The Design of a Sailing Yacht with a Bow Rudder

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on

THE MODERN YACHT

18 & 19 MARCH 1998 PORTSMOUTH

PAPERS

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on

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at the

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THE DESIGN OF A SAILING YACHT WITH A BOW RUDDER

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SUMMARY

Looking at the design of yachts, like those which competed in the latest Vendée Globe Challenge and the B.O.C. Challenge, the most striking feature of these yachts seems to be their wide aft bodies. Important reasons for the designer to choose such a hull form could be the creation of a flat and wide bottom of the hull aft, so that the yacht may reach high speeds at downwind courses and the possible drastic reduction of wetted surface when heeled.

Consequently, the designer is usually forced to use multiple rudders, because a single rudder would come out of the water when a yacht like this is heeled. The possible additional resistance due to this rudder configuration, compared to a single rudder, is a disadvantage that has to be addressed. An alternative might be the use of a single bow rudder. The question is whether this is feasible or not.

In the present study a comparison between these two design options was made for one particular design. Issues such as course stability and manoeuvrability were also taken into account.

To explore the difference in performance of the two designs, tank tests were performed at the Ship Hydromechanics Laboratory in Delft. A qualitative manoeuvring test was made as well. This paper will present the results of this comparison in some detail.

AUTHORS' BIOGRAPHIES

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Mr. Cees W. van Tongeren is Chief Designer of EG. Van de Stadt and Partners (Yacht Designers).

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. The present paper mainly deals with the hydrodynamic aspects of this design, rather than with the aerodynamic aspects.

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 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.

The specific shape of the hull lines has so been chosen so that when the ship is heeled to 15° or 20° in the upwind condition, the waterline length is extended and the lines show a almost symmetrical hull shape, which is considered to be an advantage in those conditions with respect to resistance and side force production.

A typical representation of this effect is visualised in Fig. 1 where the linesplans of the hull both upright and heeled at 20° is shown.

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 guarantees 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.

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. 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 were not quite 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.

2. 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 hull of the model used for the experiments was build according to the lines as presented in Fig. 1 and geometrical identical on a scale 1 : 7.5.

The main particulars of the model are presented in the Table 1.

TABLE 1

Length waterline	2.00m
Beam waterline	0.534m
Draft canoe body	0.081m
Total draft	0.400m
Displacement	36.35kg

As explained before the longitudinal position of the keel had to be different for the two configurations because the mast position and the sailplan remained identical. This resulted in the following positions of the keel:

• With bow rudder :	keel at ordinate 4
• With twin rudders:	keel at ordinate 5.

By moving the keel the centre of lateral resistance of the hull-keel-rudder combination was kept almost identical in both configurations.

The standard measurement set-up of the Delft Shiphydromechanics Laboratory was used for the experiments. In this set-up the model is free to heave, pitch and roll but restrained in all other modes of motion. The resistance, the side force, the yaw moment, the leeway angle, the sinkage and the running trim of the model at speed are measured during each run at a constant speed, whilst changes to the stability moment and the running trim moment are applied to account for the absence of the sail forces. The standard measurement set-up is depicted in Fig. 2.

Standard half and full width carborundum strips on the hull, keel and rudders are used as a turbulence stimulation. When applying this method all the upright

