THE ROYAL INSTITUTION OF NAVAL ARCHITECTS
AUSTRALIAN DIVISION

THE DEVELOPMENT OF THE INTERNATIONAL 12 METRE CLASS YACHT "AUSTRALIA II"

by

*Dr. Peter Van Oossenan**

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THE ROYAL INSTITUTION OF NAVAL ARCHITECTS, AUSTRALIAN DIVISION
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RINA award to Ben Lexcen

Ben Lexcen (pictured right) was recently presented with The Royal Institution of Naval Architects award for "Small Craft Group Medal for 1983" in recognition of his considerable achievements in the design of *Australia II*. The medal was presented by Australian division RINA President J.C. Jeremy (left) at the Sydney Amateur Sailing Club.

The previous recipient of this Medal in 1981 was Peter Van Oossanen in recognition of his research into the design of yachts and who is a close colleague of Ben Lexcen and the *Australia II* team.

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Over 210 Members and guests were in attendance when the Chairman introduced Peter Van Oossanen.

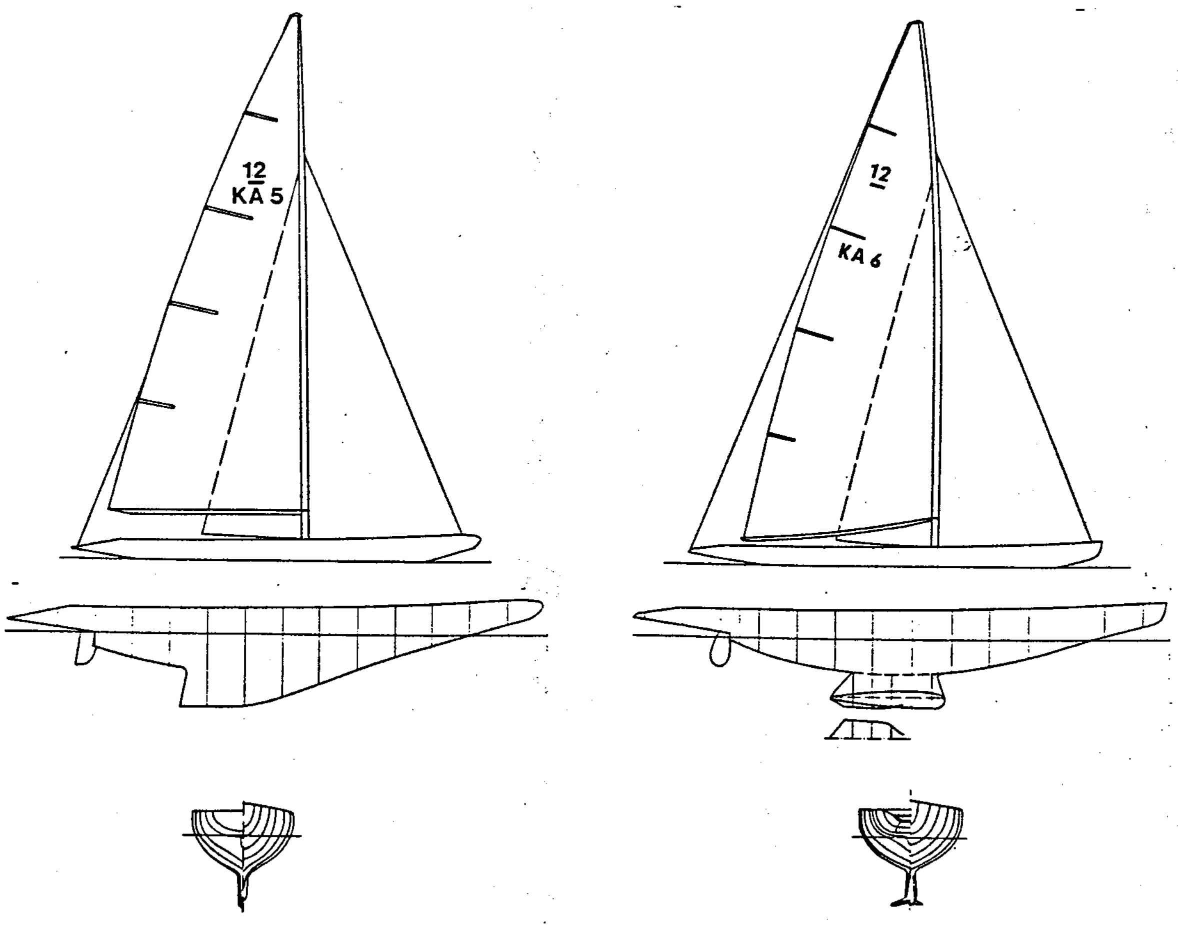
"Thank you Mr. Chairman. Ladies and gentlemen. First of all I want to say it's an honour to speak at such a large gathering here today. I have had the honour of being an author of some 3 papers in Australia for either the Royal Institution of Naval Architects or Institute of Marine Engineers and this is by far the largest gathering I've spoken to.

Secondly, I'd like to say that it was Ben Lexcen's intention to be here and that we do this thing together. Unfortunately, as you probably all know, he had to go to London for purposes of trying to stop the American's in still trying to get back the America's Cup through some devious ways and I'll explain that a little later.

My presentation tonight is really divided into two parts, if time will permit me. First of all I would like to deal with the technical aspects of Australia II, its design, its evaluation, model testing and then, as I said, if time permits I would like to say something about some of the events that took place in Newport.

ABSTRACT

In this paper the development of the 12 Metre Class Yacht "Australia II" is described as it took place at the Netherlands Ship Model Basin in Wageningen, The Netherlands, under the direction of Ben Lexcen. An account is given of the adopted design process and the technology involved. Particular attention is given to the adopted towing tank procedures and calculation techniques for predicting performance. A description is also given of the computer monitoring system used to evaluate "Australia II's" performance while sail-tuning and racing in Australia and Newport in 1982 and 1983.



Sail plan and lines drawing of "Australia" and "Australia II" (taken from the book "Ben Lexcen - The Man, The Keel and The Cup", by Bruce Stannard, Faber and Faber, London, 1984). "Australia II" represents a radical departure from the traditional 12 Metre.

1. INTRODUCTION

On September 26, 1983, "Australia II" became the first yacht in 132 years of competition to win the "America's Cup". She had beaten the U.S. Defender "Liberty" convincingly, more convincingly than the 4-3 outcome of the 7 races would suggest. In winning the America's Cup one of the most extensive projects ever involving a sailing yacht came to a successful close.

Within weeks after the 24th Match for the America's Cup in 1980, Alan Bond once again decided to issue a challenge to the New York Yacht Club. As before he appointed Warren Jones as the Executive Director of the complete campaign, with the charge to do everything possible, within a set (large enough) budget, to win the America's Cup. This time Warren Jones decided to involve more specialists in the required work. After various discussions with all of these, a plan was drawn-up such as never before in the context of challenging for the America's Cup. With respect to the number of people involved, research and development carried out, and financial commitment, all previous records were broken. In every area, i.e. in the design of the yacht and sails, sail testing, crew selection and training, boat tuning, computer performance analysis, sail instrumentation, etc., very significant and often break-through developmental work was carried out.

John Longley, who was a crew member on "Southern Cross" in 1974 and on "Australia" in 1977 and 1980 was given the task to monitor progress in each area. Together with John Bertrand, who was appointed skipper-helmsman in 1981, he was directly in charge of crew selection and training. Tom Schnackenberg, perhaps the world's best designer of 12 Metre sails, was placed under an exclusive contract to the "America's Cup Challenge 1983 Ltd". Ben Lexcen, the gifted yacht designer and personal friend of Alan Bond, was once more given the responsible task of developing the hull design. He decided to carry out his tank testing work with the author at the Netherlands Ship Model Basin (NSMB). The Netherlands Aerospace Laboratory (NLR) carried out extensive computer calculations to analyze various design configurations. Together with Glenn Read of Data General (Australia) Pty. Ltd., the author with Bert Koops, a co-worker, successfully set-up a very ambitious computer sail-performance monitoring system. Sir James Hardy, then Australia's most experienced 12 Metre helmsman, was regularly consulted for the benefit of John Bertrand and crew. In an extensive series of so-called Intensive Training Periods (ITP's) almost a hundred candidate crew members were tried out and tested for the various positions. Later, on completion of "Challenge 12", "Australia II" and "Challenge 12" raced close to a hundred serious races over half and full-length America's Cup-type courses. Between June 1982 and September 1983, "Austalia II" logged about 20000 nautical miles, representing more than 2000 hours of crew selection and training, sail testing, boat tuning and racing. In that period more than 600 hours of good performance data was logged on magnetic tape and analyzed by computer, yielding invaluable information on speed performance and the parameters which affect it.

For the first time in history the efforts of the defending syndicates and the New York Yacht Club were inferior to those of one of the challenging syndicates and one of the challenging yacht clubs. The best prepared defence syndicate, the "Freedom-Liberty" Syndicate, did not tank test their final yacht "Liberty". About 2 weeks before the first race for the America's Cup, Dennis Conner, Liberty's skipper-helmsman, decided to install a completely new on-board instrumentation system, a very dangerous move when carried out so late. No new avenues in hull and sail design, in instrumentation or computer performance analysis techniques were explored. Yet the ability of Dennis Conner and crew, and 2 serious equipment failures on board of "Australia II", made the 7-race event in September 1983, a very close affair: much closer than many, on both sides, would rightly or wrongly have guessed before the event.

The success of "Australia II" is at least as much as 50 percent due to the design and development of canoe body and keel, on the basis that the required performance level to win the America's Cup can only be successfully achieved (and pursued by sail design and good crew work) if the performance potential is present. The side force and resistance characteristics of "Australia II", when sailing to windward at the best possible speed-made-good, are significantly better than those of other 12 Metre yachts. "Significantly" in this context infers a speed differential leading to an advantage of 1 minute or more over a windward leg of the course. Over the entire true wind speed range "Australia II", in 1983, was the fastest 12 Metre ever to compete for the America's Cup on windward points of sail. On reaching and running points of sail this was not quite the case. Her losses on the 2 reaching and 1 running leg of the course, however, were usually small in comparison to the gains realized on the 3 windward legs.

In this paper the development work that so successfully led to "Australia II's" hull form and keel is described. The work took place at the Netherlands Ship Model Basin in Wageningen, the Netherlands, under Ben Lexcen's supervision. Besides an account of the course of events that took place, a detailed description is given of the technology adopted in the design process. No details of "Australia II's" hull form or her performance levels, as obtained from model tests, numerical modelling or full-scale performance analyses, are given in this paper. This is unavoidable because of the importance of this yacht as a benchmark for those involved in the first Australian defence of the America's Cup, to be held off Fremantle, Western Australia, in 1987. The results given in this paper are for typical, more conventional, 12 Metre yachts, bearing no resemblance to "Australia II".

2. REVIEW OF DESIGN PROCESS

Ever since it became apparent to most people that "Australia II" would come close to winning the America's Cup (if not actually winning it), in July 1983, a great deal has been written about her design and about the people involved in her conception. Most of what has been published to date has been conjecture and inaccurate. No detailed account of the design process adopted in 1981 has yet been published, not even in Australia. Partly, this is due to the political turn of events caused by the accusations of the New York Yacht Club that "Australia II" was not a proper 12 Metre Class Yacht and that an Australian national had not solely designed her. Partly, also, this is due to the fact that only a handful of people have detailed knowledge about "Australia II's" conception and the work that was carried out in 1981. The whole "Australia II" campaign was run on the basis that detailed information would be shared only on the basis of the "need to know" principle. Only 4 people shared this design information, viz.: Warren Jones, John Longley, Ben Lexcen and the author.

The project, in a way, began in January 1978, when the author met with Alan Bond and Ben Lexcen to discuss the possibility of carrying out a model test program in order to evaluate some specific design features for a new 12 Metre for the America's Cup to be held in 1980. This meeting, which took place at the suggestion of the author, did not lead to such a project for the 1980 event. On January 31, 1981, however, Ben Lexcen visited the author in Wageningen, the Netherlands, to see the model test facilities of the NSMB and to request a detailed work and cost specification for consideration by Warren Jones, the executive director of "America's Cup Challenge 1983 Ltd". On March 13, 1981, a meeting took place in Sydney, Australia, at which Warren Jones, Ben Lexcen and the author were present. At that meeting details of the work to be carried out were discussed and the author was requested to immediately commence the project as had been agreed with Ben Lexcen previously.

The first part of the research and development program constituted the manufacture of the 12 Metre "Australia", in the configuration in which she had competed against the U.S. Defender "Freedom" in 1980, on a 1 to 3 scale, and to accurately evaluate her performance in NSMB's large towing basin. This work started on March 23, 1981, immediately the author returned to the Netherlands. Ben Lexcen arrived on April 28, 1981, and after satisfying himself that the model was accurately built, testing commenced.

