The Design of a New Concept Sailing Yacht

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Report 1165-P **September 1998**
Projectnr. 981

Proceedings of the Seventh International Symposium on Practical Design of Ships and Mobile Units, PRADS'98, The Hague, The Netherlands, September 1998.
Edited by M.W.C. Oosterveld and S.G. Tan

TU Delft
Delft University of Technology

Faculty of Mechanical Engineering and Marine Technology
Ship Hydromechanics Laboratory

OPMENTS IN MARINE TECHNOLOGY, 11

Practical Design
f Ships and Mobile Units

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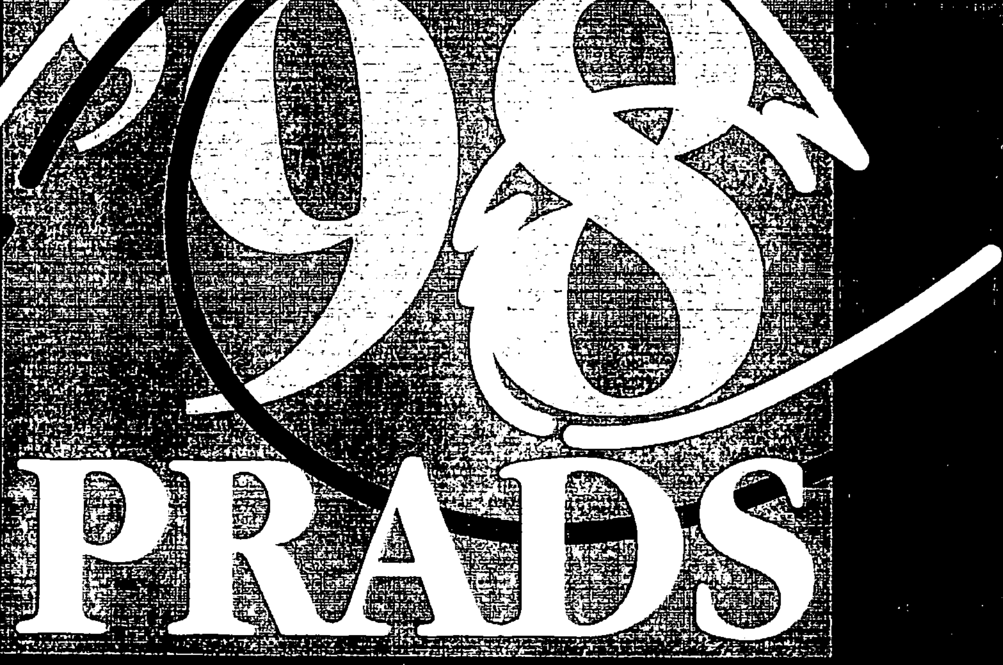

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Developments in Marine Technology, 11

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1998
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Amsterdam - Laussanne - New York - Oxford - Shannon - Singapore - Tokyo

ELSEVIER SCIENCE B.V.
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First edition 1998

Library of Congress Cataloging in Publication Data
A catalog record from the Library of Congress has been applied for.

ISBN: 0 444 82918 0

♾The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands.

These Proceedings consist of papers presented at the 7th International Symposium on Practical Design of Ships and Mobile Units. The Symposium was held at the Congress Centre in The Hague, The Netherlands, on 20-25 September 1998. The Symposium was organized by:

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KIvI	Royal Institute of Engineers in The Netherlands
KM	Royal Netherlands Navy
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PREFACE

These Proceedings contain the papers presented at the 7th International Symposium on Practical Design of Ships and Mobil Units. The Symposium was held at the CONGRESS CENTRE in The Hague, The Netherlands, on 20 - 25 September 1998.

The overall aim of PRADS Conferences is to advance the design of ships and mobile marine structures through the exchange of knowledge and the promotion of discussions on relevant topics in the fields of naval architecture and marine and offshore engineering. Greater international co-operation of this kind can help improve design and production methods and so increase the efficiency, economy and safety of ships and mobile units. Previous symposia have been held in Tokyo ('77 and '83), Seoul ('83 and '95), Trondheim ('87), Varna ('89) and Newcastle ('92).

The main themes of this Symposium are Design Synthesis, Production, Ship Hydromechanics, Ship Structures and Materials and Offshore Engineering.