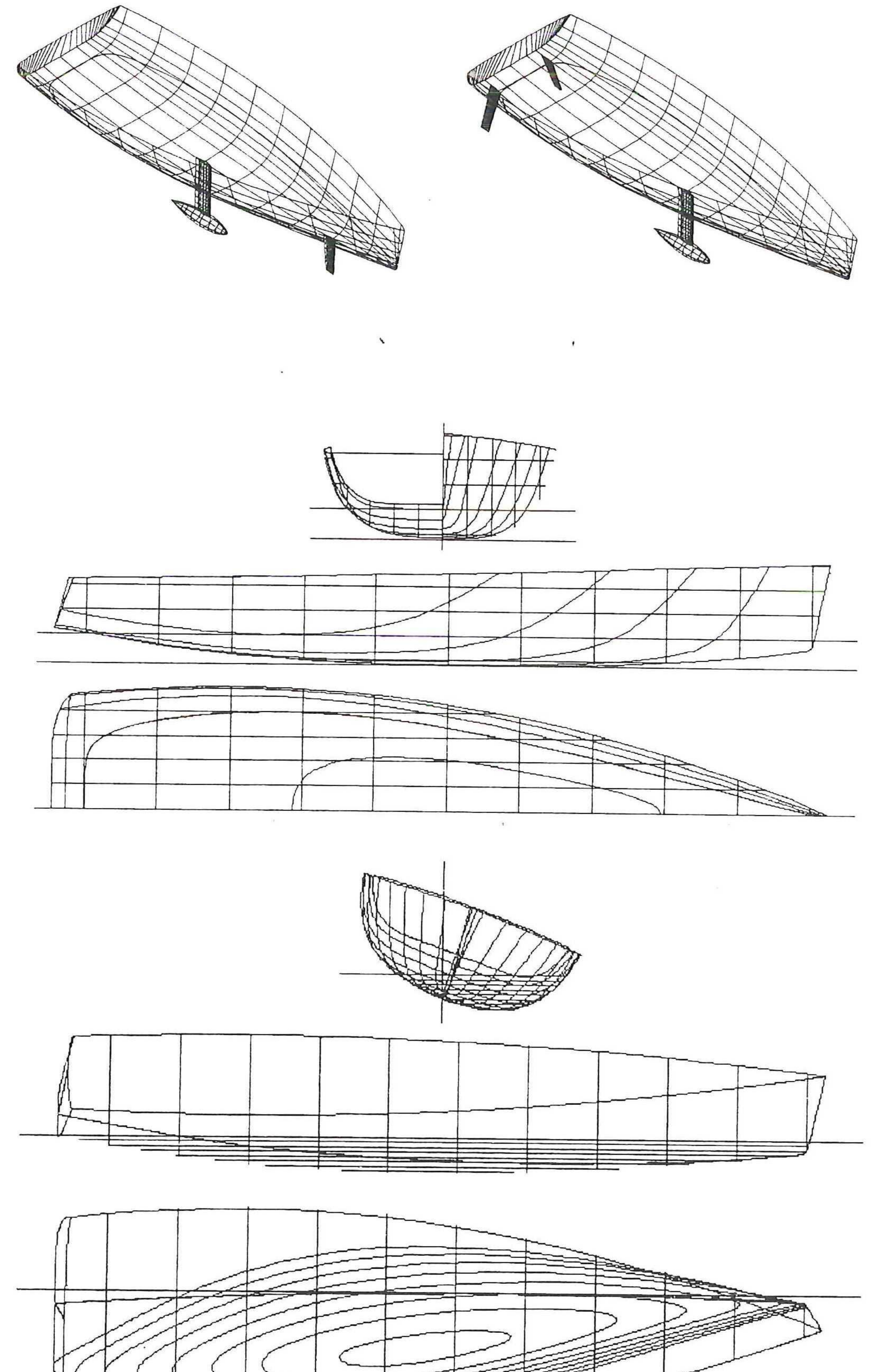


Fig. 1

resistance tests have to be carried out twice: with a half and a full width of the strips to enable correction of the measured resistance values for this additional strip resistance. This additional resistance due to the strips is obtained from the measurements and is assumed to vary with the speed squared and with the strip width.

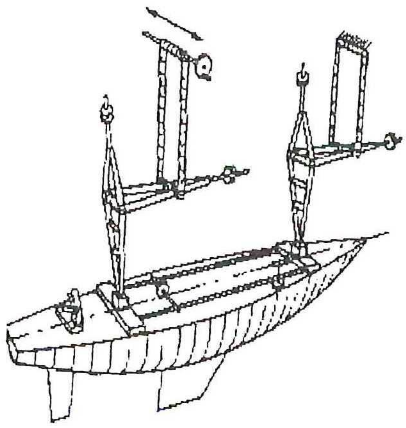


Fig. 2

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° of heel and leeway angles ranging from 1° to 10° at a minimum of 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. These will be described in some more detail at the end of the paper.

3. THE RESULTS OF THE MODEL TESTS

Upright Resistance

After the correction for the additional resistance from the turbulence stimulators, the measured resistance of the model is extrapolated to the full scale by making use of the well known Froude's extrapolation procedure. Use is being made of the ITTC -57 extrapolation line, according to:

$$C_f = \frac{0.075}{(\log \mathrm{Re} - 2)^2}$$

in which the Reynolds number Re:

$$\mathrm{Re} = \frac{V \cdot L}{\upsilon}$$

where:

V	Velocity	m/s
L	Characteristic Length	m
ν	Kinematic Viscosity	m^2/s

For the hull the characteristic length L is 90% of the design waterline length. For keel or rudder the mean chord represents the characteristic length L.

The total, frictional and residuary resistances of the two configurations in the upright condition are presented in Fig. 3.

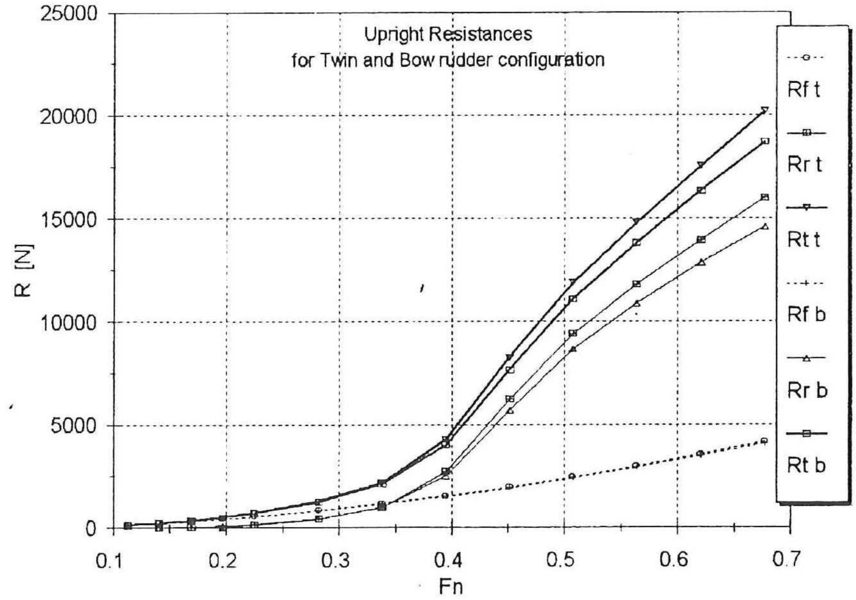


Fig. 3

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. The difference in the wetted area between the two configurations is only marginal and does therefore not contribute much to the difference in overall resistance. It remains to be further investigated whether this increase in residuary resistance is caused by the larger number of appendages in the twin rudder configuration only or that the residuary resistance is strongly influenced by the position of the rudders along the length of the hull: i.e. there is a difference in the distribution of the submerged volume of the hull with appendages over the length of the hull between the two configurations.