On April 14, 1981, the author sent a telex to Ben Lexcen in Sydney, describing a proposal to use a computer program developed at NLR for evaluating the merits of radical departures from traditional designs. In the various discussions with Ben Lexcen it had become clear that the main topic for research was to be the keel configuration. The races between "Freedom" and "Australia", in 1980, had revealed that "Australia" lacked upwind ability, in particular in not pointing as high as the U.S. Defender. The author was convinced that it was necessary to have a tool at hand with which it would be possible to quickly evaluate the many different keel configurations and design features that had been discussed since the first meeting in 1978. The time involved in the manufacture of 1/3-scale models and the testing thereof would not allow the evaluation of more than about 10 configurations in about 3 months. The computer program available at NLR, based on a finite element representation of the geometric configuration and the water surface around the hull, in being able to calculate the side force and induced drag properties, afforded the possiblity of at least qualitatively comparing different keel designs. Joop Slooff of NLR, in a telephone conversation on April 13, 1981, had expressed the possibility that the computer code could be expanded to model the free surface, at least for the very high Froude number case, without actually modelling the formation of surface waves, in a few weeks. Thereby it would also be possible to obtain some rough indications as to the comparative wave resistance properties of the different configurations.

In a telephone conversation with Ben Lexcen on April 15, 1981, approval was given to the author to sub-contract NLR to expand their existing computer code to take the free-surface into account, as proposed. In addition, it was agreed that NLR should then carry out calculations to ascertain the effects of keel sweep angle and keel taper ratio, using the same keel lateral area, canoe body design, etc., as for "Australia".

In a meeting at NLR on April 16, 1981, attended by Joop Slooff, a co-worker, the author and one of his co-workers, the details of the required calculations were discussed. It was agreed to analyse the performance of the benchmark "Australia" keel, and the same keel with a taper ratio equal to 1 and 2, with the same sweep angle[1]. In addition, it was agreed to carry out calculations for the "Australia" keel with a taper ratio equal to 2 for both a sweep angle equal to zero and an extreme forward sweep angle[2]. Four of the analyzed keel configurations are shown in Fig. 1. The lateral area of all these keels was kept the same. This work constituted the first phase of the "radical approach"-part of the total project.

On his arrival at NSMB, Ben Lexcen defined two conventional keels to be built and model-tested on the "Australia" canoe body. The first of these was a keel with less sweep-back, but otherwise the same as the "Australia" keel,

1. the sweep angle is defined as the angle between the vertical and the quarter-chord line of the keel.
2. the taper ratio is defined as the ratio of the chord length at the tip of the keel divided by the chord length at the root of the keel.

while the second keel (see Fig. 2) had exactly the same lateral profile as the "Australia" keel but had an appreciably greater thickness-chord length ratio, thereby obtaining a lower centre of gravity and hence a greater stability. After the tests with the benchmark "Australia" model finished on May 5, 1981, the "Australia" canoe body was fitted with these two new keels and tested on May 11-12 and May 15-16, 1981. These tests constituted the "traditional approach", the name given to the conventional part of the project.

The results of the model tests carried out in May 1981, revealed a not insignificant gain in the maximum speed-made-good for the thicker keel, due to the increase in stability. This gain in windward performance was obtained at the expense of a very small decrease in running ability, compared to the benchmark design.

On May 19, 1981, a meeting took place to review the results of the calculations carried out by NLR. The results revealed that the keel with a taper ratio equal to 2 and zero sweep was fractionally better than the other configurations. An analysis of the relative importance of the various drag components revealed that the positioning of the centre of side force further below the water surface, through the application of inverse taper, resulted in a small reduction in the wave resistance and in the induced drag. Since the application of sweep-back is known to be beneficial because of exactly the same reason, viz.: because of the shift of the centre of side force further towards the tip of the keel, the results of the NLR calculations were considered realistic. No need was expressed at the meeting to confirm these results through model testing. Instead, Ben Lexcen requested NLR to carry out calculations to find out if the application of winglets would result in a further performance improvement.

The reasoning behind the decision, taken at the meeting at NLR on May 19, 1981, to analyze the performance of winglets added to the bottom of the inverse-tapered keel, one on each side, was straight-forward. The "upside-down" keel, as the inverse-tapered keel was called, had shown a decrease in wave resistance but still had a high induced resistance compared to a keel with a larger aspect ratio. Induced resistance is known to be very dependent on the amount of loading (lift) near the tip of the keel and manifests itself through the shedding of vorticity. A large tip vortex is associated with a high induced resistance and vice-versa. Research carried out by the U.S. National Aeronautics and Space Administration (NASA), by Whitcomb and others, see Ref. 1[3], had revealed that for high aspect ratio airplane wings, winglets as shown in Fig. 3 were found to particularly reduce induced resistance leading to an increase in the lift-drag ratio of about 10 percent. Also, Joop Slooff reported that systematic calculations carried out by NLR for smaller aspect ratio wings for the Dutch Fokker Aircraft Company, had revealed even greater reductions in the induced resistance.

3 References are listed at the end of this paper

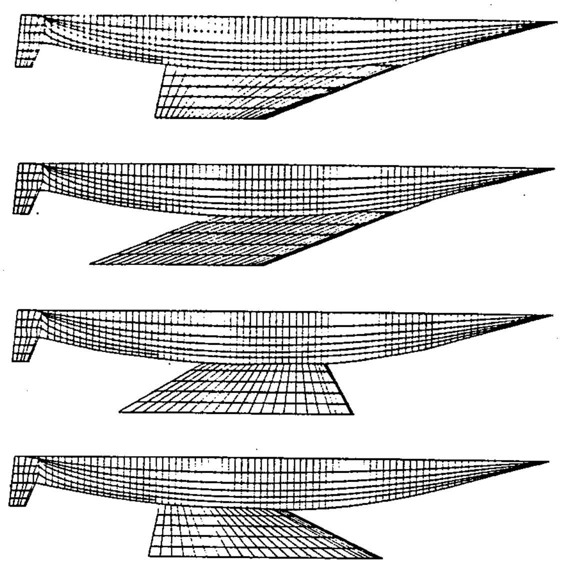


Fig. 1 - Drawing showing finite element (panel) distribution of four keel configurations analyzed by NLR.

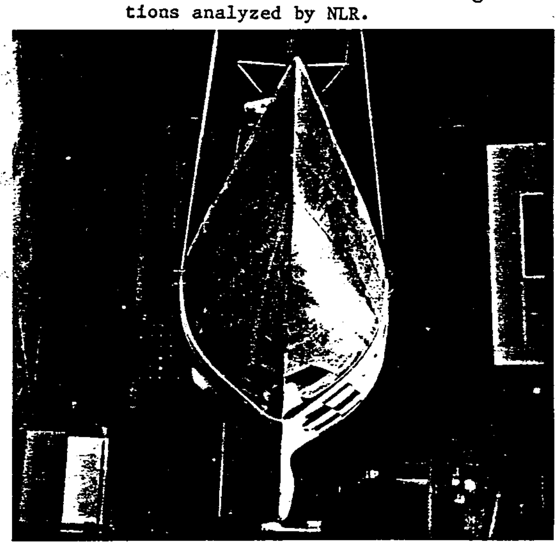


Fig. 2 - Photograph of "Australia" model with thicker keel, later adopted for "Challenge 12".

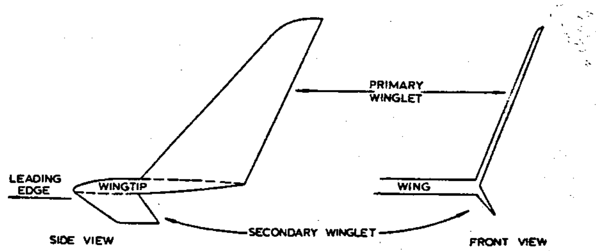


Fig. 3 - Winglet configuration developed by Whitcomb (NASA) in 1974 on which the principle of "Australia II's" winglets is based.

Warren Jones visited NSMB on May 15, 1981. In discussions with Ben Lexcen and the author it was agreed to continue the experimental part of the project and to test the best keel configurations resulting from the analyses carried out by NLR. At that time the author had already been informed by Joop Slooff that the preliminary results for the inverse-tapered keels looked promising. Directly after the NLR meeting on May 19, 1981, the author proposed to test an upside-down keel with zero sweep, with and without winglets, on the existing 1/3-scale "Australia" model. The detailed model drawings and the shape of the then crude winglet configuration were prepared by NSMB under Ben Lexcen's direction with some input from Slooff and the author. One of the parameters that remained undecided at that stage was the longitudinal orientation, or angle-of-attack of the winglets. The author proposed that the optimum setting be determined experimentally and, accordingly, a special 5-component, strain-gauge dynamoter set-up was built into one of the winglets allowing the measurement of the forces and moments acting on the winglet at various settings, from which the optimum angle-of-attack could be derived.

The tests with the upside-down keel without winglets were performed on June 9, 1981. On the following day while testing the upside down keel with winglets, Slooff reported the results of the NLR calculations for the configuration with winglets. The configuration he analyzed is shown in Fig. 4. The test results revealed a very significant decrease in induced resistance, as did also the numerical values obtained by NLR.

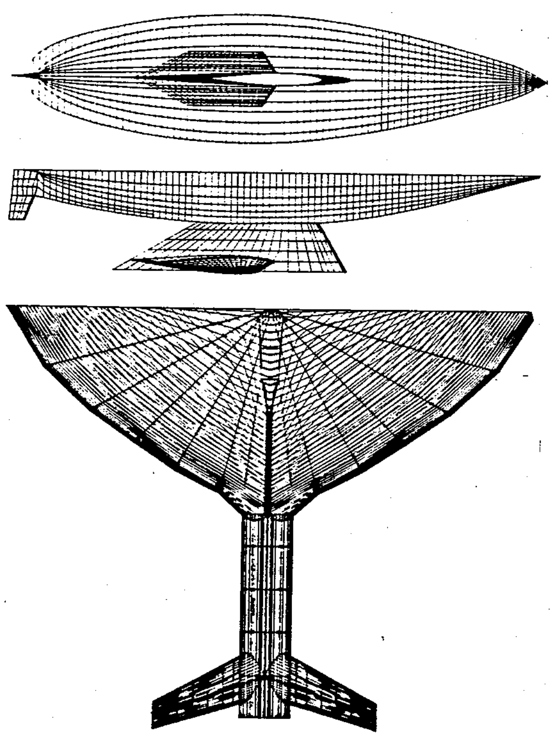


Fig. 4 – Configuration with winglets analyzed by NLR.

The gain in overall windward performance for the configuration with winglets tested on June 10, shown in Fig. 5, was only significant in the higher wind speed ranges. The analysis of the test results revealed that the excess wetted surface of the wingletted keel was the cause for not obtaining an appreciable improvement in the lower wind speed range. In this lower wind speed range the performance of the upside-down keel without winglets was better. On June 11 and 12, 1981, Ben Lexcen fine-tuned the wingletted keel configuration. He prepared a sketch (shown in Fig. 6) and a rough drawing of a configuration close to that of the final design. This design had an appreciably smaller lateral keel area and showed the cut-up of the bottom of the keel so characteristic of the final design, a design in which the winglets became an integral part of the keel – not just appendages, see Fig. 7. The detailed (model) drawings were prepared by NSMB in the following week. Ben Lexcen left for Australia on June 20, 1981. At that stage it was thought that all of the design work had been completed. In Perth, Warren Jones had become anxious about possibly not being able to keep to the time frame drawn up earlier for building the boat. It was then planned to build two identical

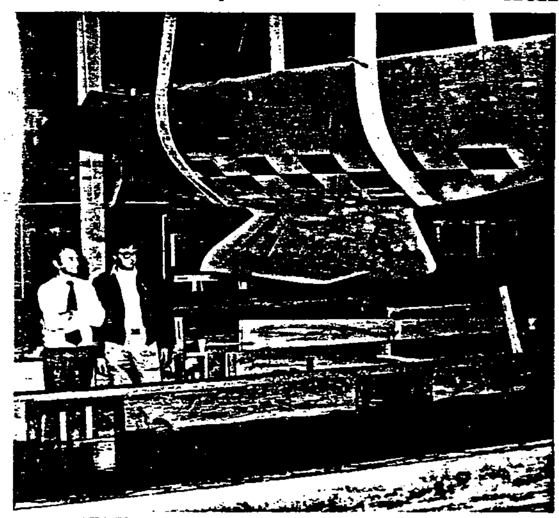


Fig. 5 – Photograph of "Australia" model fitted with the first inverse-tapered keel, tested with and without winglets.

