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Keel – Rudder Interaction on a Sailing Yacht

by

J.A. Keuning, M. Katgert and K.J. Vermeulen

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19th International HISWA Symposium on Yacht Design and Yacht Construction

13 and 14 November 2006, Amsterdam, The Netherlands, Amsterdam RAI Convention Centre

19th International Symposium on “Yacht Design and Yacht Construction”

Amsterdam, 13 & 14 November 2006

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19th International HISWA Symposium on Yacht Design and Yacht Construction

13 and 14 November 2006, Amsterdam, The Netherlands, Amsterdam RAI Convention Centre

Program Monday November 13, 2006

Moderator: Jack Somer

08:30 – 10:00	Registration
10:00 – 10:30	Opening
10:30 – 11:00	Session 1: The "Axe Bow Concept": The shape of ships to come - Jaap Gelling
11:00 – 11:30	Coffee Break
11:30 – 12:00	Session 2: The Modern Super-yacht - James Roy
12:00 – 12:30	Session 3: Investigation of sustainable technologies for the design, construction, operation and decommissioning of recreational craft - Richard Birmingham and Melanie Landamore
12:30 – 14:30	Lunch Break
14:30 – 15:00	Session 4: An investigation of aerodynamic force modeling for IMS rule using wind tunnel techniques - Fabio Fossati
15:00 – 15:30	Session 5: The Carbon and PBO RIG for the „Sailovation“ – Finite Element Analysis - Guenter Grabe
15:30 – 16:00	Tea Break
16:00 – 16:30	Session 6: Interactions between Yacht-Crew Systems and Racing Scenarios combining behavioral models with VPPs - Ajit Sheno
16:30 – 17:00	Session 7: Does it pay to play with the construction? Comparative analysis of a sailing yacht performance due to the building materials - Balázs Hunyadi
17:00 – 17:30	Welcome Reception
18:00 – 18:15	Boarding to Symposium Dinner
18:30 – 21:00	Symposium Dinner at Restaurant d'Vijff Vlieghen in Amsterdam

19th International HISWA Symposium on Yacht Design and Yacht Construction

13 and 14 November 2006, Amsterdam, The Netherlands, Amsterdam RAI Convention Centre

Program Tuesday November 14, 2006

Moderator: Jack Somer

- | | |
|---------------|--|
| 08:30 – 09:00 | Registration |
| 09:00 – 09:30 | Session 8: Development of the structural requirements in the Volvo Open 70 rule version 2 - Ian Campbell |
| 09:30 – 10:00 | Session 9: An experimental study of the hydrodynamics of a yacht with a canting keel and forward rudder - Florent Maes |
| 10:00 – 10:30 | Coffee Break |
| 10:30 – 11:00 | Session 10: The influence of the shape of the keel on the forces on the rudder of a sailing yacht - Jan Alexander Keuning |
| 11:00 – 11:15 | Closing |

Introduction

Here for the 19th time in front of you lie the Proceedings of the International HISWA Symposium on Yacht Design and Construction.

The Organizing Committee is proud that the HISWA Symposium may be held now for the 19th time, meaning that it is the oldest and the longest existing symposium in this field on the world.

As such it has always drawn the attention of all who are active in the world of yachting and certainly contributed to the excellent the name of the Dutch designers and builders as leading in the field of Innovation, Research and Development.

It has also shown that, certainly during this period, the liaison between "the theory" and "the practice" in the Netherlands is very strong, apparent fruitful and quite alive. The short "lines" and the short "distances" between all kind of interesting industries, research institutes and technical highly developed parties makes the field in the Netherlands very interesting and very innovative. In this field the Symposium has always played an important role.

The partners that organize the Symposium, i.e. the HISWA Association, the METS Marine Equipment Trade Show and the Shiphidromechanics Department of the Delft University of Technology, all three find the symposium of strong interest for their constituencies: the industry, the trade, the research field and the education. For the third time now the Symposium is organized in cooperation with the Royal Institute of Naval Architects (RINA) of London, which strengthens it's role in the international arena.

To select the right topics of interest and to guard over the quality of the papers the Paper Committee has played an important role again. The members of this Committee perform their task out of the spotlights, but take it very seriously and they earn the full gratitude for their efforts by both the organizers and the delegates. There is a good mix of topics now with special interest to some new areas.

Finally I would like to express our gratitude to our sponsors: MARIN, FEADSHIP and GDNP. Without their support the Symposium would be difficult to organize. And in particular it would not be possible to ask for such a low fee for students. In addition to this by connecting their names to the Symposium they underline and appreciate its importance.