Another effect which may influence the results and which is normally not considered is influence of the wake of the front foil on the resistance of the second (rear) foil when they are both positioned in the same longitudinal plane. This influence is only present in the full symmetrical condition, i.e. no heel and no leeway. In the twin rudder plus keel condition none of these foils is in that condition operating in the wake of any of the other appendages.

Side Force with Heel and Leeway

The tests with the model in the heeled and yawed condition were performed with 5° of (weather helm) rudder angle. This was done to overcome the effects of the negative induced side force on the appendages due to the asymmetry in the flow arising from the heel angle.

In the Figs. 4, 5 and 6 the side force of the yacht in both configurations is presented as a function of the leeway angle for the three different heeling angles and the different Froude numbers related to the angle of heel such as investigated in the model tests.

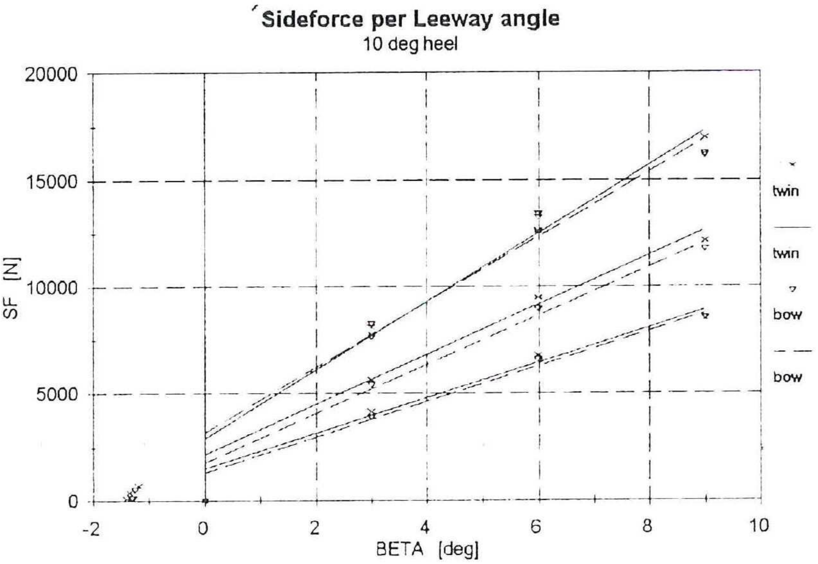


Fig. 4: Fn = 0.27-0.31-0.36

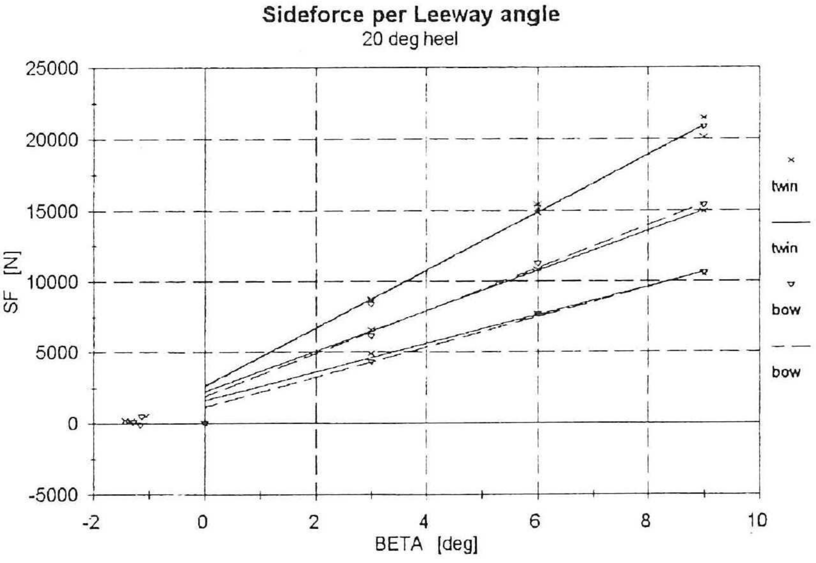


Fig. 5: Fn = 0.31 - 0.36 - 0.41

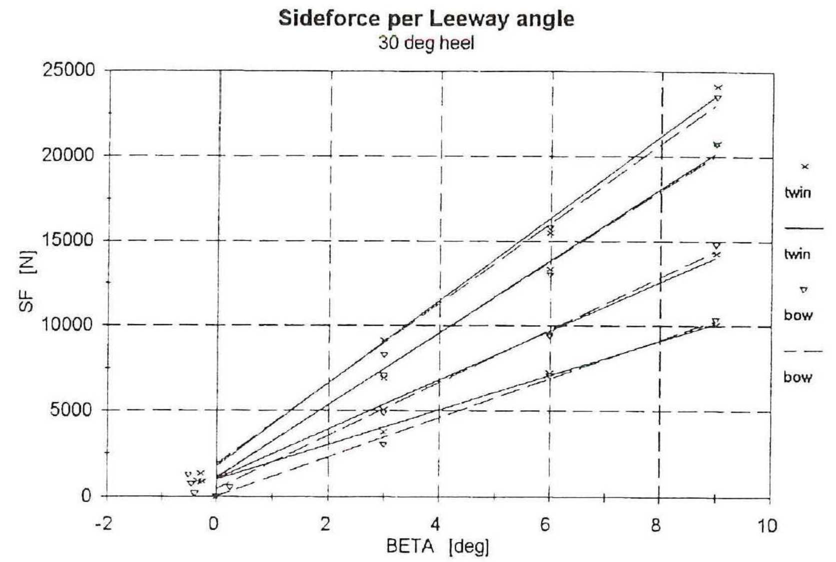


Fig. 6: Fn = 0.34-0.38-0.43-0.45

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.