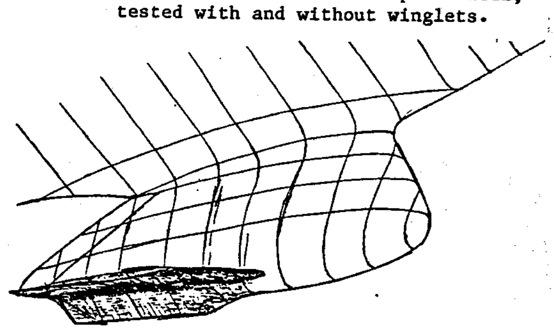


Fig. 6 – Sketch by Ben Lexcen of how he wanted the winglets to be an integral part of the keel.

boats, one in aluminium and one in fibre glass, both in Perth. Both boats would be sailed against each other in Perth in the winter of 1982 to prepare them for hard racing on Port Phillip Bay, Victoria[4], starting October 1, 1982.

The tests with configuration No. 6, with the smaller keel and near-final winglet configuration, were carried out on July 2 and 3, 1981. The results revealed that the optimum speed-made-good to windward of this configuration, compared to the benchmark "Australia" configuration, was significantly greater over the complete wind speed range. The upright resistance, however, at zero leeway, revealed that "Australia" was still faster on reaching and running points of sail, particularly in the lower wind speed ranges. In a telex to Ben Lexcen on July 6, 1981, the author suggested that a major re-design of the canoe body should be carried out in an effort to significantly reduce wetted area still further[5]. He suggested to remove the bustle, thereby achieving the required reduction in wetted surface, at the same time reducing the displacement which, for stability purposes, was no longer necessary. In this way also a higher sail area to displacement ratio would be obtained. In the telex the author pointed out that the turning ability of the yacht would improve as well. In reply Ben Lexcen proposed that NSMB prepare a drawing showing the type of modification required and that the author bring it to Australia for further discussion, to which the author agreed.

On July 10, 1981, a flow visualization test was carried out with the model as it was tested on July 2-3. An underwater video camera set-up was used to visualize the flow on windward and leeward sides of the model. This was necessary to obtain some design guidance as to how to modify the aft-body of the hull.

In meetings with Ben Lexcen in Sydney, Australia, on July 15 to 17, the whole concept of reducing the length of the design waterline to almost the minimum allowable value, by reducing the volume of the bustle, was discussed and thoroughly analyzed. Then, working through the week-end of July 18-19, Ben Lexcen prepared a final lines drawing of the aft-body, essentially removing the bustle altogether. The offsets of the changes to the canoe body and some changes to the keel and rudder were telexed back to NSMB on July 20, 1981, together with instructions to modify and test the model as quickly as possible.

While the model was being modified, Alan Bond, Warren Jones and skipper-helmsman John Bertrand, visited NSMB on July 27, 1981, to look at the model of the novel keel concept and to discuss the design configuration and its performance. The author gave a detailed presentation of the activities carried out up to then and presented a detailed analysis of the characteristics of the new design. At that meeting John Bertrand presented himself as a sceptic, expressing doubt in some of the obtained results and raising objections to the concept. Prior to the meeting Ben Lexcen had phoned the author and requested to be as convincing as possible because of on-going discussions between Alan Bond, Warren Jones and John Bertrand about whether or not to build a yacht according to this radical design. Whereas Warren Jones had expressed himself as a supporter of the winged-keel concept, correctly believing that it would take a major design-advantage to win the America's Cup in Newport against Dennis Conner, John Bertrand was obviously opposed to the concept. The outcome of these discussions was that two aluminium boats would be built, one according to the radical design and one with the conventional, thick keel and the "Australia" type canoe body. The results of a large series of races between these yachts would decide the issue as to which boat to take to Newport. As it turned out, Dick Pratt of Melbourne, Australia, heading a syndicate from Victoria, signed an agreement with Alan Bond soon thereafter to buy and campaign the more conventional boat, to be named "Challenge 12", and so both were taken to Newport in 1983.

During the meeting on July 27, 1981, it was stressed that the utmost secrecy was called for in building and campaigning "Australia II". It was estimated that other syndicates would be able to successfully copy the keel concept right up to about 6 weeks before the final races in September 1983. History would prove this supposition correct when the "Freedom-Liberty" Syndicate on July 21, 1983, tried to obtain particulars about the wingletted keel with a view to building the keel under one of their own boats.

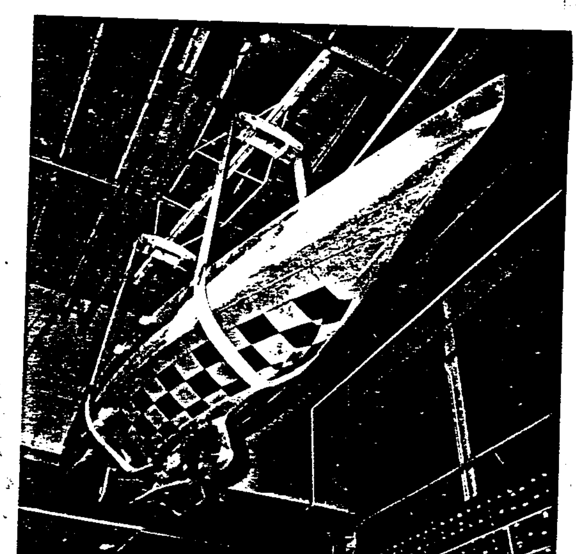


Fig. 7 – Photograph of model with second and near-final keel configuration, tested early July 1981.

4 Port Philip Bay is considered to be the location in Australia most resembling the conditions prevailing off Newport, Rhode Island.

5 The canoe body used in configuration No. 6 was still that of "Australia".

Configuration No. 7, with the radically changed canoe body and a slightly modified keel and rudder, shown in Fig. 8, was tested on August 6-7, 1981. The results of these tests were excellent. A significant performance improvement had been obtained at all points of sail in all wind conditions, a feat considered impossible 4 months before. The only area of slight concern was the reaching performance at boat speeds in excess of about 9 knots which, due to the increase in wave resistance caused by the removal of the bustle volume, thereby lowering the effective value of the prismatic coefficient, had become slightly worse[6]. At that time it was concluded that this disadvantage was not serious since it was rare, in America's Cup races, in Newport, for one yacht to pass the other on a reaching leg.

Ben Lexcen and Warren Jones were advised of the test results immediately after the results had been analysed. A report with detailed performance predictions was forwarded on August 13, 1981.

The tests carried out on August 6-7, 1981, were the last carried out in 1981 for "Australia II". Directly after these tests NSMB was requested to carry out a computer-fairing process to derive accurate offsets for lofting the hull. Hydrostatic and stability calculations were also carried out. The yacht was lofted by Steve Ward and Ben Lexcen in Perth in September 1981. A final lines drawing was prepared for both "Challenge 12" and "Australia II".

By August 1982 the author and a co-worker had implemented a suit of computer programs on a Data General NOVA 4X computer in Perth, able to analyse the logged performance of "Australia II". A telemetry system was installed on the yacht capable of relaying all of the outputs of the OCKAM instrumentation system on board of the yacht to her tender "Black Swan", where it was logged on magnetic tape. It required the best part of 6 months to learn how to sail "Australia II" and to obtain the same performance levels as found in the towing tank. On-the-wind "Australia II" would sail as fast as "Challenge 12" until it was found that she needed to be sailed much closer to the wind to obtain her best speed-made-good potential. Thereafter nearly every race between the two yachts resulted in an advantage of over 3 minutes for "Australia II", nearly all of it being gained on the windward legs of the course. Only in very light conditions were the differences smaller.

6 This advantage was only to become a handicap when racing against "Liberty". Of all "Australia II's" opponents, only "Liberty" was able to gain significantly on the 2 reaching legs of the course. While model testing at the Delft University of Technology in The Netherlands in 1981, Johan Valentijn had succeeded in adopting a higher-than-normal value of the prismatic coefficient for "Magic", which he also adopted for "Liberty".

3. DESCRIPTION OF TECHNOLOGY INVOLVED

3.1 Introduction

The technology adopted in the development of "Australia II" proved to be of the greatest importance. The towing tank proved decisive in being able to pin-point even the smallest differences between alternative configurations[7]. The use of a finite element computer program to calculate the detailed flow behaviour of different design configurations also proved to be important. Even though this type of computer program cannot yet calculate viscous flow characteristics such as viscous resistance, flow separation, etc., this computer program yielded important information as to the relative merits of alternative configurations, particularly with respect to side force, induced resistance and wave resistance.

In having sold "Australia" in 1980 to the British "Victory" Syndicate, the "Australia II" Syndicate, not having a "trial-horse", had to rely heavily on the ability of instrumentation and computer-analysis techniques to fine-tune performance. Each of the many factors influencing boat speed, viz.: sail selection, optimum trim tab angles, use of weather helm, optimum use of crew weight, detection of and compensation for wind gradient and wind sheer, etc., had to be tackled in this way.

7 In the United States considerable belief in the towing tank was lost when tests for "Mariner" revealed that the resistance decreased when removing the aft part of the bustle, leaving a flat, truncated aft-body. It is now known that these test results were due to the effect of laminar flow over the small model used. Apart from some work carried out for "Courageous" and "Enterprise" by Hydronautics on 1 to 4 scale models, very little model testing of note has been carried out in the U.S.A. since 1970.

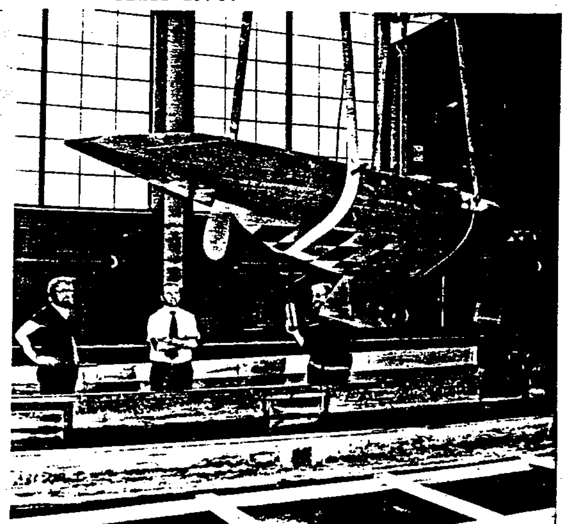


Fig. 8 – Photograph of final model tested in August 1981. Except for changes to rudder and trim tab this model is identical to "Australia II".

A description of the above-mentioned technologies, as used in the "Australia II" project, will now be given.

3.2 Use of the Towing Tank

In the towing tank upright resistance tests at zero yaw (leeway) angle and heeled tests at varying yaw angles have to be carried out. Upright resistance tests have to be performed to determine the running and broad-reaching qualities of the yacht. Side force and resistance measurements at various angles of heel and yaw are necessary to determine the windward and close-reaching qualities of the yacht and, in particular, the optimum speed-made-good to windward. The test set-up used at NSMB for the heeled tests is one developed from the set-up initially adopted by the National Research Council in Ottawa, Canada, see Ref. 2. It was chosen after careful study of all possible techniques and after consultation with different people. The test set-up developed at NSMB represents a significant step forward in the testing of yacht models. A review of the different techniques that have been adopted in the past and a detailed description of the NSMB test rig can be found in Ref. 3.

Tests at various angles of heel and yaw are carried out by towing the model at the effective centre of effort of the sails (approximately 2.87 m above the water surface for a 1/3-scale model at zero heel) by means of a tow-mast set-up. The model is restrained in surge and yaw and is free to heave, pitch, sway and heel. The test rig requires the yaw angle to be set at the beginning of each run. While the model is accelerated, side force is generated on the keel, rudder and canoe body. This leads to the occurrence of a force and a torque in the tow-mast because the model wants to heel and adopt a different yaw angle. Strain-gauge dynamometers fitted to the mast sense this and electronic signals are fed to two electric motors, one which lowers the complete test rig and one which moves the test rig longitudinally in the model. In this way, after 15 to 20 seconds, the test rig attains a position for which the axial force and torque in the tow-mast are zero in accordance with the physics of sailing, see Ref. 4. Since the lowering of the mast is accompanied by a sway and heel motion of the model, it follows that the final equilibrium position of the model will be attained when the over-turning moment due to the hydrodynamic side force is equal to the righting moment of the model. Hence it is essential for the model to possess the same vertical centre of gravity as the actual yacht. Likewise, the final longitudinal position of the tow-mast in the model is attained when the torque or moment in the tow-mast is zero, i.e. when in plan view, the tow-point is positioned along the resultant force vector acting on the underwater hull, from which the centre of lateral resistance can be approximately determined.