I hope you will enjoy the material supplied and the gathering at the symposium itself. I hope you will be able to meet a lot of interesting people, who are attending the symposium. This time and the times to come!

Jan Alexander Keuning
Chairman Symposium Organizing Committee

"Keel – Rudder Interaction on a Sailing Yacht"

by:

J. A. Keuning, M. Katgert and K. J. Vermeulen
Delft University of Technology, Shiphidromechanics Department

1 Introduction

In their earlier publications on "the yaw balance of sailing yachts" (Keuning and Vermeulen, Ref [1] 2003) and "the mathematical model for the maneuvering of a sailing yacht" (De Ridder, Keuning and Vermeulen, Ref [2] 2005) an assessment method has been presented for determining the force distribution in yaw and sway over the hull, keel and rudder. In Ref [1] it was used to deal with the yaw balance of a sailing yacht on a straight course and in Ref [2] the similar approach was used to determine the necessary forces and moments on a maneuvering sailing yacht.

In this assessment method use was made of what is called: the Extended Keel Method (EKM) as introduced by Gerritsma in 1971, Ref [3] for calculating the side force on the keel and rudder (and hull) of a sailing yacht.

This EKM yielded very good results for the total side force of the hull, keel and rudder together in the upright condition, indicating that the mayor part of the side force is produced by the appendages, in particular for boats with average to high aspect ratio keels and rudders. In assessing the yaw moment it turned out that the canoe body of the hull has a significant contribution not accounted for with the EKM. A modified approach to the correction method as introduced by Nomoto in 1975, Ref [4] yields good results for the yaw moment as well.

In the calculation procedure used for the yaw moment the side force of the keel and the side force on the rudder with their respective distances to the Center of Gravity play an important role. So the actual side force distribution between the keel and the rudder is of significant importance in assessing the yaw moment. This distribution however is strongly influenced by the underlying assumptions made in the EKM on the influence of the keel on the rudder. This influence makes itself felt through:

- a reduction in "free stream" velocity of the incoming fluid on the rudder (since it operates in the wake of the keel) and
- a reduction of the effective angle of attack on the rudder through the vorticity shed off by the keel caused by the lift generated on the keel, i.e. the down wash.

In order to account for the effect of the keel on the rudder a correction of the effective angle of attack on the rudder of 50% of the leeway angle was suggested by Gerritsma as well as a reduction of the velocity by 10%. Overall this yields a reduction of the side force on the rudder by some 60%. Other formulations as those formulated by S F Hoerner, Ref [5] have also been used.

It was felt however that some more information on the downwash angle was asked for. In particular more information on the influence of the aspect ratio of the keel and the rudder on this downwash was needed because Gerritsma's approach does not account for different aspect ratios.

So it was decided to carry out a series of dedicated experiments to determine the down wash angle of a series of different keels on one particular rudder. To be able to "blend" these results into a larger database it was decided to make use of one of the models of the Delft Systematic Keel Series (DSKS) as well as three of the keels used in that series. This procedure also allowed for the re-evaluation of the expressions presented in the past on keel residuary resistance and side force production of a sailing boat.

The results will be presented in this paper.

2 The approach

The approach that has been followed in the present study is as follows.

A sailing yacht model has been equipped with a keel and a rudder, which are both connected to the model by means of separate dynamometers. The rudder was connected in such a way that a positive and negative rudder angle could be applied. The model as a whole could be heeled, trimmed, heaved and yawed.

By taking measurements with a series of yaw (leeway) angles applied to the model the side force on the keel could be varied. At each yaw angle the rudder angle has been varied with 10 different rudder angles from 15 degrees to starboard till 15 degrees to port. This whole series of conditions has been repeated with 0 and 15 degrees of heel applied to the model. This procedure in the end has been repeated with all different keels.

By interpolation between the tests the rudder angle, at which the side force on the rudder is equal to zero has been determined and comparing this with the leeway angle of the model as a whole, the downwash angle on the rudder could be determined. It should be noted that this downwash angle is therefore the "averaged" downwash angle over the entire rudder span.

3 The Measurements

3.1 The model

The model which has been used for the measurements, is hull number # 366, which is a lower beam/draft ratio version of parent hull # 329, a 1992 vintage America's Cup class model. The lines plan of this hull is presented in figure 2.1.