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 line with the definitions used in the Delft VPP both these resistance components are determined by taking into account changes in the residuary resistance (R_r) only. The frictional resistance at heel is subtracted from the total resistance in the yawed and heeled condition first. By doing so changes in total resistance due to changes in wetted area are eliminated. So the definition of the heeled resistance becomes:

$$R_h = R_{r,\varphi,SF=0} - R_{r,\varphi=0}$$

Where φ stands for heeled condition and where SF = 0 means that no side force is being produced. The induced resistance:

$$R_i = R_{r,\varphi,\beta} - R_{r,\varphi,SF=0}$$

Where β stands for yawed condition, so with side force.

In the assessment of the heeled and induced resistance of model with the twin rudder configuration, the change in wetted area due to the emergence of the windward rudder at heel is taken into account in the calculation of the frictional resistance.

In Figs. 7, 8 and 9, the residuary resistance as a function of the generated side force squared is presented for 10°, 20° and 30° heeling angle and three (or four at 30°) different Froude numbers respectively.

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

From these graphs it may be seen that 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 higher) over the entire heel angle and speed range investigated when compared with the twin rudder arrangement, the change being most evident at the lowest angle of heel i.e. at 10° and becoming smaller with increasing heel.

In general it may be concluded from these measurements that the side force production is lower for the bow rudder configuration when compared to the twin rudder arrangement and also that the lift is being generated at the cost of a slightly higher (induced) resistance.