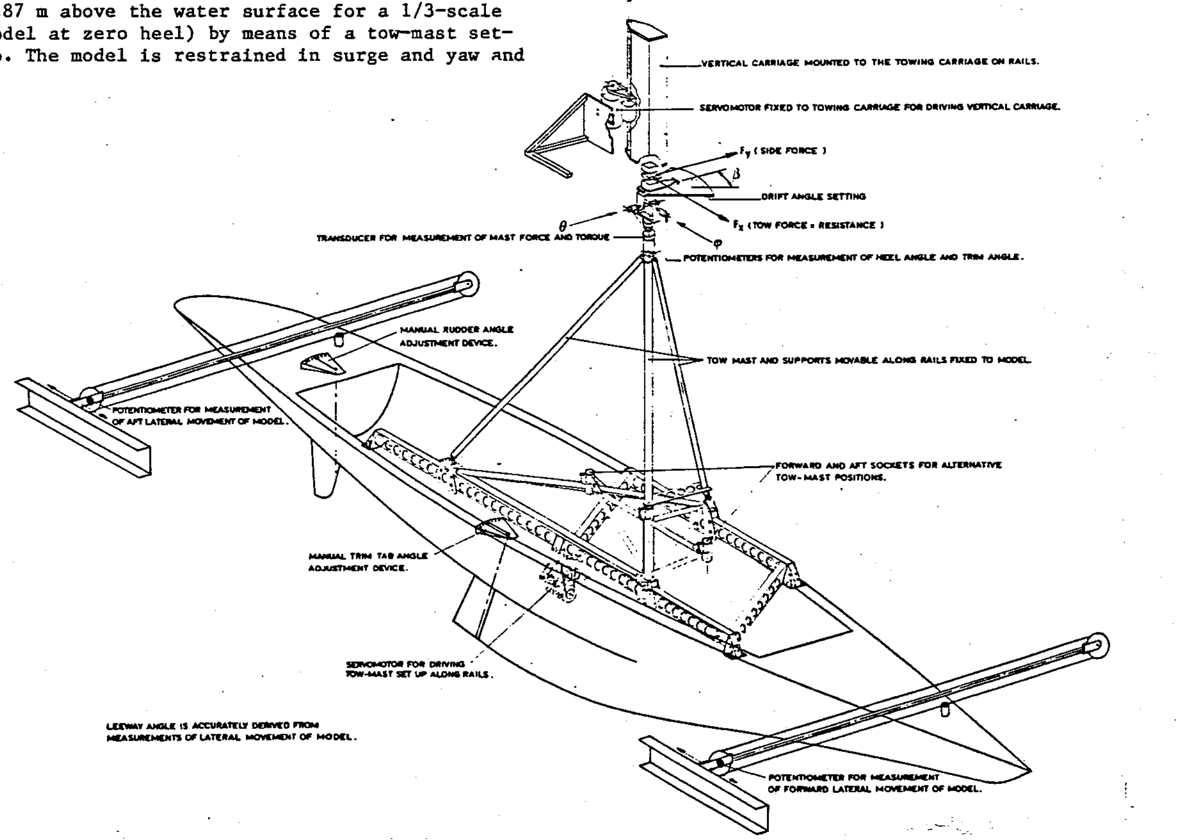


Fig. 9 - Drawing of experimental rig developed by NSMB used for carrying out tests with models of yachts at various angles of heel and yaw.

Figure 9 shows a drawing of the test rig. A photograph is given in Fig. 10. Even though the leeway angle is set prior to each run by rotating the lower portion of the test rig and model, the actual yaw angle is determined from the measurement of the lateral movement of the model at the bow and stern. The measured yaw angle differs slightly from the pre-set yaw angle due to the unavoidable (though very small) flexibility in the tow mast set-up.

Upright resistance tests are carried out in the conventional way. The models are towed at deck-height and the tow force is measured. In addition, the rise or sinkage of the model at the bow and the stern is measured. To ascertain the error by towing at deck-height and not at the effective centre of effort of the sails, measurements are carried out on some of the models with an altered ballast distribution to account for the additional moment exerted on the model by the resultant sail force, forcing the bow downward. The results of these tests reveal that even though the resulting trim down by the bow is somewhat greater when towing at the effective centre of effort of the sails, the resistance only differs by e.g. less than 2% at 8 knots boat speed. The results obtained moreover indicate that this difference is essentially the same for all models. In 1980, therefore, it was decided to tow all yacht models at deck-height using traditional towing tank procedures, with the advantage of being able to use different resistance dynamometers in different ranges of the resistance force, in addition to other advantages, leading to a slightly more accurate determination of the upright resistance of the model.

No turbulence stimulation means are adopted. For Reynolds number values in excess of 5×10^6 this is generally not necessary. On using the racing-trim waterline length to calculate the Reynolds number of the canoe body[8], it follows that as long as the model speed is in excess of about 1 m/sec no significant influence of laminar flow on the canoe body will be found for a 1/3-size model. For the keel and rudder this is not the case since the average length of the keel on a 1 to 3 scale typically varies between 1.0 and 1.5 m , for which a speed in excess of about 3 m/sec is required to attain Reynolds numbers in excess of 5×10^6.

Typical full-scale chord lengths of the rudder are around 0.75 m, for which full-scale speeds in excess of around 7.5 m/sec are required to attain Reynolds numbers in excess of 5×10^6.

8 The flow along the canoe body usually follows the (heeled) waterlines or diagonals, in which case the use of the racing trim waterline length for the calculation of the Reynolds numbers of the flow along the canoe body is accurate enough. Only in the case the flow follows the buttock lines (often in very low L/B and high B/T forms) should a smaller length be taken.

It follows that laminar flow will also exist on the keel, winglets and rudder of the actual yacht at small leeway and rudder angles. Such effects are more prone to occur on "Australia II"-type keels with winglets, now being adopted by designers.

On using turbulence stimulation devices on keel and rudder, such as studs or trip wires, any effect of laminar flow will be lost. Also the process of determining, by measurement, the resistance of studs or trip wires is a tedious procedure which has to be repeated for every model to obtain sufficiently accurate results. Hence no turbulence stimulation devices on 1 to 3 scale models of 12 Metres are adopted at NSMB. At this scale the minimum Reynolds number for the keel at a model speed of 1.5 m/sec (about 5 knots for the actual yacht[9]) is about 2×10^6.

Any significant influence of laminar flow on resistance can be detected and corrected for by adopting the 3-dimensional resistance extrapolation technique utilizing Prohaska's method for the determination of the so-called form factor k, as described in Ref. 5. On setting out in a graph the total resistance coefficient divided by the 2-dimensional flat plate friction coefficient (C_{TM}/C_{FM}), any serious effect of laminar flow will present itself through a noticeable drop in the curve as the Froude number approaches zero. In Fig. 11, showing the results of this analysis for the upright resistance of a typical 12 Metre such an effect is clearly noticeable for F_n^4/C_{FM} values below about 0.5, corresponding to a model speed of about 1.4 m/sec.

9 Due to the set time limit within which races for the America's Cup have to be completed, it is not realistic to consider performance in detail at speeds less than about 5 knots.

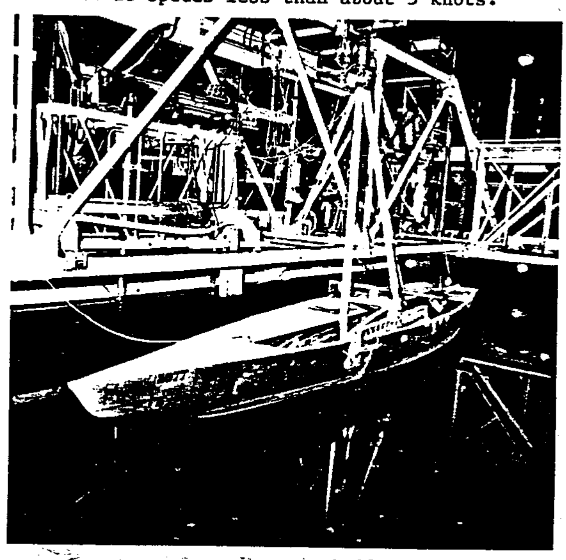


Fig. 10 – Photograph of a 12 Metre model with test rig under the carriage of NSMB's Deep Water Basin.

For the important speeds in excess of 1.5 m/sec, therefore, no significant influence of laminar flow is present. At lower speeds the significant influence of laminar flow on the results of resistance measurements can be accounted for by using the limiting form factor value for $F_n = 0$. The analysis of the resistance test results in this way is carried out with the value of the wetted surface at zero speed. The actual variation of wetted surface with forward speed is small and the influence thereof is insignificant, unless designs of widely-differing form are to be compared.

With the value of the form factor determined, the viscous resistance of the model is found from:

$$R_{VM} = (1+k)C_{FM} \cdot 1/2\rho V_M^2 S_M \qquad (1)$$

in which the flat plate friction coefficient, according to the 1957 ITTC friction line is:

$$C_{FM} = \frac{0.075}{\log(R_{nM}-2)^2} \qquad (2)$$

where $$R_{nM} = \frac{V_M L_{WL}}{\upsilon} \qquad (3)$$

in which V_M = model speed in m/sec;
L_{WL} = racing trim waterline length of model in m;
υ = kinematic viscosity for the prevailing temperature of the tank water (m^2/sec).

The wave resistance at any speed of the model follows from:

$$R_{WM} = R_{TM} - R_{VM} \qquad (4)$$

where R_{TM} = total resistance, measured for the model in N or kN;
S_M = total wetted surface of model for $V_M = 0$ in m^2.

The full-scale viscous resistance is found from:

$$R_{VS} = 1/2\rho V_S^2 [(1+k)C_{FS_C} \cdot S_C + (1+1.2(\tfrac{t}{c})_K + 70(\tfrac{t}{c})_K^4)C_{FS_K} \cdot S_K + (1+1.2(\tfrac{t}{c})_W + 70(\tfrac{t}{c})_W^4)C_{FS_W} \cdot S_W + (1+2(\tfrac{t}{c})_R + 60(\tfrac{t}{c})_R^4)C_{FS_R} \cdot (0.64)S_R] \qquad (5)$$

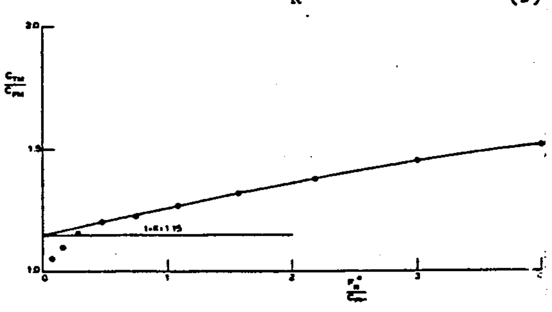


Fig. 11 - Determination of extent of laminar flow following Prohaska's procedure, see Ref. 5.

in which V_S = speed of yacht in m/sec;
k = form factor as used in equation 1;
S_C, S_K, S_W, S_R = wetted area of canoe body, keel, winglets and rudder, respectively, in m^2;
$(\frac{t}{c})_K, (\frac{t}{c})_W, (\frac{t}{c})_R$ = average thickness-chord ratio of keel, winglets and rudder, respectively;
$C_{FS_{C,K,W,R}}$ = frictional resistance coefficient of canoe body, keel, winglets and rudder, respectively

$$= \frac{0.075}{(\log R_{nC,K,W,R} - 2)^2} - \frac{1800}{R_{nC,K,W,R}} \qquad (6)$$

$$R_{nC,K,W} = \frac{V_S \cdot L_{WL} (\text{or } L_K \text{ or } L_W)}{\upsilon} \qquad (7)$$

and $$R_{nR} = \frac{0.8V_S \cdot L_R}{\upsilon} \qquad (8)$$

In equation 5, the assumption is made that the form factor of the canoe body for the full-scale Reynolds number is equal to the form factor of the complete model at the model Reynolds number. This is obviously an approximation only, but one which does not lead to significant errors. In fact this procedure of calculating the frictional resistance of canoe body, keel, winglets and the rudder separately, made possible by assuming a realistic value for the form factor of the canoe body, leads to a more accurate determination of the full-scale resistance since it is hereby possible to include effects of laminar flow on keel, winglets and rudder through the use of equations 6, 7 and 8.

The full-scale wave resistance is found from:

$$R_{WS} = (\lambda)^3 R_{WM} \cdot \frac{\rho_{salt}}{\rho_{fresh}} \qquad (9)$$

where λ = the scale factor.

This procedure is used to find the full-scale resistance at zero heel and zero leeway, viz:

$$R_{TS} = R_{VS} + R_{WS} \qquad (10)$$

Results for a typical 12 Metre are given in Table 1 and in Fig. 12.

The performance comparison of different designs on the basis of upright resistance tests alone is relatively less significant since 12 Metre yachts are faster downwind when sailing at between 140 and 160 degrees to the true wind. At these points of sail, a yacht has some heel and leeway. Nevertheless, it is of some interest to compare the performance of the different model configurations on a square run.