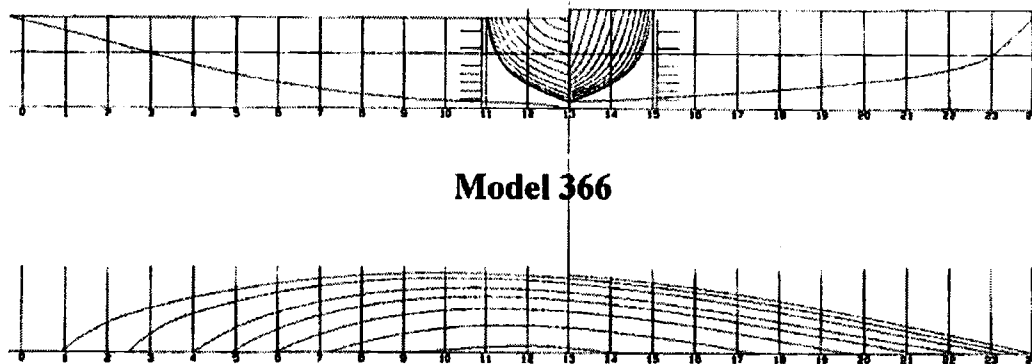


Figure 1: Lines plan of the model hull #366 used for the experiments

Four different keels have been used for this study, varying in aspect ratio and thickness/chord ratio. These keels are denoted #1, #3, #4 and #5. The principal dimensions are presented in Table 1 and the lateral views of the keels can be found in Figure 2. Furthermore one rudder, of which the principal dimensions are also presented in Table 1, has been used for the measurements.

			Keel 1	Keel 3	Keel 4	Keel 5	Rudder
Lateral Area	A_{lat}	[m ²]	0.086	0.086	0.086	0.086	0.066
Wetted Area	S	[m ²]	0.176	0.177	0.189	0.177	0.321
Aspect Ratio	AR	[-]	1.623	0.696	0.696	3.769	0.115
Span	b	[m]	0.374	0.245	0.245	0.57	0.321
Mean chord	c_{mean}	[m]	0.231	0.352	0.352	0.15125	0.115
Sweepback angle	Λ	[°]	9.85	14.42	14.42	3	18
Volume	\square_k	[m ³]	0.00155	0.0016	0.00305	0.000853	
Thickness/chord ratio	t/c	[-]	0.1	0.066	0.15	0.1	

Table 1: Main particulars of the various keels and the rudder

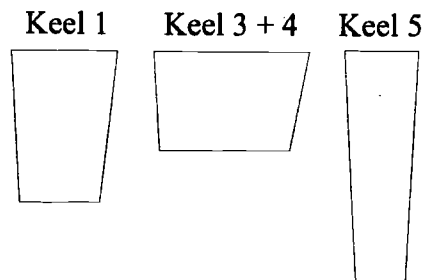


Figure 2: Lateral plan view of the four keels used in the experiment.

3.2 The Measurement Setup

The tests have been carried out in the #1 towing tank of the Delft Shiphydrodynamics Laboratory. This tank has a length of 145 meter, a width of 4.5 meter and a maximum attainable water depth of 2.5 meter. The model has been fitted to the towing carriage by means of the so called 'Hexamove'. This is a hydraulic activated system capable of controlling the positioning and movement of the model in 6 degrees of freedom. This system was used for the sake of absolute controllability of the model during the tests and it guaranteed that during each comparable test condition (with the different keels) the attitude of the model in the water with respect to sinkage, trim, heel and leeway was always exactly the same. For every run, the model was heeled and yawed as required. The sinkage and trim values were taken from earlier measurements carried out with the same model and were as reported by R. Meulemans, Ref [6] and B.J.B. Binkhorst, Ref [7].

The forces and moments on the hull, the keel and the rudder were measured by means of a set of five 6 DOF dynamometers: three fixed to the hull, one for the keel and one for the rudder. Keel and rudder were attached to their respective dynamometer in such a way, that all the forces and moments on these appendages were absorbed only by the dynamometer, and not by the hull.