Proposals for over two hundred papers have been received for PRADS '98 from 25 countries, and 126 have been accepted for presentation at the Conference. Given the high quality of the proposed papers, it has been a difficult task for the Local Organising Committee to make a proper balanced selection.

Some topics which attracted many papers were Design Loads, Design for Ultimate Strength, Impact of Safety and Environment, Grounding and Collision, Resistance and Flow, Seakeeping, Fatigue Considerations and Propulsor and Propulsion Systems. The great current interest in these topics and the high quality of the papers guarantee a successful Conference.

The success of PRADS '98 depends on the great contributions of the participants with a special acknowledgement to the authors.

We as Local Organizing Committee have done our utmost to create the proper atmosphere for an interesting and enjoyable conference.

M.W.C. Oosterveld and S.G. Tan

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M.W.C. Oosterveld and S.G. Tan, editors.

The Design of a New Concept Sailing Yacht

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ABSTRACT

This paper describes several design aspects of a novel type sailing yacht, comprising an unconventional underwater configuration with a bow rudder, a rotating wing mast and a single sail that is operated without any sheets.
The feasibility and critical design aspects of this idea, originated from Van de Stadt Design, was investigated by the department of Marine Technology of the Delft University of Technology. Also, model tests were performed in order to compare the hydrodynamic performance of the bow rudder configuration with a yacht with twin stern rudders.
Although the new design does show advantages in certain conditions, negative aspects such as lack of directional stability, need for continuous adjustment of the sail and the complexity of a sheetless control of the sail, make the feasibility of the concept questionable.

1. INTRODUCTION

A few years ago Van de Stadt Design in Wormerveer (The Netherlands) developed a new design concept, which could best be described as their idea about "the cruising yacht of the future".
The concept aimed to combine maximum (on board living) comfort combined with a reasonable speed potential. The most striking design novelties concern the appendage (keel and rudder) configuration, the replacement of the one or two stern rudders with a single bow rudder and the sail and rig, with a rotating wing mast and no sheets to control the sail, see Figure 1.

The rather unusual rudder configuration was a result of the chosen hull shape, beamy and with flat lines towards the stern. The reasoning behind this and some results of the tanks tests made are handled later in this paper.

A single sail rig was selected, operated without any sheets, increasing the ease of sailing. The absence of stays reduces resistance and disturbance of the flow around the sail.

The sail was fully battened. Sail battens, applied at the full length of the sail, enables the use of roach, creating an elliptical planform. This is a very efficient planform, when considering the aerodynamic performance.
For further aerodynamic improvement over the commonly used rigs, the yacht was designed with a wing mast that can be rotated in every desired position. The sail can be rolled up in the boom, for quick lowering or reefing of the sails.

As the yacht was to be constructed of a sandwich composite with a wooden core, known as 'woodcore', attention was paid at the calculation method of this composite.

This paper will present the advantages and drawbacks of this particular design, by looking at the different aspects separately.

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* Paper is based on MSc. student thesis at DUT