The heeled tests are carried out at "standard" speeds of 1.5, 1.75, 2.0, 2.25, 2.375, 2.50, 2.625 and 2.75 m/sec, corresponding to full-scale boat speeds of 5.05, 5.89, 6.73, 7.58, 8.00, 8.42, 8.84 and 9.26 knots respectively. At each speed between 5 to 8 test runs are carried out, each run at a different leeway angle, between 1 and 8 degrees. The measurements include model speed, total side force, total resistance, heel angle, trim angle, leeway angle, final position of the tow mast and the final values of the axial force and moment in the tow mast. The main purpose of these tests is to determine the resistance increase associated with the development of side force. The main component of this resistance increase is induced drag. Induced drag is considered to vary linearly with the square of the side force, see Ref. 6. At large heel and yaw angles (heel angles greater than 20° and yaw angles greater than 5°), however, the resistance increases at a greater rate, particularly at higher Froude numbers. This additional resistance is treated as so-called residual resistance and scaled-up by multiplying by the scale factor-cubed, as if it is dependent on Froude number only. It is probable that a small part of this secondary resistance component is viscous in nature, however, but without experimentally determining the form factor values valid for various combinations of heel and yaw, it is not possible to exactly determine the scaling relations for this resistance component. In Fig. 13 a typical resistance-side force (squared) relation is given. The drawn curves through the data points have the equation:

$$R_{TM} = C_1 + C_2 \frac{L_{TM}^2}{\cos^{C_3}\theta} \qquad (11)$$

in wich R_{TM} = total resistance of the model in N;

L_{TM} = total side force of the model in N;

Θ = heel angle;

C_1 = the appropriate value of the upright resistance at zero side force;

C_2, C_3 = constants.

The values of C_1, C_2 and C_3 are determined by a least-squares technique. The values for the results shown in Fig. 13 are given in Table 2. The induced resistance for the model can be determined from equation 11 by setting the heel angle to zero and subtracting the C_1 coefficient, viz:

$$R_{IM} = C_2 L_{TM}^2 \qquad (12)$$

Figure 14 shows a typical result for the dependence of side force on heel angle. The slope of these curves is dependent on stability. It should be noticed that the curves for the various speeds shown do not constitute one single curve. Generally the slope of the side force-heel angle curves varies with speed. This is due to the fact that the waterline length increases with speed and the effective breadth of the heeled waterline generally decreases with speed due to the wave-trough amidships. The curves in Fig. 14 are computer-faired according to the relation:

$$L_{TM} = C_4 \sin^{C_5}\theta \qquad (13)$$

The values found for C_4 and C_5, using a least-squares technique, are given in Table 3.

From equation 11 and 13 it follows that the total model resistance can be written as:

$$R_{TM} = C_1 + C_2 \cdot C_4^2 \frac{\sin^{2C_5}\theta}{\cos^{C_3}\theta} \qquad (14)$$

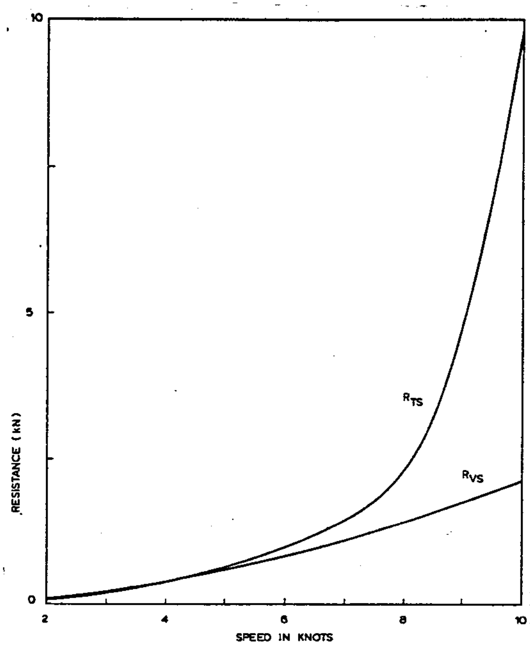


Fig. 12 - Extrapolated results of upright resistance tests for a typical 12 Metre.

V_M in m/sec.	R_{TM} in N	F_n $\frac{V_M}{\sqrt{gL_{WL}}}$	$R_n \times 10^{-6}$ $\frac{V_M \cdot L_{WL}}{\nu}$	$C_{FM} \times 10^3$	$C_{TM} \times 10^3$ $\frac{R_{TM}}{\frac{1}{2}\rho V_M^2 S}$	$\frac{C_{TM}}{C_{FM}}$	$\frac{F_n^4}{C_{FM}}$
0.291	0.71	0.0428	1.3058	4.4270	2.4669	0.5572	0.0008
0.450	1.87	0.0662	2.0193	4.0460	2.7366	0.6763	0.0047
0.600	4.22	0.0883	2.6924	3.8214	3.4656	0.9069	0.0159
0.748	6.87	0.1093	3.3566	3.6614	3.6300	0.9914	0.0391
0.899	10.16	0.1323	4.0342	3.5356	3.7192	1.0519	0.0867
1.048	14.04	0.1542	4.7028	3.4355	3.7539	1.0927	0.1647
1.201	18.82	0.1767	5.3894	3.3501	3.8601	1.1522	0.2913
1.351	24.38	0.1988	6.0625	3.2789	3.9502	1.2048	0.4766
1.501	29.92	0.2209	6.7356	3.2171	3.9278	1.2209	0.7401
1.650	36.98	0.2428	7.4042	3.1630	4.0177	1.2702	1.0992
1.801	45.06	0.2650	8.0818	3.1141	4.1084	1.3193	1.5847
1.945	54.30	0.2862	8.7280	3.0722	4.2451	1.3818	2.1851
2.099	65.76	0.3089	9.4191	3.0314	4.4149	1.4563	3.0036
2.248	78.25	0.3308	10.0877	2.9955	4.5798	1.5289	3.9991
2.398	99.31	0.3529	10.7608	2.9621	5.1080	1.7244	5.2364
2.550	138.60	0.3753	11.4429	2.9310	6.3042	2.1508	6.7669
2.703	200.45	0.3978	12.1295	2.9019	8.1145	2.7963	8.6289
2.851	285.52	0.4196	12.7936	2.8756	10.3893	3.6129	10.7771
3.000	393.88	0.4415	13.4622	2.8509	12.9434	4.5402	13.3276

V_M = model speed
R_{TM} = model resistance
C_{FM} = flat plate friction coefficient according to ITTC 1957

L_{WL} = 4.707 m
g = 9.81 m/sec.^{2}
ν = 1.049x10^{-6}m^2/sec. (for 18.3° C)
S = 6.762 m^2
ρ = 1000 kg/m^3

Table 1 - Results of upright resistance measurements and calculation of C_{TM}/C_{FM} and F_n^4/C_{FM} for a typical 12 Metre model.

Table 2 - Values of C_1, C_2 and C_3 (see equation 11) for a typical 12 Metre model.

Model speed in m/sec	C_1	C_2	C_3
1.750	47.29	0.0002666	0.8762
2.000	64.45	0.0002091	1.0048
2.250	84.99	0.0001621	1.0442
2.500	130.75	0.0001585	0.9942
2.625	177.24	0.0001598	0.9357
2.750	240.97	0.0001755	0.8549

Table 3 - Values of C_4 and C_5 (see equation 13) for a typical 12 Metre model.

Model speed in m/sec	C_4	C_5
1.750	1155.5	0.9199
2.000	1054.5	0.8743
2.250	1039.5	0.8469
2.500	1030.0	0.8376
2.625	1036.9	0.8398
2.750	1015.1	0.8466

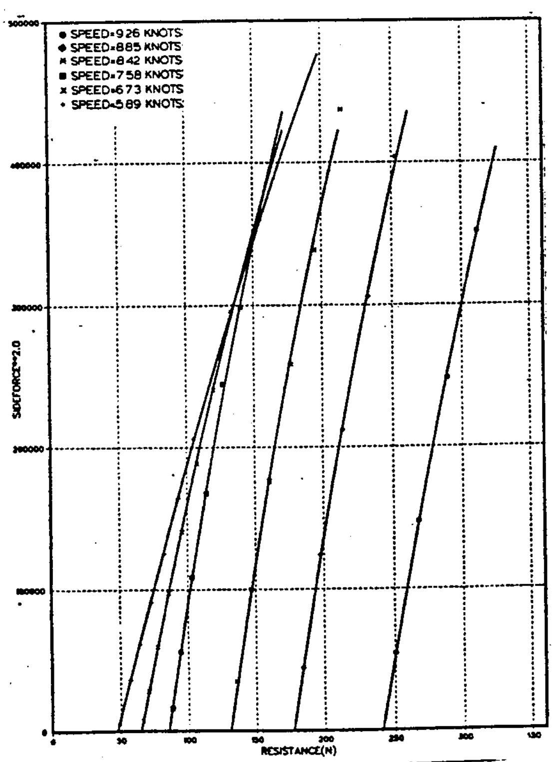


Fig. 13 - Variation of side force-squared with resistance for a typical 12 Metre model.

Typical results are shown in Fig. 15. Study of such results reveals that differences exist between the resistance as found from the upright resistance test and the resistance values valid for zero heel. These differences should be considered as real and significant rather than due to experimental errors. The values for C_1, valid for zero heel and zero leeway, are those extrapolated from data points for leeway angles between 1 and 8 degrees. The boundary layer flow and wave-making characteristics of 12 Metres under heel and leeway are different to those at zero heel and leeway. On extrapolating the resistance values, as found from the side force tests, to the limiting values for zero heel and leeway, a resistance value is found which is usually between 5 and 15 percent higher in comparison to the respective values derived from the upright resistance test at zero yaw angle, depending on the type of bustle shape employed and on the degree the flow on the leeward side of the model can cross-over to the windward side, at small yaw angles. Further research is required in this area to fully understand the reasons for this phenomenon. It is probable that during upright resistance tests, at exactly zero leeway angle, the boundary layer on hull, rudder and keel is subject to more laminar flow and less separation, resulting in a small, local leeway region in which the resistance is less. This phenomenon could be subject to some scale effect. For this reason the resistance values found from the side force tests rather than from the upright, zero leeway tests are used in predicting performance at all points of sail, particularly since a yacht usually sails at some leeway angle, even downwind.

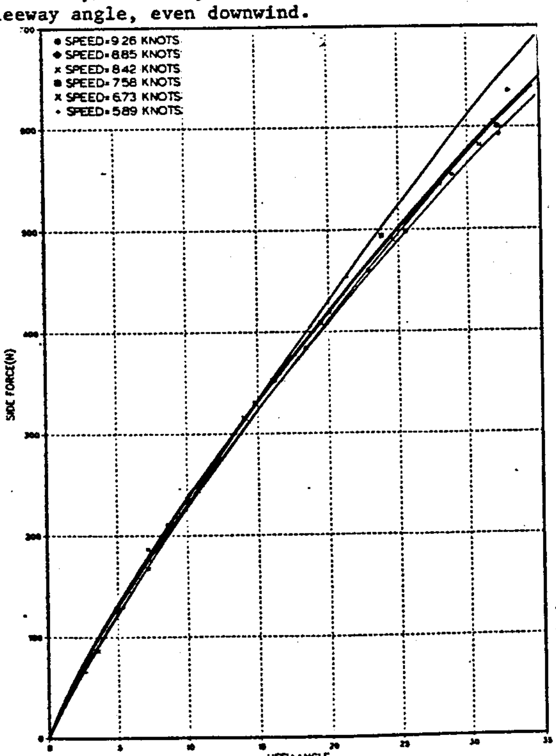


Fig. 14 - Variation of side force with heel angle for a typical 12 Metre model.

A mathematical relation between the total model resistance and the leeway angle is obtained by a least-squares technique using the following mathematical relation:

$$R_{TM} = C_1 + C_6(1-\cos\beta)^{C_7} \qquad (15)$$

Typical values for C_6 and C_7 are given in Table 4. Figure 16 shows the corresponding curves and the measured data.

Equations 11, 13 and 15 provide the basis for calculating the full-scale performance at the various points of sail. For every speed and for 10 Newton intervals in model side force, starting with zero side force, consistent sets of values are calculated for θ (from equation 13), R_{TM} (from equation 11) and β (from equation 15).