During the tests the following quantities were measured:

- Forward speed of the model
- The position of the model in surge, sway, heave, roll, pitch and yaw
- The forces and moments in x, y and z-direction of the 5 pick-ups

The reference coordinate system is as shown in Figure 3, in which:

β = Leeway angle

φ = Heel angle

θ = Trim angle

δ = Rudder angle

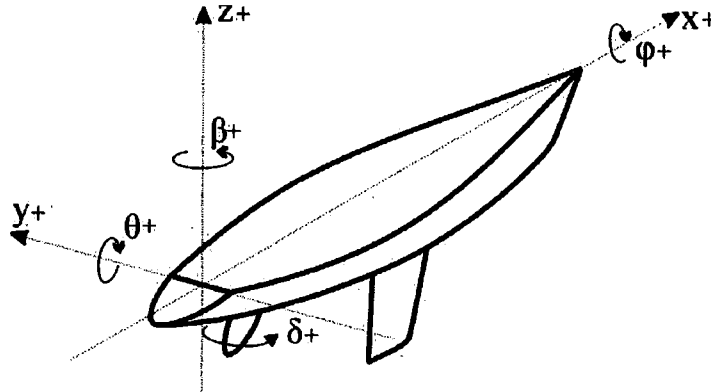


Figure 3: Coordinate system used during the experiments.

3.3 The Measurement Program

An identical series of tests (with respect to forward speed, rudder angle and leeway angle) has been carried out with the model equipped with each of the four different keels. The rudder was present in all tests.

A series of additional runs has also been carried out with the model without any keel but with only the rudder fitted. The tests have been carried out with the model both in the upright condition and in the heeled condition (15 degrees), as mentioned before. So the following tests were carried out:

- **Upright condition**
Used for the determination of the total resistance of the hull and four different keels in a large speed range. The residual resistance of the appendages has been determined in this upright condition in the speed range from $Fn. = 0.10$ up to $Fn. = 0.60$.
- **Leeway without rudder angle**
For three forward speeds ($Fn. = 0.27$, $= 0.35$ and $= 0.38$) and four leeway angles (-3° , $+3^\circ$, $+6^\circ$ and $+9^\circ$) tests have been carried out with heel $\varphi = 0^\circ$ and $\varphi = 15^\circ$ with a fixed rudder angle $\delta = 0^\circ$.
- **Leeway with varying rudder angle**
For one speed ($Fn. = 0.35$) and four leeway angles (-3° , $+3^\circ$, $+6^\circ$ and $+9^\circ$) tests have been carried out with rudder angles varying between $\delta = -15^\circ$ to $\delta = +15^\circ$ with heel angle $\varphi = 0^\circ$ and $\varphi = 15^\circ$.
- **Rudder performance**
To measure the rudder performance on its own without the presence of the keel, tests have been carried out without keel at one speed ($Fn. = 0.35$) with varying rudder angles between 5° and 20° .

3.4 The Elaboration Procedure

During the tests the model and the keels and rudder were fitted with carborundum strips for turbulence stimulation according to the standard procedure of the Delft Shiphydrodynamics Laboratory. On the hull three strips have been used which were 40 mm. wide. On the keel and rudder one single strip was placed at roughly 5% of the chord length from the leading edge of the profile. On the keel the strip was 30 mm and on the rudder 20 mm wide. The added resistance from these turbulence strips was corrected for by carrying out all upright resistance tests twice: once with half width of the strips and once with full width strips. The difference between these two measurements was used to determine the specific resistance of the turbulence strips. The model resistance was then calculated by subtracting the strip resistance from the measured total resistance.

4 The Results

4.1 Keel resistance

To determine the residual resistance of the appendages, the viscous resistance of the appendages has to be known. This is acquired by calculating the frictional resistance coefficient of both keel and rudder according to the ITTC '57 formulation and using the form factor of the appendages as expressed by the empirical formulations as given by Hoerner, Ref [5]:

$$(1+k)_{hoerner} = 1 + 2 \cdot \left(\frac{t}{c}\right) + 60 \cdot \left(\frac{t}{c}\right)^4$$

The added fin tip drag coefficient is calculated using the following expression:

$$C_{Dv, \text{fintip}} = 0.01875 \cdot \left(\frac{t}{c}\right)_{\text{tip}}^2$$

The residual resistance of the appendages is then acquired by subtracting these components from the total measured appendage resistance, i.e. :

$$R_{res} = (C_i - C_f \cdot (1+k) - C_{Dv, \text{fintip}}) \cdot \frac{1}{2} \rho V^2 S$$