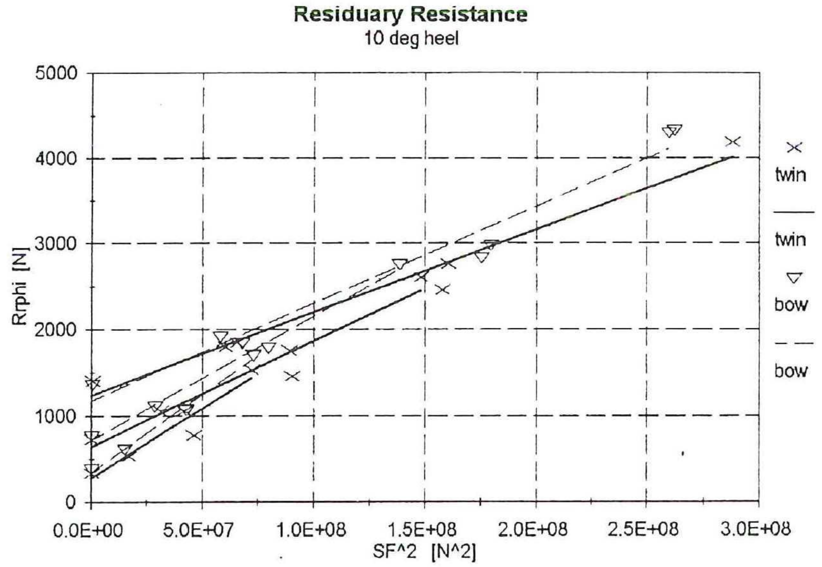


Fig. 7: Fn = 0.27 - 0.31 - 0.36

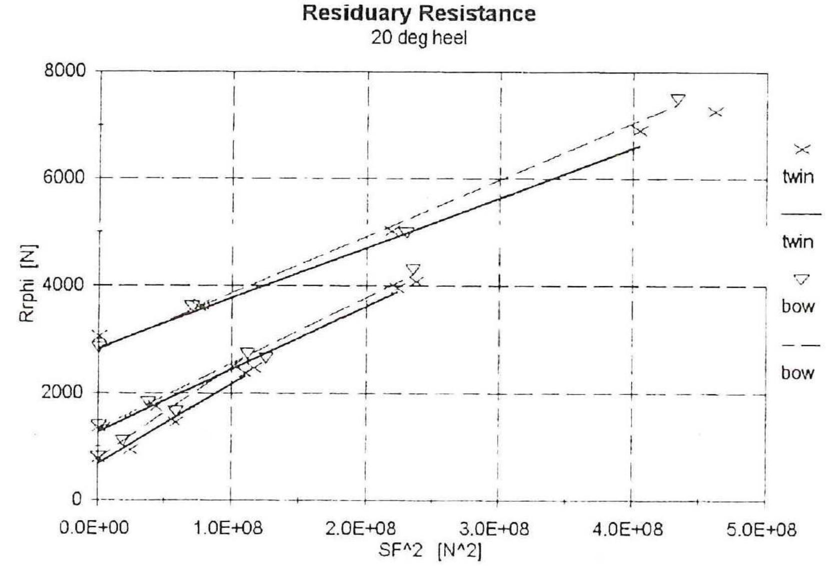


Fig. 8: Fn = 0.31 - 0.36 - 0.41

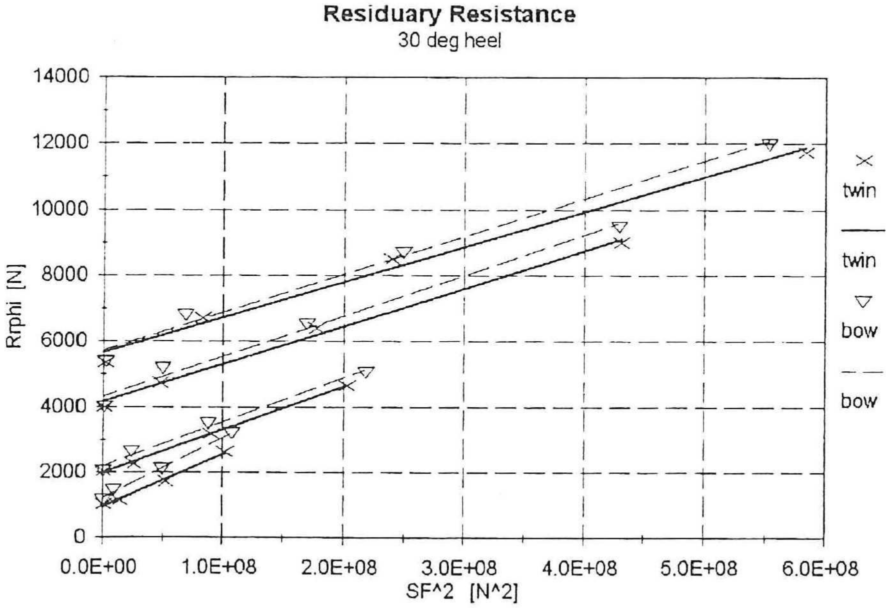
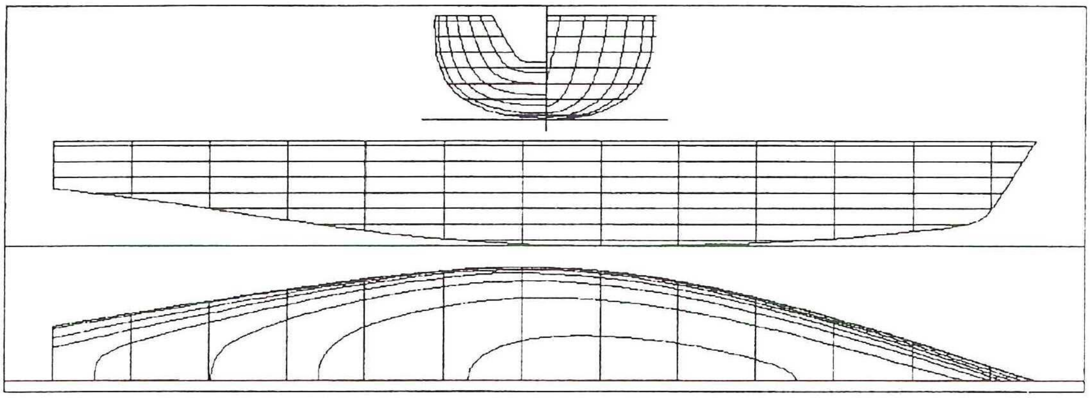


Fig. 9: Fn = 0.34 - 0.38 - 0.43 - 0 .45



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                                          Comparison Yacht        Future Yacht


Lwl      WATERPLANE LENGTH                   15.006  m                 15.008  m
B        MAX. WATERPLANE BREADTH              3.758  m                  3.986  m
Tc       DRAUGHT CANOE BODY                   0.692  m                  0.603  m
T        DRAUGHT TOTAL                        3.000  m                  3.000  m
Cp       PRISMATIC COEFFICIENT                0.556                     0.576

LCB      LCB OF THE CANOE BODY IN % VAN Lwl  -2.10   %                 -5.65   %
         (i.r.t. HALF Lwl)
VOLc     VOLUME OF DISPLACEMENT CANOE BODY   15.46   m3                14.95   m3
VOLt     VOLUME OF DISPLACEMENT TOTAL        15.86   m3                15.36   m3
Sc       WETTED SURFACE OF THE CANOE BODY    41.73   m2                44.95   m2
Sk       WETTED SURFACE OF THE KEEL           5.89   m2                 4.89   m2
Sr       WETTED SURFACE OF THE RUDDER         1.09   m2                 1.09   m2
Ck       MEAN CHORD LENGTH OF THE KEEL        0.700  m                  0.700  m
Cr       MEAN CHORD LENGTH OF THE RUDDER      0.465  m                  0.465  m
Aw       WATERPLANE AREA                     37.13   m2                40.17   m2
GM       METACENTRIC HEIGHT                   1.790  m                  2.488  m

STAB. ARMS FOR PHI= 10, 20, 30 EN 40 GR.      0.30     0.56     0.75  0.90
                                              0.42     0.74     0.96  1.11

CREWWGT CREW WEIGHT                           320.  kg      320       kg

CREWCGH POS. CREWWEIGHT I.R.T. CENTERLINE    2.00   m        2.0     m



For VPP runs both hulls equiped with same sail configuration:


  ---------- SAILCONFIGURATION ---------

  -------(input measurements in m.)-----


HBI   =  1.551     BAS   =  2.130     IG    = 18.300     J     =  5.500
P     = 22.900     E     =  7.830     LPG   =  5.500     LPIS  =  0.000
SL    = 18.335     SMW   =  9.900     ISP   = 18.500     SPL   =  5.500
MGU   =  2.975     MGM   =  5.089     HB    =  0.313
BD    =  0.391     FSP   =  0.000     ZLT   =  1
TL    =  3.700
MDT1  =  0.000     MDL1  =  0.000     MDT2  =  0.000     MDL2  =  0.000
```

Fig. 10

4. COMPARISON WITH A MORE CONVENTIONAL YACHT HULL

From the results and comparisons obtained from the presented measurements it became clear that the choice for the bow rudder configuration was not too obvious for the particular hull shape under investigation. From the model experiments and the associated performance analysis it appeared that in most cases the bow rudder appendage arrangement would perform worse than the twin rudder arrangement.

In addition to this outcome it also appeared of interest to consider whether the choice for the particular hull shape, which necessitates the use of either the twin or the bow rudder, was very sensible taking into account the fact that the design was supposed to be dealing with the *cruising* yacht of the future .

To investigate this further it was decided to extend the comparison made so far between the different appendage layouts on the 'future' yacht to a comparison also between the particular 'large beam aft' hull shape to a comparable 'moderate beam aft' hull with a more contemporary hull shape.

So an additional design was developed along these lines of thought. The hull lines of this 'comparison' design are presented in Fig. 10. Inevitably the comparisons between the two designs made hereafter are somewhat hampered by the fact that these designs are not comparable in every detail. The main particulars of both designs such as displacement, sail areas and stability are presented in the Table 3.

The first issue for the comparison between these designs will be on the upright resistance.

In Fig. 12 the measured resistance curve of the original design is presented, together with the approximation based on the use of the polynomials as presented in Ref. [4] which are based on the results obtained from the Delft Systematic Yacht Hull Series (DSYHS). Using the same polynomials the upright resistance of the new 'comparison' design has been calculated and the results hereof are also presented in the Fig. 12.

First it should be noted that the upright resistance of the 'future' design is predicted to be quite good using the polynomial approximation even though the hull of this design certainly is not drawn along the lines of the DSYHS!