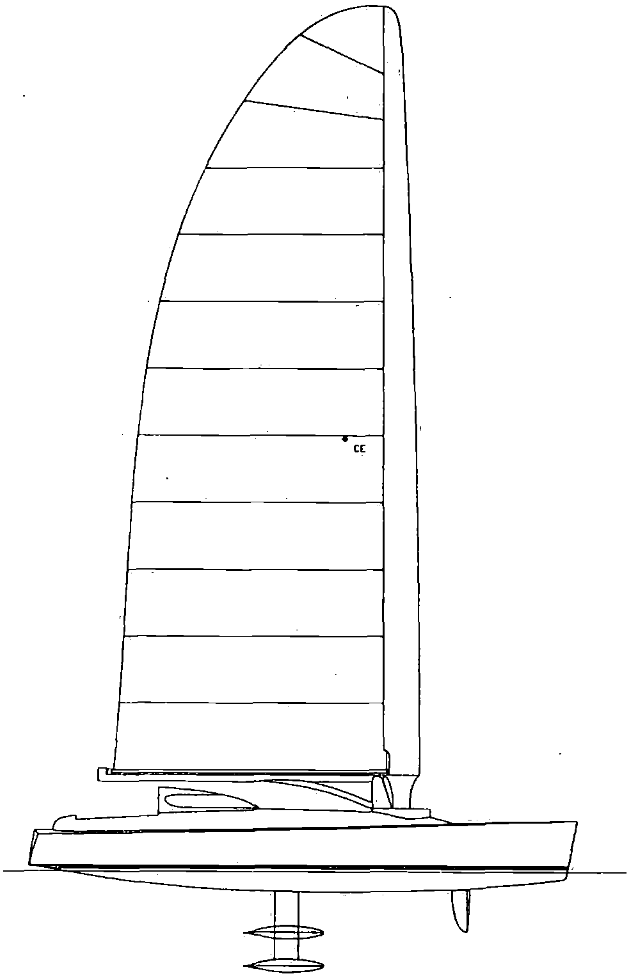

Figure 1 New Concept Design

2. RIG CONSIDERATIONS

2.1. Rotating wingmast

The wing-masted sail is primarily known from the trimarans and catamarans. In fact, the early development of the wing mast in the C-Class catamarans led to a highly efficient rig, within a narrow window of true wind speed. Another effort, described in [1], showed an increase in off-wind drive force of 50%, whereas going-to-windward drag was reduced by 20%.

But, the benefits are only utilised fully if the crew is prepared to adjust their sails to the right shape and the right twist and to trim them to the right angles as they sail. All limits of adjustment must be removed, because these types of rigs are not better than the conventional ones unless they are properly adjusted. The performance is there, but you have to sail more intelligently to get it. *"Be alert, be accurate, or be last."* [1]. This need for adjustment includes the mast too. By nature, wing masts are very stiff in the plane of the sail. Because of this, these masts do not bend sufficiently for adjustment of sail fullness, and so the sail shape cannot be much changed. As a result, a situation with a separation bubble on one side or the other, was the norm in practice. The flow would be 'clean' at one trim angle only. Therefore, in the designing and construction of the mast the correct flexibility must be attained to enjoy the adjustability of the flexible mast and the efficiency of the wing mast.

In heavy weather, the wing mast can put the yacht and its crew in hazardous situations. As it cannot be reefed, a highly efficient high aspect wing is placed in high wind speeds. If it is left feathering in the wind, with little damping of the movement, heavy oscillation could occur. This fluttering could lead to damage and eventually to loss of the mast. If it is stabilised, lift will develop, with the risk of uncontrollable behaviour regarding speed, course, heel, etc.

Another problem may be a situation where the mast is jammed in one position, without any possibility to control it. In this design, the mast was dimensioned in such a way that the yacht does not capsize in the most severe wind condition, with the mast jammed in an unfavourable position.

2.2. Sheetless rig

As a sheeting system was abandoned, alternatives for operating the sail were investigated. The problem of abandoning a sheeting system is counteracting the huge moment induced by the sail force. The solution is found in a balanced rig, like the AeroRig®, see Figure 2. However, since only one sail is used with this design, this was quite impracticable.

An alternative balanced rig was designed, featuring an A-mast, see Figure 3. Some of the benefits are:

- No mast interference, better sail performance
- Balanced rig
- The mast itself can be used as lift generator

Some disadvantages:

- Drag generator
- Its heavy weather performance is unsure

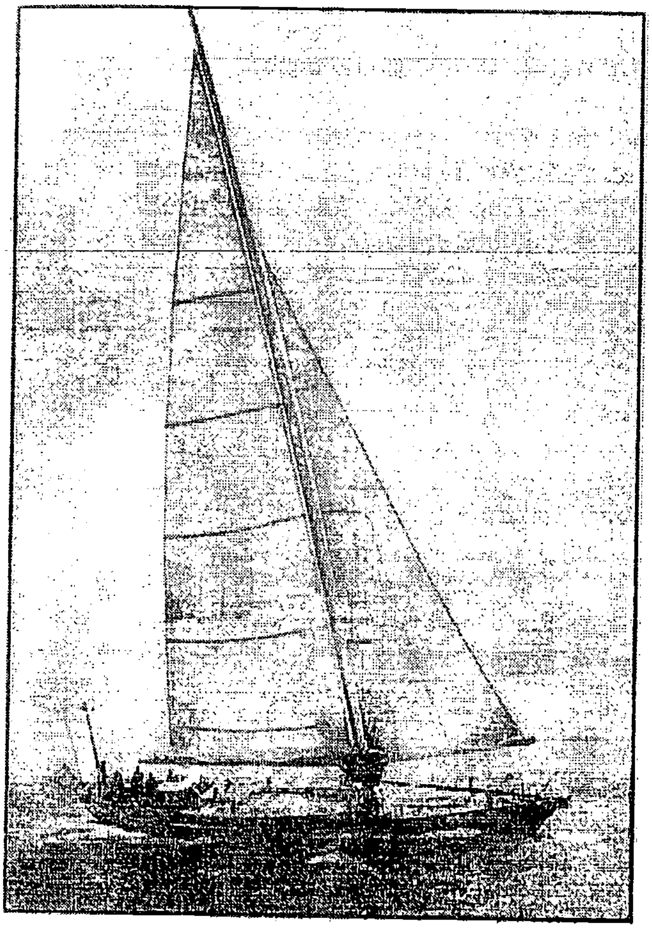

Figure 2 AeroRig®, by permission of Carbospars Ltd.

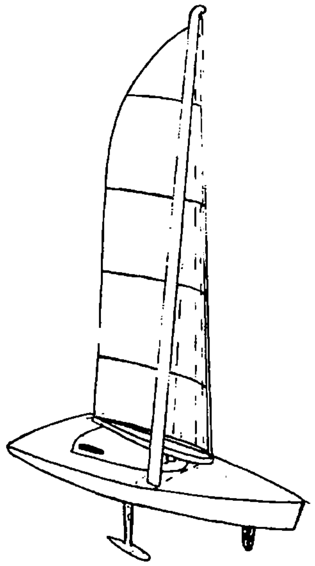

Figure 3 A-mast

A second alternative could lie in operating the boom at the mast by using hydraulic rams to set the desired angle to the mast. An advantage was:

- The rig can be rotated over 360 degrees, enabling gybing over the bow

A disadvantage:

- The system induces a great loading on the mast, which makes the mast design very complex, leading to a heavy mast.

The mast and boom were disconnected in the third alternative, used at this design, which would release the mast from its loading, see Figure 4.

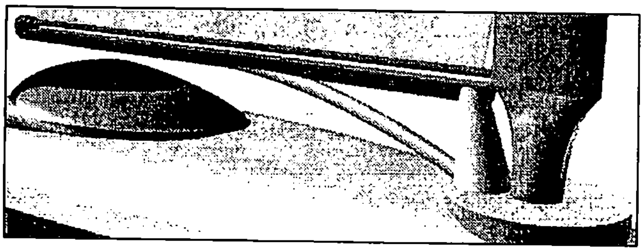

Figure 4 Sheetless boom

The boom is placed on a disk mounted on the cabin roof, which can be rotated over 360 degrees. The disk is fitted with bearings in the deck, immediately connected to a gear wheel. A hydraulic motor drives this wheel. The mast can be set to any desired angle to the boom.

Advantages were:

- 'Clean' mast structure
- Equipment below deck

The complexity and weight of the system were clear disadvantages.

To meet the requirement of the possibility to lower the sail at the boom, a high tensile bar was introduced at the boom, which is connected at the mast and the end of the boom. This bar is used to roll up the sail, after which a protection cover is placed over the sail.

It is clear that the problem caused by the abandoning of sheets of a single sail rig is not easily solved. To counteract the moment, induced by the sail forces, a complex and heavy system is to be fitted on the yacht. It remains to be seen whether this disadvantage is compensated by the increased sailing comfort.

3. SANDWICH CALCULATIONS

The yacht's hull was designed to be made of woodcore sandwich material. This is usually calculated according to the *ABS Guide for Building and Classing Offshore Racing Yachts, 1986*, where the sandwich is treated as a 'common' sandwich, in which the core only contributes in shear strength. For a woodcore sandwich however, this is simplification that could lead to an unnecessary increase in hull weight, as the wooden core is likely to contribute in the strength of the sandwich, both in flexural as in shear strength. The problem is that there is no known method for calculating the required core and skin dimensions of woodcore sandwiches that would give a better result. The section will describe a calculation method for the section modulus of woodcore sandwich panels, in which the core contributes in the strength, based on transformed beam theory.

