For a span of 30 years, in every case but one of mine, the best model in the tank won. That one exception? *Mariner* versus *Courageous*? No. *Gretel* versus *Weatherly*.

#### Robert Curry, Member

The author is to be complimented on an informative and thought-provoking paper. My comments are confined to the structural design section.

A brief review of the scantling requirements for aluminum 12M boats and an estimation of fiber-reinforced plastic (FRP) scantlings required to provide a boat of equivalent strength and stiffness have led me to the following conclusions:

With single-skin construction using E-glass chopped strand mat/woven roving or woven roving reinforcement alone, equivalent local plate panel strength and local plate panel stiffness can be attained with a weight similar to that of aluminum. However, it seems extremely difficult to obtain a hull-girder stiffness equivalent to aluminum with this lay-up, and probably impossible if the FRP hull is to have a weight similar to an aluminum hull.

Using single skin of unidirectional carbon and S-glass, equivalent plate panel strength and plate panel stiffness can be attained for much less weight than for aluminum. In addition, it would appear that a hull-girder stiffness comparable to that of an aluminum hull could be attained at about the same weight.

With FRP, however, the optimum strength and stiffness for weight is obtained with sandwich construction. Using unidirectional carbon and S-glass skins and a 1-in. (25.4 mm) core, local plate panel strength and local plate panel stiffness equivalent to an aluminum boat can be obtained with frame spacing of about 40 in. (101.6 cm), compared to the standard 16-in. (40.6 cm) frame spacing required for an aluminum boat. In addition, it seems that with this lay-up, hull-girder stiffness equivalent to an aluminum hull could be obtained with less weight, as the weight saved by the omission of much of the framing would more than offset the increased thickness of the deck and bottom skins required to obtain equivalent hull-girder stiffness.

The author expresses the opinion that developing structural standards for 12M boats to allow as wide a choice as possible of materials and structural arrangements would result in advances in the structural design of 12M boats that could be passed on to other sailboats. However, there is already the ABS guide for building and classing offshore racing yachts that gives requirements in simple engineering format for all materials, including high-performance unidirectional laminates. Therefore, in fact, the existing advanced structural technology of offshore racing yachts is already available for use in the structural design of FRP 12-Meter boats.

## P. Ward Brown, Member

The author raises many points about the complex process of 12-Meter design, so that it is difficult to single out a particular topic for discussion.

I was particularly impressed with the author's remarks about the limitations of testing full-size 12M hulls because it is sometimes said that the ultimate large model is the full-size hull itself and that the full-size hull gives the most accurate results. However, Mr. Van Hemmen points out that the factors that make accurate model testing possible are just the factors that make full-scale testing difficult. Full-scale testing requires a lot of calibration and it seems from Fig. 5 in the paper that the available full-size speedometers have an accuracy of only 5 percent when the author says an accuracy of 1 percent is barely sufficient.

Since full-size upright testing is so difficult, and full-size heeled tests would be needed to predict windward performance, it seems inevitable that model tests in a towing tank are going to be an essential part of sailboat design technology. As this paper makes clear, all the towing tank does is to measure drag, side force and heeling moment at a series of speeds. How these data are employed depends on the skill of the designer. Some designers request full expansion of the data and the prediction of speed made good to windward. Other designers become so skilled in the use of the tank that they can do their development work directly with model results.

Whichever way the tank is used, it is a development tool that can be used to identify promising design concepts. When the tank is used in this way, it is appropriate to consider the cost of using third-scale models to minimize scale effects. The whole thrust of Dr. Davidson's sailboat testing technique was to provide methods for judging the comparative performance of different designs, at an economical cost. Third-scale models cost three times as much as eighth-scale models and cost twice as much to test, so that the \$10 million the author says has been spent to test third-scale models would be equivalent to \$5 million if eighth-scale models were used; or, twice as much testing could be done for the same money.

Finally, I would like to comment on the need for accuracy in model construction. When comparisons are made between full-size, third-scale and eighth-scale model results, it is vital that exactly the same shape be compared. Because of the confidential nature of 12M testing, sometimes the designer delivers the model to the towing tank without lines drawings so that the tank has no way of checking the accuracy of the model. And when eighth-scale and third-scale models are tested in different tanks the model templates should also be compared. This is especially important if modular models are constructed. The same is true of the full-size hull because it is not unusual for the lines to be changed after the model tests and even during construction. In this case there are bound to be differences between the tank predictions and actual sailing experience, and the rush to blame the towing tank for all differences is harmful to the entire design community.

Economical model tests contributed for 40 years to the successful defense of the America's Cup from *Ranger* to *Courageous*. Considering the sailboat technology developed in those years, including model test techniques, sail coefficients and performance prediction, it is understandable that Mr. Van Hemmen feels that the towing basin is still essential in the design of 12-Meter yachts.

## Author's Closure

I would like to thank the discussers for their insight and opinions, and will respond to their remarks by subject rather than by individual discussion.

It would appear that the discussions can be divided into three

main categories: (1) model testing, (2) sail coefficients and full-scale trials, and (3) structures. My remarks will address the discussions in this order.