As may be concluded from this figure the upright resistance of the 'comparison' design is lower in particular at the lower Froude numbers to about Fn = 0.40 at which point a crossover appears to exist and thereafter is considerably higher (up to 7%) at the highest Froude numbers. This implies that the down wind running and broad reaching speeds will be smaller in particular in the stronger winds but at lower wind speeds the 'comparison' design will perform better under those headings. It remains to be seen however if these really high speeds will be of serious interest to the cruising sailor, because they also do imply the use of high sail power (spinnakers etc.) in those 'windy' conditions.

The upwind conditions may not be compared by looking at the upright resistance only, therefore a VPP has been calculated for both designs, i.e. the 'future' yacht with the twin rudder appendage layout and the 'comparison' yacht with the 'standard' appendage layout. The performance calculations for the 'future' yacht are based on the data obtained from the described towing tank measurements and for the 'comparison' yacht on the algorithms as supplied with the Delft VPP. This is quite feasible because the 'comparison' design fits very well within parameter space spanned by the DSYHS from which the algorithms are derived. For the sake of comparison the sail layout and sail area has been kept identical for both designs. A considerable difference however is present in the transverse stability of both designs: the 'future' yacht has an almost 25% higher GM value, mainly due to its larger beam.

A remark should be made here also about the range of positive stability of both yachts and their 'stability' in the upside down position. The calculations made for both design clearly show the differences: the upright stability moment of the 'future' yacht is much larger, however the stability upside down also and the energy underneath the stability curve in that position is also considerable higher. See Fig. 11.

A performance comparison between the two designs is presented in Fig. 12 in which for two representative true wind speeds, i.e. 5 and 20 knots, the speed of the yachts is plotted on a basis of the true wind angle.

This figure clearly shows that the 'comparison' design is considerable faster upwind in the light airs and still a little bit in the stronger winds. Reaching in light air however hardly shows any difference between the two, but in stronger winds the 'future' design is almost one knot faster, as was to be expected! In running conditions however the difference between the two design alternatives diminishes again.