The side force is scaled-up by the relation:

$$L_{TS} = \lambda^3 L_{TM} \cdot \frac{\rho_{salt}}{\rho_{fresh}} \qquad (16)$$

$$R_{TS} = R_{VS} + C_2 \frac{L_{TS}^2}{\cos^{C_3}\Theta} \cdot \frac{1}{\lambda} \qquad (17)$$

Where R_{VS} follows from equation 5. The hydrodynamic or hull drag angle is then calculated from:

$$\varepsilon_H = \tan^{-1}(R_{TS}/L_{TS}) \qquad (18)$$

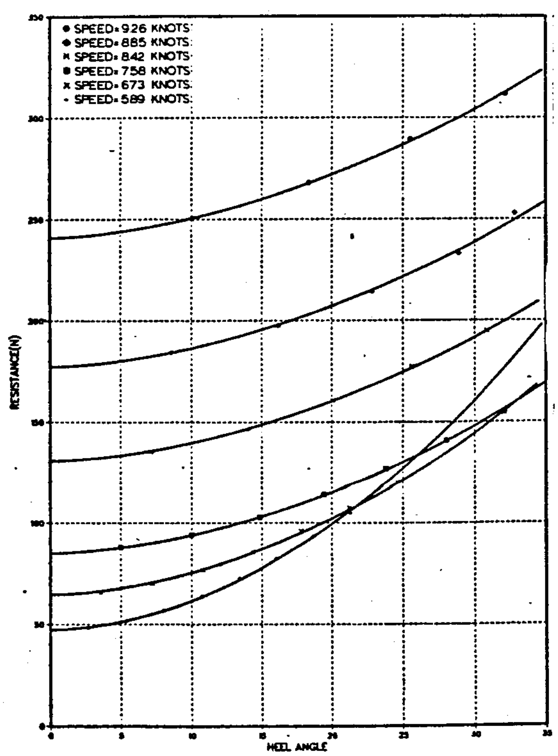


Fig. 15 - Variation of resistance with heel angle for a typical 12 Metre model.

Table 4 - Values of C_6 and C_7 (see equation 15) for a typical 12 Metre model.

Model speed in m/sec	C_6	C_7
1.750	3803.5	0.9016
2.000	3510.6	0.8466
2.250	3456.5	0.7940
2.500	4044.1	0.7440
2.625	4214.3	0.7199
2.750	4711.2	0.6964

From Fig. 17 it follows that the apparent wind angle can be expressed as:

$$\beta_{AW} = \varepsilon_H + \varepsilon_s - \beta \qquad (19)$$

where the sail drag angle is defined as:

$$\varepsilon_s = \tan^{-1}(D_s/L_s) \qquad (20)$$

and β = leeway angle.

The values of the sail drag and lift forces, D_s and L_s, are themselves functions of the apparent wind angle. To determine β_{AW}, D_s and L_s it is necessary to carry out an iteration process, starting with an estimated first value for ε_s.

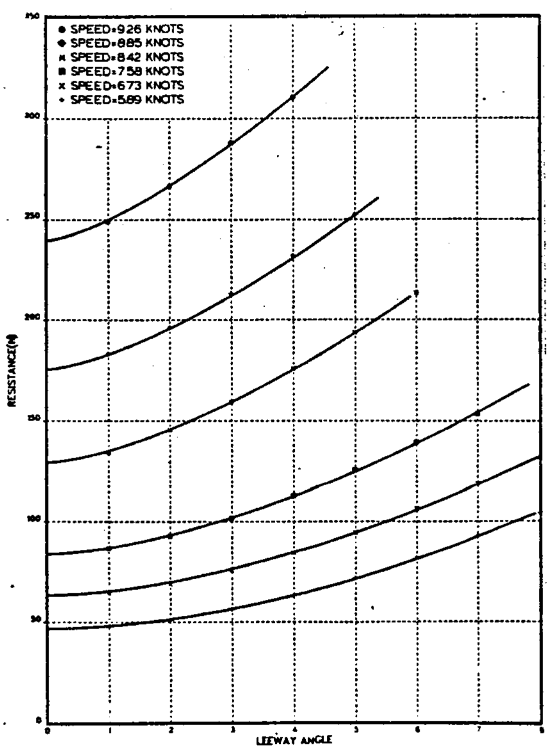


Fig. 16 - Variation of resistance with leeway angle.

Starting with a nominal value of 9 degrees for ε_s, a first value of β_{AW} is determined from equation 19, viz: $\beta_{AW} = \varepsilon_H - 9^o - \beta$. The lift and drag coefficients for each sail are then calculated. If $\beta_{AW} < 80$ degrees, sail coefficients for sailing to windward are used. If $\beta_{AW} > 80$ degrees, sail coefficients for sailing downwind are used. The adopted sail coefficients are as follows:

- for sailing to windward with mainsail and genoa:

$$C_{Ls} = (1.04+0.006\beta_{AW}+0.0000125\beta^2_{AW})\cdot\left(\frac{GEA}{GEA+MSA}\right) +(0.04113\beta_{AW}-0.0003267\beta^2_{AW})\cdot\left(\frac{MSA}{GEA+MSA}\right)$$

$$C_{Ds} = 0.044+\frac{0.089C^2_{Ls}}{1-\theta/5000} \qquad (21)$$

- for sailing downwind with mainsail and spinnaker:

$$C_{Ds} = 1.2\left(\frac{MSA}{MSA+SPA}\right)-(0.3-0.0231\beta_{AW} +0.00008\beta^2_{AW})\left(\frac{SPA}{SPA+MSA}\right)$$

$$\text{and} \quad C_{Ls} = \frac{C_{Ds}}{\tan(23.4+0.37\beta_{AW})} \qquad (22)$$

In equations 21 and 22, β_{AW} is in degrees and
GEA = area of genoa in m^2;
MSA = area of mainsail in m^2;
SPA = area of spinnaker in m^2.

With these values for C_{Ls} and C_{Ds}, the sail drag angle is calculated according to $\varepsilon_s = \tan^{-1}(C_{Ds}/C_{Ls})$ and a new value for β_{AW} is calculated from equation 19 and the process is repeated until convergence is reached.

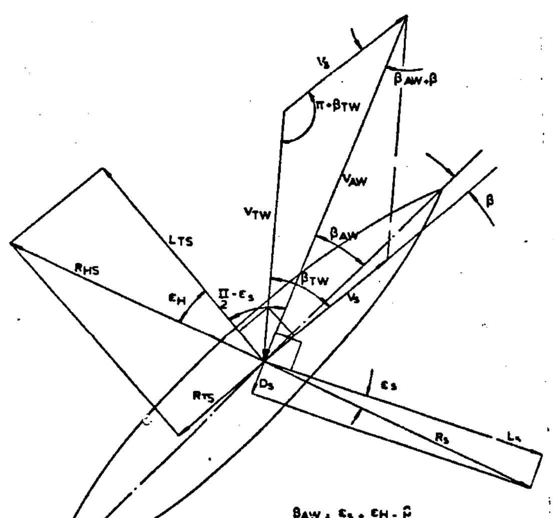


Fig. 17 - Definition of forces, velocities and angles used for yacht without heel, when aerodynamic and hydrodynamic forces are in equilibrium.

With the resultant values for β_{AW}, ε_s, ε_H, C_{Ds} and C_{Ls} the resultant sail force coefficient is calculated from:

$$C_{Rs} = \sqrt{[C^2_{Ls}+C^2_{Ds}]} \qquad (23)$$

The resultant hydrodynamic force on the hull is calculated from:

$$R_{HS} = \sqrt{[L^2_{TS} +R^2_{TS}]} \qquad (24)$$

Since the resultant sail force equals the resultant hydrodynamic hull force (for equilibrium), it follows that:

$$R_{HS} = 1/2\rho_A\cdot V^2_{AW}\cdot C_{Rs}\cdot S_s\cos\theta \qquad (25)$$

where ρ_A = mass density of air (1.226 kg/m^3);
V_{AW} = apparent wind speed at the effective centre of effort in m/sec;
S_s = total sail area in m^2.

The apparent wind speed is then determined from:

$$V_{AW} = \sqrt{\left[\frac{R_{HS}}{1/2\rho_A C_{Rs}\cdot S_s\cos\theta}\right]} \qquad (26)$$

The true wind speed, at the centre of effort, then follows from:

$$V_{TW} = \sqrt{[V^2_S+V^2_{AW}-2V_SV_{AW}\cos(\beta_{AW}+\beta)]} \qquad (27)$$

The masthead true-wind speed is calculated from $V_{TW_m} = 1.135V_{TW}$, valid for the sail plan of 12 Metre yachts[10].

The apparent wind speed at the masthead follows from:

$$V_{AW_m} = \sqrt{[V_{TW_m}^2+ V_S^2 - 2V_{TW_m}\cdot V_S\cos(\pi-\beta_{TW})]} \qquad (28)$$

The true wind angle at the masthead does not differ to that at the centre of effort, hence:

$$\beta_{TW} = \sin^{-1}\left(\frac{V_{AW}\sin(\beta_{AW}+\beta)}{V_{TW}}\right) =\sin^{-1}\left(\frac{V_{AW_m}\sin(\beta_{AW_m}+\beta)}{V_{TW_m}}\right) \qquad (29)$$

The apparent wind angle at the masthead is:

$$\beta_{AW_m} = \sin^{-1}\left(\frac{V_{TW_m}\sin(\pi-\beta_{TW})}{V_{AW_m}}\right)-\beta \qquad (30)$$

The speed-made-good to windward follows from

$$V_{mg} = V_S\cos\beta_{TW} \qquad (31)$$

10 The coefficient 1.135 accounts for the difference between the wind speed at the centre of effort and the masthead. All wind measurements on the yacht are taken at the masthead so that, for correlation purposes, predictions need to be made for masthead wind speeds and angles.

This calculation process is carried out for all data points. For each speed a curve of V_{mg} against V_{TW} is constructed. The tangent curve to these individual curves represents the optimum speed-made-good for the yacht, as shown in Fig. 18.

With each of the models additional side force experiments are carried out to determine the influence of (weather) helm and trim tab angles (which augment side force) on windward performance. Generally, 12 Metres adopt 2 to 5 degrees of weather helm and 2 to 4 degrees of trim tab, depending on sail trim, wind speed, and size of rudder and trim tab. At model speeds of 2.0, 2.25 and 2.375 m/sec, a series of test runs are carried out for weather helm angles of 0, 3 and 6 degrees and trim tab angles of 0, 3 and 6 degrees, yielding 9 helm-trim tab combinations altogether. The resulting influence on speed-made-good is determined for each helm - trim tab setting combination, allowing the optimum helm - trim tab setting to be determined for boat speeds between 6.7 and 8.4 knots, corresponding to a true wind speed range of 8 to over 20 knots.

Photographs of both windward and leeward sides of the model are taken during each test run for the purpose of documenting differences in wave patterns between the various designs. Differences in wave patterns can be correlated with differences in hull form. Together with the results of resistance measurements, wave pattern information can be used to arrive at hull forms with good resistance properties.

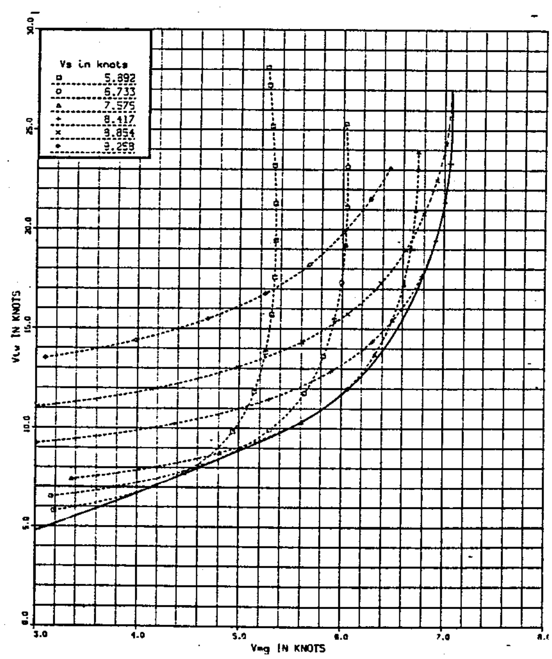


Fig. 18 - Predicted speed-made-good to windward versus true wind speed at the masthead for a typical 12 Metre model.

During heeled tests observation of the flow along the windward side of the model is particularly important. The wave pattern along the aft-body is strongly influenced by flow separation and the local curve of sectional areas. Important design guidance can be obtained by drawing the curve of sectional areas corresponding to the heeled waterline for the heel-leeway combination at the optimum speed-made-good point of sail, for each test speed. The photographs, shown in Fig. 19 show the wave profile on the windward side of the "Australia" and the "Australia II" models at the optimum speed-made-good point of sail for a test speed of 2.5 m/sec. To facilitate the tracing of wave profiles from the photographs, the models are painted in black and yellow blocks.

3.3. Use of computer programs

Extensive use was made of both a so-called velocity prediction program (VPP) and a so-called panel program for the calculation of the three-dimensional, potential flow, including the effect of lift. The VPP used is described in Ref. 6 and 7 while the panel program used is described in Ref. 8.