3.1. Symmetrical Sandwich

In this section the moment of inertia of symmetrical sandwiches, in relation to their neutral axes, is given.
The theory used is that of composite beams, see [3].

The moment of inertia is as follows:

$$I = b_s \cdot \left[\frac{t \cdot (c+t)^2}{2} + \frac{E_{T,c} \cdot c^3}{12 \cdot E_{T,s}} \right] \text{ mm}^4 / \text{mm},$$

in which

b_s = breath of skins, strip 1 mm

t = thickness of the skins

c = thichness of the core

$E_{T,c}$ = tensile modulus core material

$E_{T,s}$ = tensile modulus skin material

The section modulus is:

$$W = \frac{I}{z_{max}} = \frac{I}{\frac{1}{2}c + t}$$

3.2. Asymmetrical Sandwich

The case gets a little more complicated for asymmetrical sandwiches, built of different materials of different thickness.
The following relationships for the neutral axis and moment of inertia is applicable:

$$z_{axis} = \frac{\frac{1}{2} E_i t_i{}^2 + E_c c\left(t_i + \frac{1}{2} c\right) + E_o t_o \left(t_i + c + \frac{1}{2} t_o\right)}{E_i t_i + E_c c + E_o t_o}$$

$$I = b_i [t_i \left(z_{axis} - \tfrac{1}{2} t_i\right)^2 + \frac{E_o}{E_i} t_o \left(z_{axis} - \left(t_i + c + \tfrac{1}{2} t_o\right)\right)^2$$
$$+ \frac{E_c}{E_i} c\left(z_{axis} - \left(t_i + \tfrac{1}{2} c\right)\right)^2 + \frac{E_c}{12 E_i} c^3]$$

Indices:

i = inner skin

o = outer skin

c = core

b_i = breadth of inner skin, strip 1 mm

t = thickness of skins

c = thickness of core

E = tensile modulus

At a height z, with a modulus E, the section modulus becomes:

$$W = \frac{I}{z_{axis} - z} \cdot \frac{E_i}{E}$$

The above method led to a reduction in hull weight of approximately 10%, compared to a hull calculated with the sandwich method, a small percentage of the total weight. However, calculating the hull with transformed beam theory is even more advantageous for lightweight yachts.

4. BOW RUDDER

The philosophy behind the development of such a design concept was based on the following considerations:
In order to be able to obtain a relatively high speed in the running and broad reaching conditions a wide after body with flat and beamy sections, see Figure 5, is considered to be advantageous.

These sections may develop sufficient hydrodynamic lift to be able to support the weight of the craft and so overcome the sharp resistance increase known from ordinary displacement craft at speeds above the "hull speed". In addition this hull geometry with its large and beamy flat-bottomed sections aft has proven to be a very stable platform in running conditions, with or without flying a spinnaker or asymmetrical.

Another important aspect for obtaining high speeds in those conditions is the minimisation of the overall weight of the craft. In order to be able to reduce the weight of the craft and still maintain a sufficiently high transverse stability the metacentric height has to be made as high as reasonably feasible. This allows a minimal ballast weight, which in addition is all concentrated in a bulb at the bottom end of the deep fin keel. A consequence may be the relative large range of "stability" in upside-down position (see also [2]).

The specific shape of the hull lines has so been chosen so that when the ship is heeled to 15 or 20 degrees in the upwind condition, the waterline length is extended and the lines show a almost symmetrical hull shape, see Figure 6, which is considered to be an advantage in those conditions with respect to resistance and side force production. A considerable reduction in the wetted area of the hull due to heeling angle of the yacht is also envisaged, further contributing to a lower overall resistance in the upwind / heeled condition.

So far, the general solution to the problem of the considerable loss of submerged rudder area with these hull shapes when they heel, is found in the application of two rudders both "off centreline" and "with dihedral" instead of the one single rudder at the centreline. This set-up guaranties full downwind control and also in the upwind condition at least one of the rudders is completely submerged without any negative effect of the free water surface disturbance. Also from a redundancy point of view the application of two rudders is beneficial even though they are no longer protected by the (centreline) keel in the case of collision or grounding. The disadvantages of the twin rudder layout obviously lay in the additional resistance arising from the extra appendage and the mechanically more complicated and vulnerable steering device.