5. DIRECTIONAL STABILITY ASSESSMENT

Since there were some serious doubts about the positive directional stability of the bow rudder concept it 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.

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

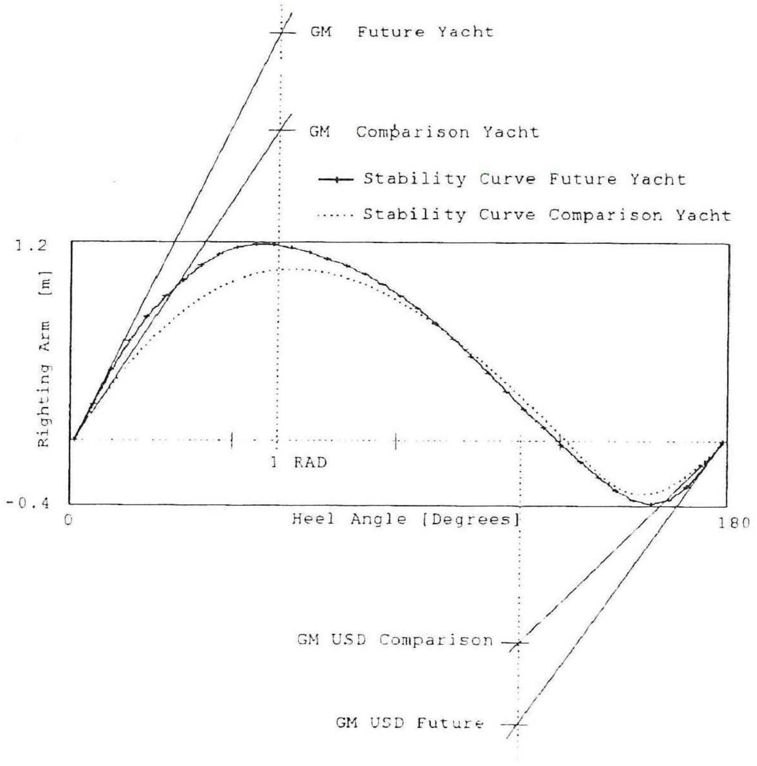

Fig. 11

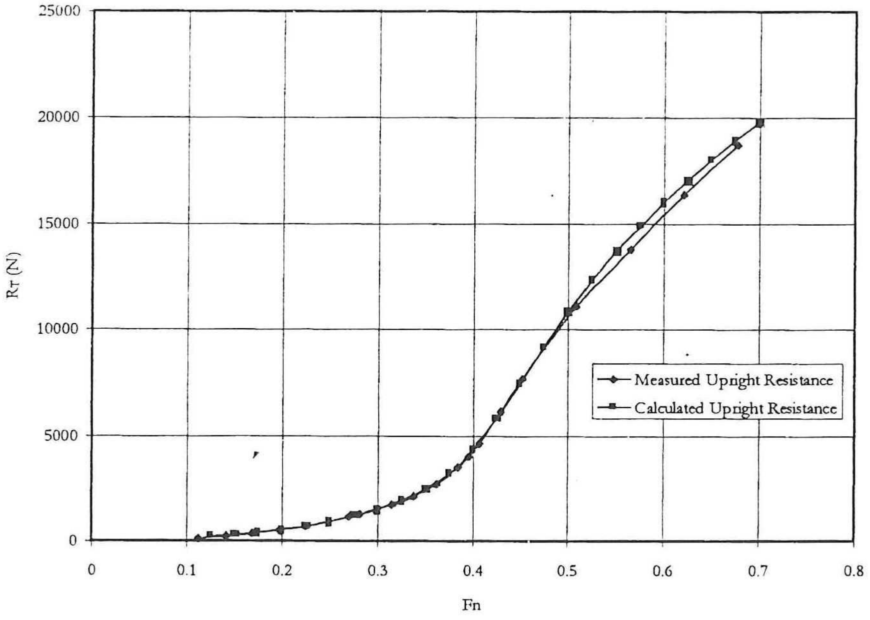

Fig. 12a: Upright Resistance of Future Yacht

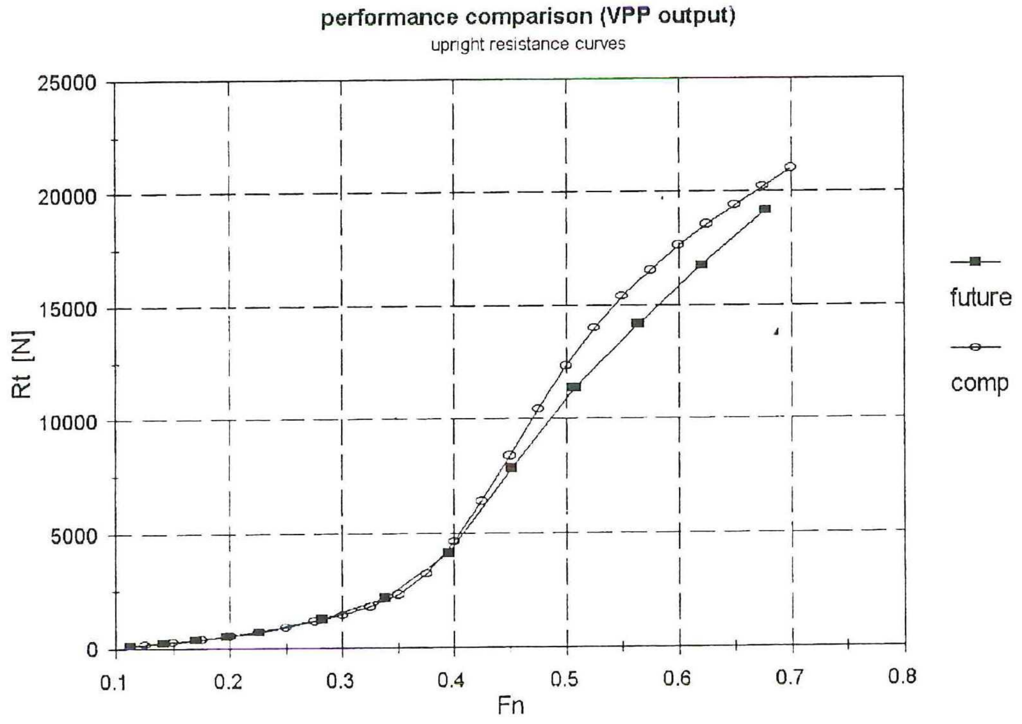

Fig. 12b

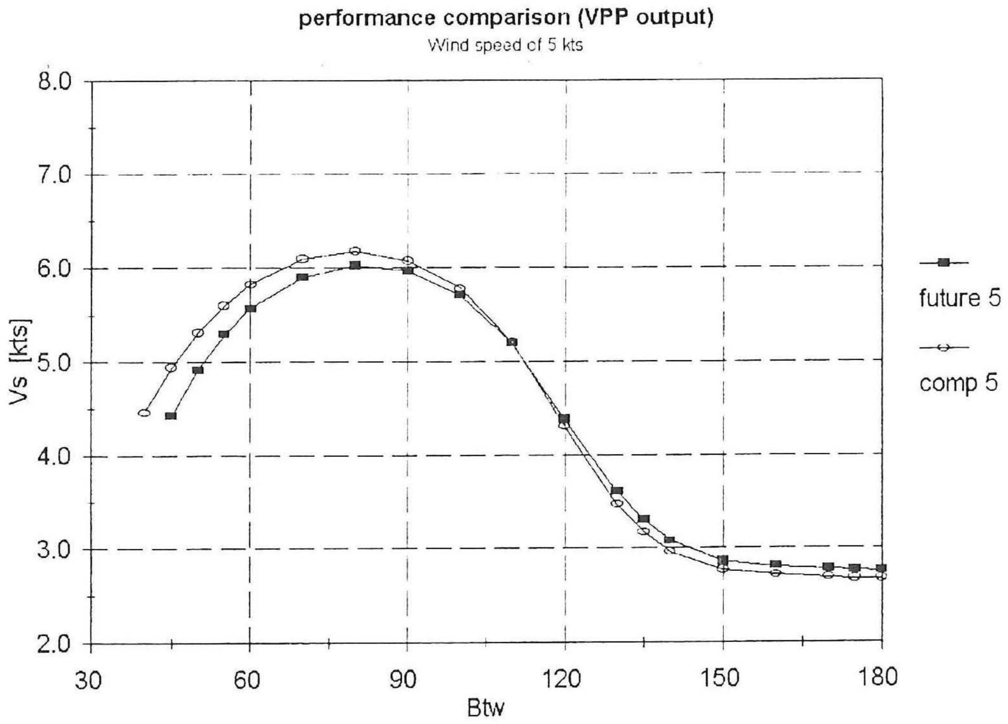

Fig. 13

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.

Twin Rudder Configuration

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

The results of these tests came out as was to be expected, knowing hat 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.

Bow Rudder Configuration

The tests with this appendage layout all ended unsuccessfully, 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 Fig. 15 for a typical path recording of such a test.

6. CONCLUSIONS

From the results from either the model experiments or the calculations as presented above it became clear that the 'future' yacht with a bow rudder configuration did not prove to be better than the same hull with a twin rudder configuration. The performance in terms of resistance and side force of the twin rudder configuration was roughly equal to the bow rudder version. The only exception was found in the upright resistance in which condition the bow rudder performed slightly better.

In addition the bow rudder arrangement showed an alarming lack of directional stability.

The application of the typical 'wide after body, flat section, fine forward, high GM' hull shape appears to be profitable in particular for broad reaching conditions and higher wind speeds. The performance is somewhat less in upwind conditions. Whether this justifies the application of such hull forms depends obviously strongly on the kind of application it is designed for in combination with the clients demands. For high performance or racing applications every speed increase is essential, for the cruising yachts it remains to be seen whether the inevitable trade-off between comfort and high speeds makes the application worthwhile.

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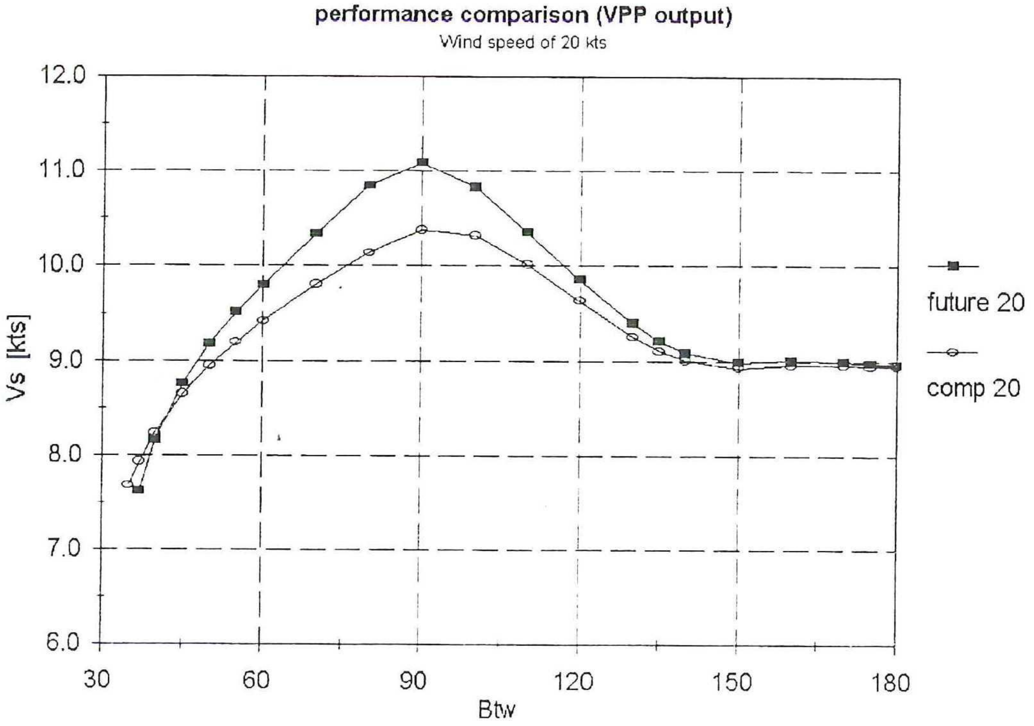
performance comparison (VPP output)
Wind speed of 20 kts
12.0
11.0
10.0
9.0
8.0
7.0
6.0
Vs [kts]
30
60
90
120
150
180
Btw
future 20
comp 20

Fig. 14

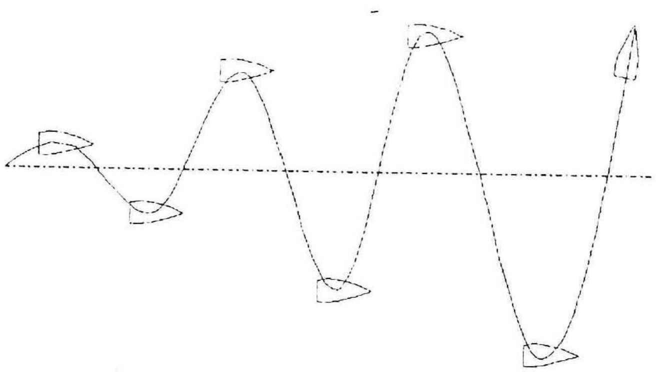

Fig. 15