In a velocity prediction program resistance and side force can be calculated for any combination of boat speed, heel angle, leeway angle, trim tab angle and rudder angle, for any canoe body, keel and rudder configuration. Also, the forces on the sails can be calculated for any range of true wind speed and direction relative to the yacht's heading. Comparison of the transverse sail force with the calculated side force of canoe body, keel and rudder yields an equation from which the leeway angle can be deduced, while the comparison of the overturning moment due to the transverse sail force with the yacht's stability characteristics yields an equation from which the heel angle can be deduced. The whole calculation scheme is shown in Fig. 20.

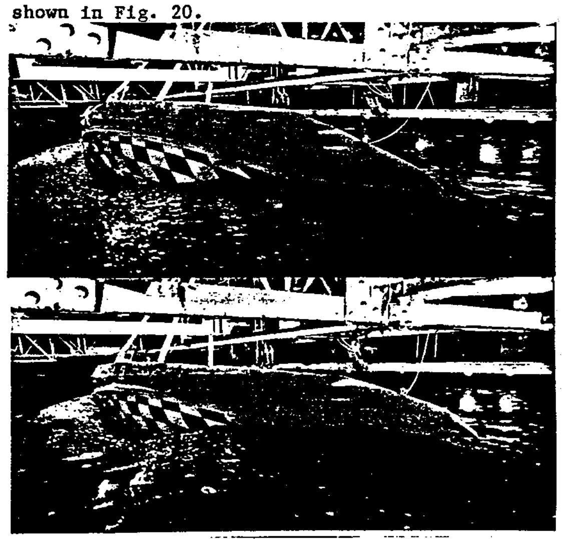


Fig. 19 - Wave profiles of the "Australia" (top) and the "Australia II" (bottom) models at the optimum speed-made-good point of sail for a boat speed of 8.42 knots.

In the course of the project many design decisions were based on the outcome of calculations with the VPP developed at NSMB by the author. Particularly in the last stage, when finalizing the design of the aft-body, the consequences of reducing the waterline length, the consequences of a larger sail area, reduced stability, etc, were all explored by the VPP before finalizing the lines of the final model to be tested.

In the NLR panel program, the flow about the hull is simulated by means of so-called source-sink and vortex distributions. The surface of the hull, keel and rudder and of a specific area of the free surface around the yacht is divided into small quadrilateral panels. For some of the calculations described in Section 2, as many as about 2000 panels were used. Each panel is given a pre-determined source strength. On those parts of the yacht developing lift a system of bound and free vortices is superimposed. The free vortices are shed at the trailing edges of the keel, the aft-body of the hull and the rudder along pre-determined paths. The bound vortices are positioned on the centre-plane of the keel, aft-body and rudder. The non-dimensional distribution of vortex strength along a vortex line is also pre-determined, leaving only the total circulation as an unknown for any longitudinal strip of panels.

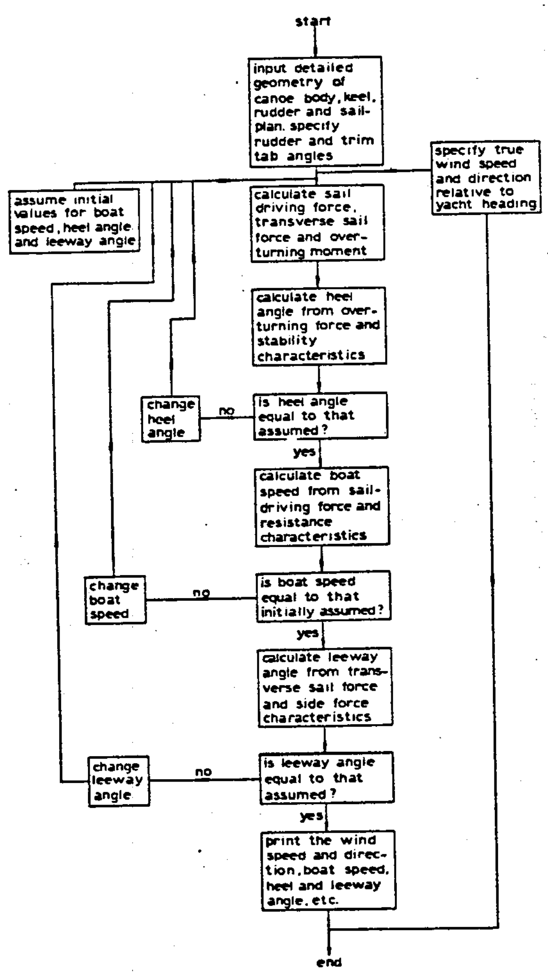


Fig. 20 - Calculation scheme adopted in most velocity prediction programs.

In 1981, when NLR was requested to carry out calculations with their panel program, no time was available to expand the computer code to properly account for the free surface, at which the pressure must be constant. Only a simplified representation of the free surface was included, obtained by prescribing that in the horizontal plane of the free surface (the plane y=0) the velocity of the flow field around the hull is zero in the direction of motion and not at right angles to the direction of motion such as is usually done when treating the plane y=0 as a plane of symmetry, for aircraft, or for submarines deeply submersed. The plane y=0 was nevertheless treated as a plane of symmetry in the sense that the sign of the source and vortex distributions was changed across y=0. This relatively simple approximation is really only valid when the Froude number F_n approaches infinity.

The resulting values for the vertical velocity in the simulated free surface was squared and integrated over the flow field considered, to obtain some idea of the relative disturbance of the free surface pertaining to different design configurations, thinking that

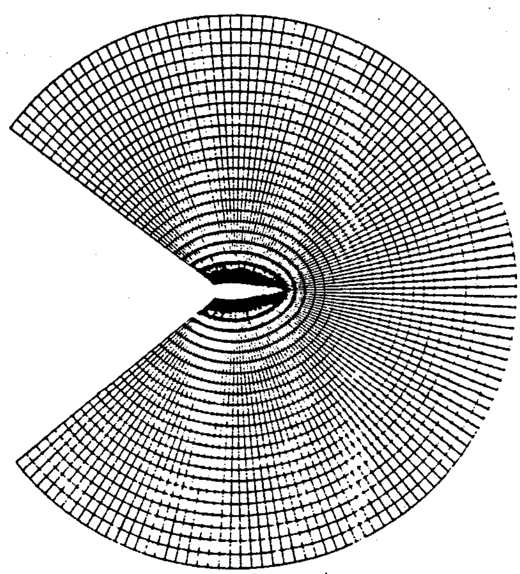


Fig. 21. Area of integration used by NLR to obtain relative results for the wave resistance using the three-dimensional potential flow program.

this disturbance level would be proportional to the wave drag. Numerical difficulties with respect to the unrealistic contribution of the free vortices to this value of $\int v^2 dS$, were avoided by omitting from the area of integration a circle segment of about 65°, extending from the stern of the yacht, see Fig. 21. In a real fluid the free vortices roll-up and dissipate. This is not modelled in the computer program. The numerical determination of surface waves was not attempted[11].

3.4. Full-scale performance evaluation

In 1982 the author and a co-worker implemented a suit of programs on a Data General Nova 4X computer in Australia, for the purpose of analyzing the performance of "Australia II". To this end each of the outputs of the OCKAM instrumentation system on "Australia II" was logged on magnetic tape on board "Australia II's" tender "Black Swan". A telemetry link between the yacht and "Black Swan" was set-up for this purpose which, besides allowing the registration of all measured and calculated entities on the yacht, also allowed the display of these entities on board "Black Swan" for those on board to analyse and follow while sail-tuning, crew training or racing. Each day, after returning to the dock, the information on tape was analyzed on the DG NOVA 4X. After screening the data, the best performance attained on that day was detected and stored in a data base, together with important information relative to the sails used, wind and sea conditions, particulars about the crew, etc. For sail selection purposes a program was developed to allow the retrieval of all data in the data base for each sail combination, for the same wind and sea conditions, etc. A plot was then drawn showing all the attained speed-made-good values as a function of true wind speed for the sails concerned. Similar curves could be drawn to analyse the performance of different helmsmen, influence of different trim tab angles, sail trim, amount of weather helm, etc.

For each tape a print-out was made of the most important performance variables such as boat-speed, wind speed and wind angles (true and apparent), heel and leeway angles, rudder and trim tab angles, speed-made-good, etc. One line of data on this print-out represented the average performance during a selected time interval. Usually a 20 second interval was used for this purpose. After each day of sailing this print-out of the day's performance would be scanned to detect differences in performance on different tacks, such as is often associated with special wind and wave conditions, or incorrect calibration of the on-board instrumentation system, etc. Also, this print-out displayed all of the messages and commands made on the Data General Micro Nova MP100 computer on board "Black Swan" relative to sail changes, crew and weather changes and, during races, relative to the tactical situation. In this way each print-out represented a concise history of the events during that day and the performance achieved.

On a special Calcomp drum plotter it was possible to draw a graph of any of the logged variables as a function of time. Every day the true wind direction, boat speed, speed-made-good, rudder and trim tab angle, etc., would be plotted on a sensitive time scale to analyze the periodicity in changes in wind direction, to analyze tacking performance, etc. Also, a plot was prepared of the track of the yacht around the course and the track of the yacht during pre-start manoeuvres. The pre-start manoeuvres and the track of the yacht for each of the 7 races against "Liberty" are shown in Figs. 22 through 29.

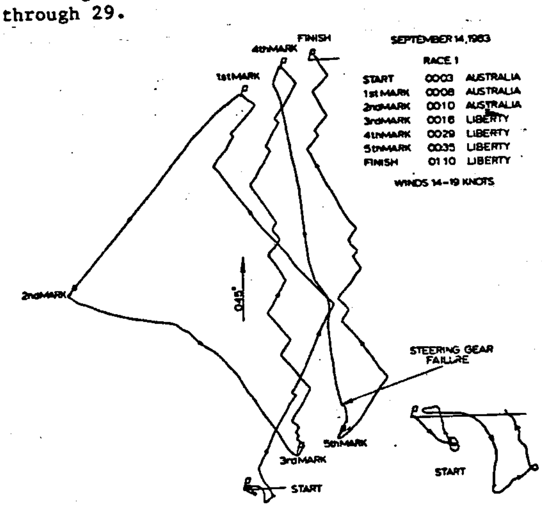


Fig. 22. Computer plot of "Australia II's" track around the course in the first race against "Liberty". The given wind speed range is that recorded at the masthead.

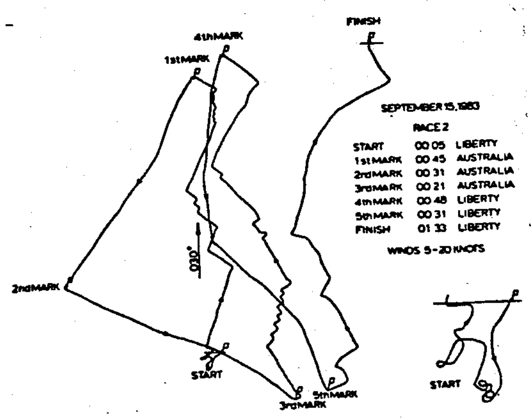


Fig. 23. Computer plot of "Australia II's" track around the course in the second race against "Liberty". Due to current the "position" of the various marks is not the same.

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11 In 1982-1983, NLR was sponsored to expand their panel program to fully account for the free surface. The resulting program, called HYDROPANEL, has recently been used by NSMB for different 12 Metre projects.

Special computer programs were prepared to calculate and plot a complete polar performance diagram for the yacht on the basis of a minimum of about 10 to 20 measured data points representing the performance attained. These data points were selected automatically each day from the logged data by prescribing threshold values for steadiness of the data and performance level. Each data point was stored in a separate "polar" data base, together with the values of the independent variables such as the sails used, crew composition, wind and wave description, etc.

Special computer codes were prepared and installed on an EPSON HX20 computer tied into the OCKAM CPU on board of the yacht, such as a program to detect wind gradient and wind shear and how to correct for them in providing

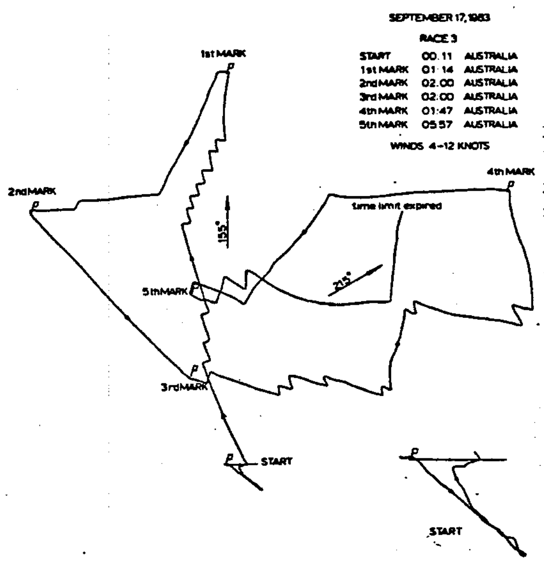

Fig. 24. Computer plot of "Australia II's" track around the course in the third race against "Liberty".