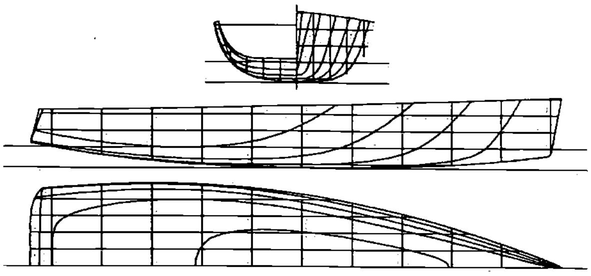

Figure 5 Upright Linesplan

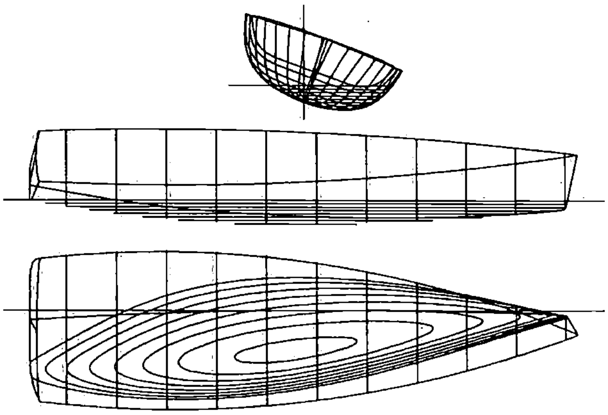

Figure 6 Heeled Linesplan

This led Van de Stadt Design to the idea of the introduction of one single rudder on the centreline near the bow of the yacht in combination with a single keel also on the centreline.

This bow rudder would then no longer be emerged due to the heeling of the yacht so this single rudder would be sufficient. Interest in the bow rudder was also triggered after the successful application during the America's Cup regatta in Perth, 1987.

Without doubt such a "bow" rudder would ask for some skill of the helmsman: in order to let the rudder contribute to the overall side force production of the yacht it should have to generate positively (windward) orientated side force in the stationary condition, which would make a "lee helm" yaw balance of the yacht necessary because the rudder is in front of the keel now. Whether this is acceptable to the "human controller" remains to be seen. In addition the use of a bow rudder also calls for a considerably more aft position of the main foil (the keel), of which the longitudinal position however is strongly dictated by the presence underneath it of the

(large amount of) ballast and its position with reference to the centre of buoyancy of the hull.
Serious drawbacks were also envisaged with respect to the course keeping qualities of this bow rudder concept. Much was uncertain about this aspect of the design and available calculation procedures (e.g. [4]) were not considered applicable to the hull and the circumstances under consideration.
Finally the sea keeping behaviour of a design as the one presented here is believed to be advantageous. The large LCB - LCF separation calls for moderate pitch motions in head waves and the relative fine bow shape will prevent a high added resistance and also serious pounding in head waves.

Since a considerable amount of the considerations, which have led to the introduction of the present concept, are related to hydrodynamics, it was decided to carry out an extensive series of model experiments with the two possible variations of the design in order to be able to make a more founded comparison possible.

5. THE MODEL TESTS

The model experiments, which were planned for the two configurations of the design, were intended to make a Velocity Prediction of both concepts possible. To be able to do this the standard tests of the Delft Shiphydromechanics Laboratory for sailing yachts have been carried out. In addition to these tests a simple first assessment test has been carried out with a "free running" model in both configurations to gain some insight in the course keeping qualities.
The tests program consisted of a full upright resistance test from Fn = 0.10 to Fn = 0.70, and a full series of heeled and yawed tests with 0, 10, 20 and 30 degrees of heel and leeway angles ranging from 1 to 10 degrees at least three different forward speeds. The forward speeds selected were made dependent on the heel angle selected and ranged from Fn = 0.25 to Fn = 0.45.
A series of free running tests for the determination of the course keeping capabilities of the two different configurations concluded the tests.

5.1. Upright Resistance

The total, frictional and residuary resistances of the two configurations in the upright condition are presented in Figure 7. The difference in the upright resistance between the two configurations is clearly visible in this graph. This difference in the total resistance appears to be largely caused by the increase in the residuary resistance of the twin rudder configuration when compared to the single (bow) rudder configuration.