The author agrees with the argument that models smaller than  $\frac{1}{3}$ -scale can provide credible model testing data. Only in limited cases is it absolutely necessary to test models to large scale, and often it is just as reliable and more economical to use models to a smaller scale. Since we were dealing exclusively with one model testing facility, and since the size of the model would not have significantly altered the cost of testing (using smaller models in a big tank does not drastically reduce the cost of testing), it became standard practice to test to  $\frac{1}{3}$  scale. By sticking to one model scale, the risk of data comparison problems would be minimized. In retrospect, there were a number of testing sequences which could have been performed more economically at a smaller scale. These tests dealt mostly with radical features where qualitative results were more important and where data comparison was not of overriding importance.

With regard to Dr. Savitsky's objections about the author laying the blame of design failures at the model basin's doorstep, it should be pointed out that the paper stresses the designer's responsibilities for interpreting the model basin data. It is also clear from the paper that these responsibilities include proper comparison with baseline models and proper attention to possible calibration problems.

Mr. DeSaix's remarks about practical problems with model testing are almost entirely in agreement with both the author's opinion and the actual methods of the Eagle Syndicate's tank testing program. It deserves mention that in the author's opinion wetted surface area is the largest determinant in downwind speed in 12M racing, especially in light and medium air. Upwind the other drag-inducing factors are more important.

Mr. DeSaix's remark about the final hull being dissimilar to any of the models tested is basically true. However, it should be noted that the discussor himself states that changes from model to model should be made methodically, and based on trends. In this regard it is useless to throw a number of features into a model and to test it. Upon completion of the model testing program, the designer will generally get a good idea of the trends observed, and will attempt to carefully combine these trends into his final design. To model test the final design will either confirm the correctness of the designer's interpretation, or will serve notice to the designer that his interpretations were invalid. In the first case the money for the test was wasted; in the second case it will generally be too late to do anything about it. As long as the designer does not depart too radically from his previous models, there is no problem with altering the design between the model basin and the loft floor.

The following comments apply to the remarks about sail coefficients and full-scale trials. Sail coefficients are by far the weakest area in sailboat performance prediction. However, a good grasp of sail coefficients is required to be able to determine the proper size of a 12M. Using sail coefficients that were not developed for 12M yachts would result in improper sizing, which could ruin any subsequent development work. Our full-size project was aimed mostly at developing proper 12M sail coefficients, and while our full-scale drag tests were interesting, they were performed merely because we had the opportunity to compare the full-scale drag of a 12M with both a conventional and a winged keel, and we already had the data acquisition equipment in place. From the full-scale tests, sail coefficients significantly different from those published were developed. Those sail coefficients resulted in 12M performance predictions that were significantly different from those that would have resulted from using *Gimcrack* coefficients, or other published numbers.

Mr. Curry's remarks about the comparative strengths and stiffnesses of various composite structural arrangements agree with studies performed by the author; however, it should be

noted that the 12M rules do not allow carbon fiber as reinforcement for the hull structure. While the ABS rules for offshore racing yachts are a very useful guide for structural design, and allow the designer a large amount of freedom, it should be noted that at present those rules are not applicable to the design of 12M hulls. While the author prefers a 12M class without structural rules (all designers do—less paperwork), the ABS rules would be vastly superior to Lloyd's Rules when advancing the state of the art of yacht structures is the object.

Mr. Pagan's remarks on classification of 12M yachts from Lloyd's point of view are sincerely appreciated. While his remarks are valid from the standpoint of commercial shipping, or even that of recreational or offshore racing, they do not apply to America's Cup racing.

Aside from Lloyd's interpretation of the rules, which we feel has been evenhanded, but needlessly complicated, there were basically two central arguments raised in the response. First, discontinuation of class approval will make America's Cup racing prohibitively expensive, and secondly discontinuation of class approval will result in Fastnet-type disasters. With regard to the cost question it should be noted that a 12M hull costs around \$300 000, compared with about \$7 million for the average single boat campaign; even if the cost of the hull would double to \$600 000, it would increase the cost of a campaign only by 4 percent. A 4 percent increase will not make a difference in the amount of interest from possible competitors. Development costs will not significantly increase, because composites manufacturers are very eager to assist in the development of composite 12M yachts. The Eagle Syndicate was very

enthusiastically and capably assisted by SP Systems, a company very much interested in applying their materials to 12M racing. Furthermore, the knowledge gained from 12M programs will be used by the manufacturers to improve upon composite design in general. It is the author's opinion that Fastnet-type disasters are prevented by the discontinuation of class. Since failures in the closely monitored 12M arena can be much more effectively analyzed than failures in the middle of the ocean, it will be possible to apply the knowledge gained to the design of offshore racing and cruising yachts. While there is a certain amount of personal risk involved with hull failures (certainly not in proportion to the amount of risk involved with ocean racing), it should be noted that 12M yachts seldom venture far offshore, and that they are always followed by tenders which could provide immediate assistance in case of a failure.

It should be noted also that failure is central to engineering. While every engineer and designer would rather go through life walking just on the safe side of failure, it is essential that the failure limit be known, because otherwise the designer cannot consciously design to the limit of failure. The central question then becomes where failure can best be investigated, and it is the author's opinion that the 12M class is the best possible setting for pushing the failure limit.

Finally, it should be noted that gradual design changes will just as surely lead to failure as radical design changes, since a certain trend, whether radical or gradual, will always continue until failure. The rate of improvement in the state of the art is directly proportional to the rate of failure, and this rule is just as valid in model testing as it is in structural design.