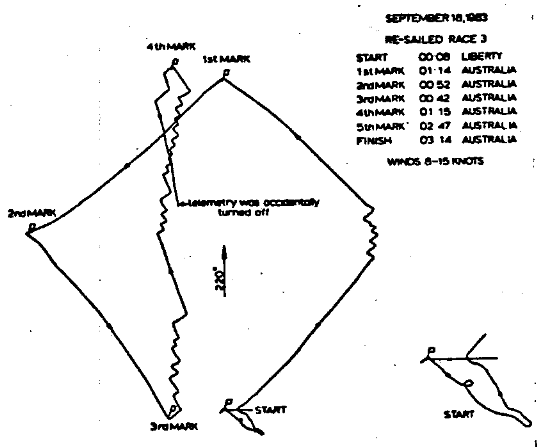

Fig. 25. Computer plot of "Australia II's" track around the course in the re-sailed third race against "Liberty".

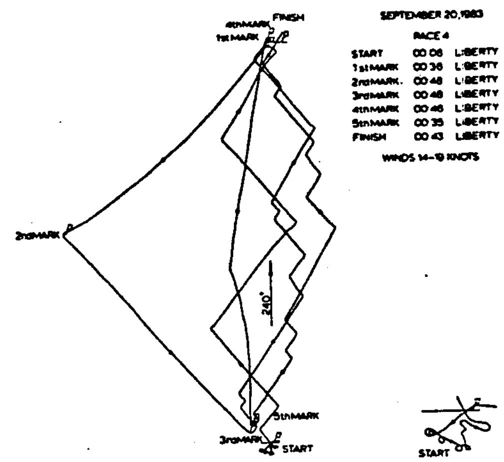

Fig. 26. Computer plot of "Australia II's" track around the course in the fourth race against "Liberty".

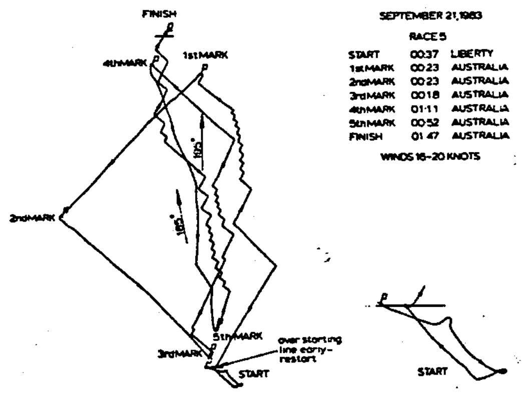

Fig. 27. Computer plot of "Australia II's" track around the course in the fifth race against "Liberty".

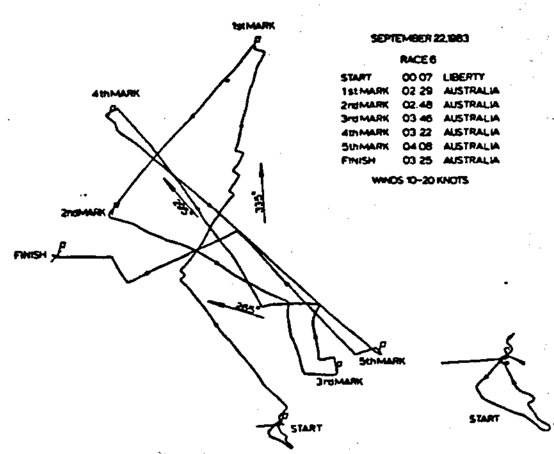

Fig. 28. Computer plot of "Australia II's" track around the course in the sixth race against "Liberty".

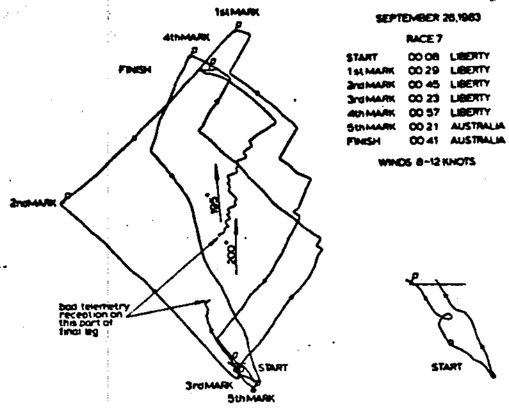

Fig. 29. Computer plot of "Australia II's" track around the course in the final, seventh race against "Liberty".

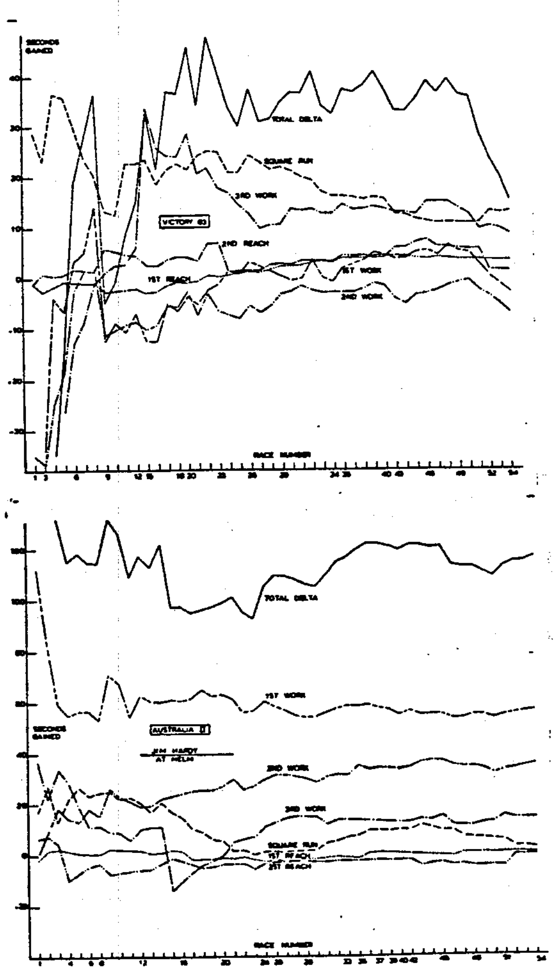

Fig. 30. Averaged number of seconds gained (or lost) on each leg of the course during the Challenge elimination races for "Victory 83" and "Australia II".

accurate target boat speeds and speed-made-good values for the helmsman. This program was particularly successful and allowed the crew to determine the effective wind on which the target boat speeds could be based, rather than on the masthead true wind speed value which, in Newport, was often not representative of the effective wind in the sails because of wind gradient and shear.

Also, during the challenger elimination races, the author developed a statistical-analysis program with which the performance of each of the challenging yachts, over each leg of the course, could be analyzed. The results were used to pin-point strengths and weaknesses of each of the opponents and, particularly, whether or not the performance of any of the yachts was improving over any particular leg of the course. An example, showing the performance of "Victory 83" and "Australia II" as calculated by this program is shown in Fig. 30.

The initial reason for developing the computerized performance analysis system for "Australia II" was the sale of "Australia" to the British "Victory" syndicate. Besides being able to accurately determine the performance of "Australia II" while sailing alone, without a "trial horse" (before "Challenge 12" was built), the system also proved invaluable in providing documentation of performance data which could be discussed with the crew. In Newport, this was done daily, after each race or early the following morning. Particularly with "Australia II's" navigator, Grant Simmer, the author was able to develop an important relationship allowing most of what was learnt through the use of the computer to be implemented on board the yacht.

4. SOME FINAL REFLECTIONS

The scientific community has a lot to offer yacht designers. It seems that in the USA in particular this has been forgotten although it is difficult to believe that this is the case with respect to the great partnership between Prof. Ken Davidson and Olin Stephens, responsible for the design and conception of many of the great America's Cup Defenders. The most accurate analysis of why the United States lost the America's Cup has perhaps been given by John Marshall, president of North Sails and mainsheet trimmer on board "Liberty".

"........Where the Americans lost out was they had to some extent lost confidence in science to do anything. Going all the way back to the terrible experience with "Mariner", there was a poisonous undercurrent against the radical, and especially against the radical as validated by science. You could try something radical, but you didn't want to say that it would work because "the tank said so". That is the ultimate stupid remark in America. Ben Lexcen said it will work because the tank said so. So "Magic" for instance, never had any particular hope other than a wishful hope of being successful.....".

The design and conception of "Australia II" has revealed that a partnership between the practical-oriented yacht designer and disciplined laboratory workers, given the required time and research funds, can result in a yacht worthy of racing for the America's Cup the ultimate trophy in sailing.

Besides giving the role of science in yacht design more credibility "Australia II's" win also illustrates that the search for the most favourable design does not necessarily lead along the beaten path. It is the author's belief that the optimum configuration in 12 Metre design is yet to be found. The number of variables to be researched is large.

The performance of the wingletted keel, when draft is restricted, is significantly superior to more traditional types of keels. Some argue that this is not the case and it will probably take the next America's Cup races in 1987 to prove to them that this type of keel is here to stay. Already a few designers and yacht owners have decided to adopt this configuration when the draft is restricted. When this is not the case the wingletted keel has very few advantages to offer over a deep-fin keel. Besides an appreciable gain in windward performance, a greater stability, etc, the wingletted keel also has some disadvantages. These are mainly associated with its greater complexity, both with respect to design and construction. For example, the orientation of the winglets on the keel is important. It is relatively easy to make a mistake and to design a configuration with inferior performance. The winglets need to be positioned in a particular way to obtain the maximum benefit.

In 1984, the author worked together with the International Technical Committee of the Offshore Racing Council in an effort to rate winglets under the International Offshore Rule. After carefully considering the results of different tests and calculations carried out up to November 1984 a proposal was put forward to rate winglets (and any protrusion on the keel) by calculating an effective rating-rule draft equal do the draft down to the location at which the upper surface of the winglet intersects the keel and adding to this value the span of one of the winglets. The measurement of this effective draft can be simply accomplished by determining the skin girth down along the keel to the tip of one of the winglets. If this or an equivalent proposal is accepted, many more designers will be tempted to experiment with winglets.

What should the role of a (foreign) towing tank be in working together with a designer in developing an America's Cup yacht? This question suddenly became important when the New York Yacht Club in 1983 attacked the "Australia II" syndicate for the role the Dutch had played in the conception of "Australia II". In contemplating this question it should be realized that the modern towing tank is not just a place where a model can be run up and down a basin full of water. On the contrary, the big towing tank organizations nowadays are complete maritime research centres, capable of carrying out sophisticated calculations and performing complicated experiments. Above all, however, the scientists - in particular the naval architects - at these institutions have been exposed to many different types of projects and thereby gained a wealth of experience. Solving problems such as how to find the required hull form for minimum resistance is their daily work. It is customary for an organization such as NSMB to make available this knowledge on specific topics when working together with designers. This, however, does not make them responsible for the final design and any suggestion in this direction is incorrect. Ben Lexcen alone was responsible for the design of "Australia II". It is likely, however, that if he had not worked at NSMB but somewhere else on the "Australia II" project, the yacht would have looked quite different and probably not have a winged keel. From the point of view of the towing tank a project with such a result is not at all exceptional but very typical. If the New York Yacht Club was not aware of these facts when they granted the "Australia II" Syndicate permission to go to NSMB for their research, then the people involved did not "do their homework" or else were also of the opinion (as so many others in the USA) that the towing tank has very little to contribute to yacht design anyway.

The author was consulted by the Royal Perth Yacht Club after the America's Cup Races in 1983 about their policy relative to the use of towing tanks in general and the use of foreign towing tanks in particular. The author advised that all syndicates should have access to adequate towing tank facilities and he proposed that "adequate" in this case be defined by the capability to carry out model tests on a one-third scale. The advice was given that if such a facility is not present in the country of the challenging yacht club, permission should be granted to use a foreign towing tank. Accordingly, U.S. syndicates were denied to go abroad for their testing[12], while Australian defence syndicates and others were not.

Presently, the author at NSMB has been requested to carry out research for many different challenging and defending 12 Metre syndicates. For NSMB such a role is not at all unusual since quite often competing organizations and companies, all vying for the same contract, carry out their research and development work at NSMB. For NSMB and other towing tank organizations the turn of 12 Metre syndicates to the towing tank is very welcome in a time when projects are scarce. For some of the individuals involved it is an opportunity to combine their love for sailing and the sailing yacht with their profession.

12 The U.S. has excellent towing tank facilities. The David W. Taylor Naval Ship Research and Development Centre in Washington, for example, is a world leader in ship hydrodynamics.

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