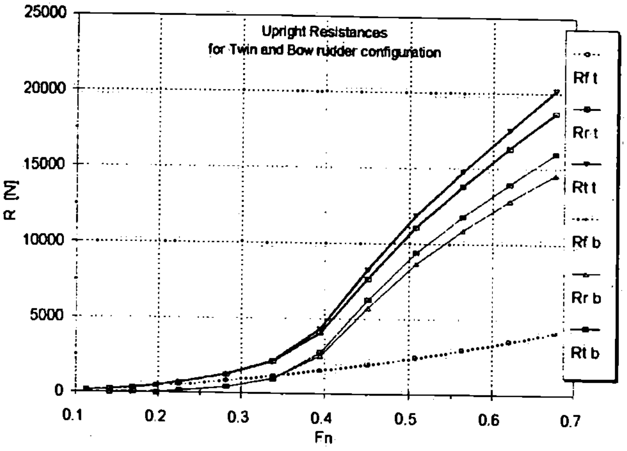

Figure 7 Upright Resistance

5.2. Side Force with Heel and Leeway

In Figure 8 the side force of the yacht in both configurations is presented as a function of the leeway angle for a typical heeling angle of 20 degrees and the different Froude numbers related to the angle of heel such as investigated in the model tests. For the larger leeway angles the side force generation of the hull with the twin rudder configuration is in general somewhat higher, the differences between the two configuration are however small but are consistent over the speed- and heeling angle range investigated. This may be partly explained by the difference in the total lifting generating area of the twin rudder configuration compared with the single rudder configuration.

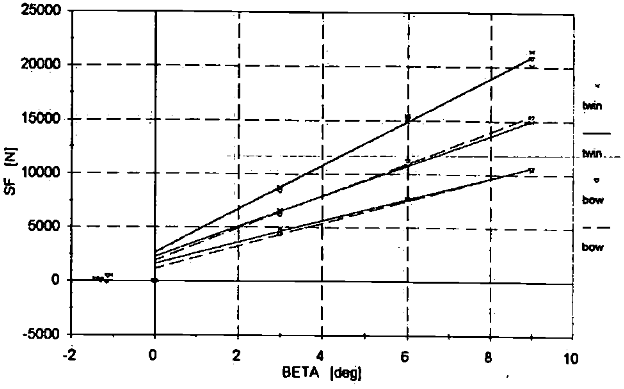

Figure 8 Side force at 20 degrees heel

5.3. Heeled and Induced Resistance

Due to its heeling angle and the side force production, a sailing yacht experiences two types of extra resistance: resistance due to heel and induced resistance due to the lift generated. The heeled resistance is defined as the extra residuary resistance component when the yacht is heeled and with zero side force, whereas the induced resistance is the additional resistance induced by the developed side force.

In Figure 9 the residuary resistance as a function of the generated side force squared is presented for 20 degrees heeling angle and three different Froude numbers respectively.

The lines drawn in these figures are determined by applying a linear least square regression method trough the measurement points obtained from the towing tank data.

In general, the bow rudder configuration generates more induced resistance (i.e. the slope of the resistance curves with respect to the side force squared is steeper) over the entire heel angle and speed range investigated when compared with the twin rudder arrangement.

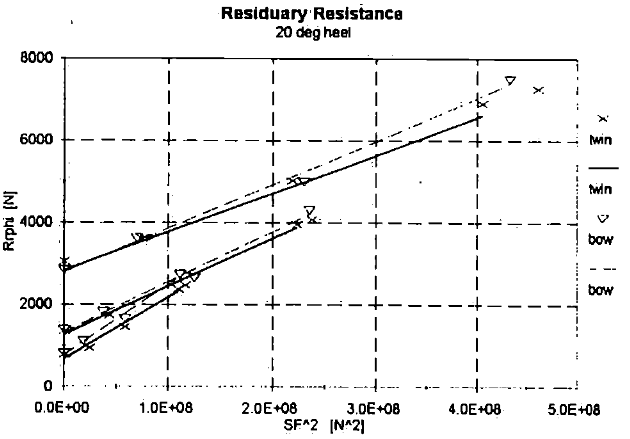

Figure 9 Residuary resistance at 20 degrees heel

5.4. Directional Stability Assessment

Since there were some serious doubts about the positive directional stability of the bow rudder concept is was decided to carry out some additional tests dealing with this problem. Due to the limited time available for such a test it was only possible to carry out some indicative tests which would enlighten the course keeping capabilities of both concepts.

5.4.1. Test procedure

The tests were performed with a more or less free running model in the towing tank. The rudder(s) were put in a zero rudder angle position. The model was free to move transversely. The "tow force" on the model was applied longitudinally in the centre of effort of the sails but at deck level, such as to introduce no serious heeling components.

During these tests the model was brought up to speed (around Fn = 0.25) and once stable in that condition the model was released. If a stable condition persisted, a small disturbance in yaw was supplied and watched if the model tended to return to its original equilibrium condition. The tests have been carried out with both rudder arrangements.

5.4.2. Twin Rudder Configuration

To check the feasibility of this test procedure the test were first carried out with the twin rudder configuration.

The results of these tests came out as were to be expected, knowing that the twin rudder aft configuration is a quite stable configuration. As soon as the model was released, it slowly moved to a stable position a little "off centreline". This small offset of course is necessary to counteract the inevitable side force produced by the hull which is counteracted by the transverse component of the towing force.

Since the model now assumed a stable starting position it was possible to test the course keeping stability by disturbing the model in yaw and sway. After supplying a small disturbance in this direction the resulting motion of the model was clearly very well damped and soon the model came back to its original course and position.

5.4.3. Bow Rudder Configuration

The tests with this appendage layout ended all unsuccessful, i.e. the model immediately started to diverge from its initial course as soon as the run started. Due to its very large excursions in yaw and sway and also due to the limited towing chord length the angle at which the tow force was applied increased very quickly therefore bringing the model to start oscillating fiercely back and forth with ever increasing amplitude.

This combination of large yawing and swaying amplitudes diverged in an uncontrolled motion. The physical restrictions of the towing tank walls necessitated a quick ending to these runs. Change in rudder angles and / or towing force centre of effort did not change this picture dramatically. See Figure 10 for a typical path recording of such a test.

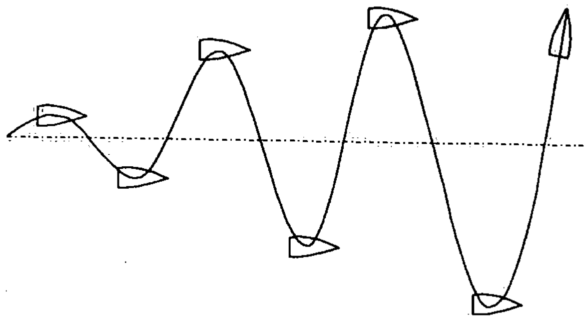

Figure 10 Model path

6. CONCLUSIONS AND RECOMMENDATIONS

The use of the bow rudder doesn't offer a clear improvement over the conventional twin rudder configuration. The tank tests showed more or less equal hydrodynamic performance, except for upright conditions like downwind sailing.
However, one could opt for a maximum of available rudder action when sailing with high speeds at these courses especially. After all, the sail will produce a yawing moment that has to be corrected by the rudder.
The sailing comfort when sailing with a bow rudder is to be questioned; due to the directional instability of the yacht the helmsman has to be alert and give rudder continuously. A feedback control system, which is known from the aviation industry, could offer a solution.

The aerodynamic performance of this particular wingmasted rig stayed insecure. The lack of usable information on this type of mast and sail forced the dimensioning and velocity prediction to be done on assumptions and estimations. It is therefore uncertain whether this cat rig outperforms the sloop rig.
The handling of a wingmasted sail appears to be a specialist's cup of tea. When sailed without adjusting continuously, the performance is not explicitly better than the round-masted sail. The question then arises whether this type of rig is suitable for cruising yachts. After all, an innovation often isn't accepted until it proves to be better.
The abandoning of a main sheet system is questionable. The weight increase, the complexity and the lack of sail controllability of an alternative system are disadvantages that doesn't seem to be compensated by the ease of handling. Especially, when considering that a main sheet can be operated hydraulically too, enabling 'push-button sailing'.

Calculating with a contributing wooden core resulted in a weight decrease of approximately 2%. In this case the gain is therefore not sensational. However, in a market where every weight decrease is welcomed, the racing market for instance, this method could be useful.

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