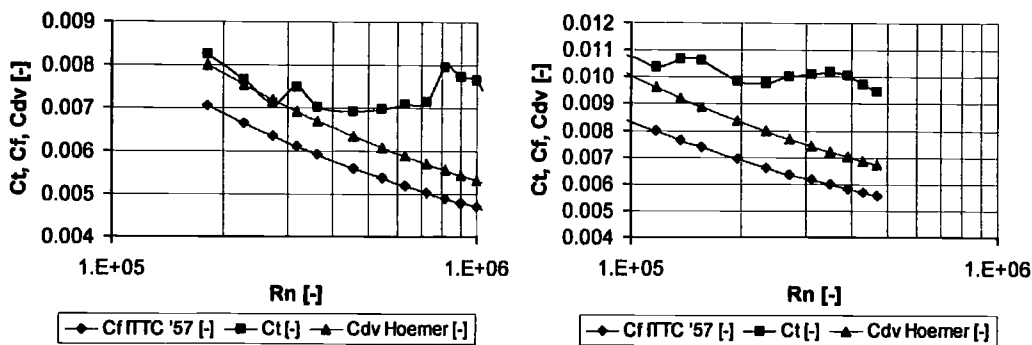


Figure 4: Resistance coefficients keel 3 (left) and keel 5 (right)

As an example of these resistance coefficients the results for keel 3 and 5 are presented in Figure 4. In this figure $C_{Dv\ Hoerner}$ is the added viscous drag of the fin tip together with the viscous drag of the keel, or:

$$C_{Dv\ Hoerner} = C_f \cdot (1 + k) + C_{Dv, \text{fin tip}}$$

Just as in the previous publications by Binkhorst, Ref [7], the existence of a residuary resistance component in the upright keel (appendage) resistance is evident from these results. It shows in the plots as an abrupt (upwards) deviation of the total resistance coefficient of the appendage from the viscous coefficients with increasing forward speed. This trend proved to be true for all the four different keels tested, albeit to different extents.

The measured total resistance of the keels is used to determine the residual resistance of the appendages. The research carried out by B. J. Binkhorst, Ref [7], showed a clear relationship between the distance of the vertical center of buoyancy of the keel volume from the free surface (Z_{cbk}) and the magnitude of this residual resistance of the keel. A larger distance from the free surface yields a higher residual resistance. The current measurement data has been used to further check and verify this trend.

In Figure 5 the results for all 4 keels are presented of this "specific residual resistance" versus the "relative depth of the center of buoyancy of the keel volume". The aforementioned trend as formulated by Binkhorst in Ref [7] is clearly also present in the present measurements, i.e. the residuary resistance increases with increasing separation between the center of buoyancy of the keel volume to the free surface. The increase however appears to be less pronounced for the larger distances.

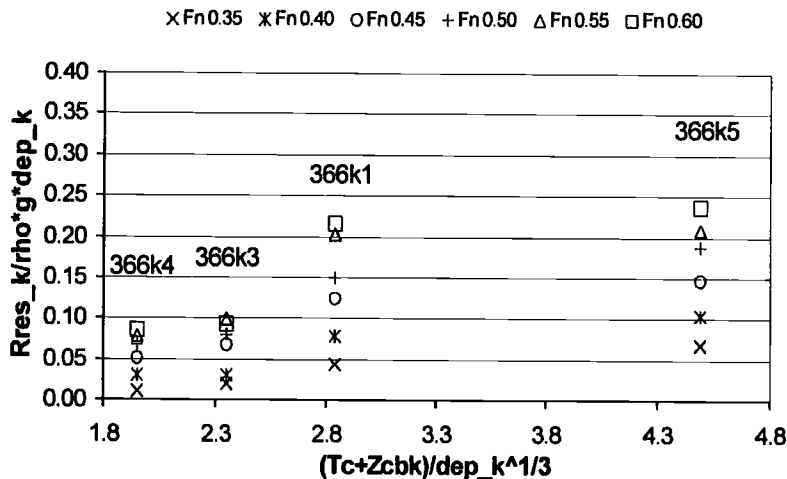


Figure 5: Residuary Resistance of the keels as function of immersed volume depth

4.2 The Rudder Resistance and “Keel Wake” or “Velocity Reduction Factor”

The resistance data of the rudder has been used to calculate the residual resistance of the rudder as with the keels. In addition to this, the measured data has been used to assess the free flow velocity reduction over the rudder.

Gerritsma, Ref [3], measured this reduction of the free flow velocity in the rudder plane due to the presence of the keel in the zero leeway and upright condition. He found a ‘free flow velocity reduction’ of some 10% when compared with the undisturbed free flow velocity. With the present measured data these values may now be verified.

Both the resistance of the rudder in free flow without the presence of the keel in front of it and the resistance of the rudder in the wake of all the four different keels has been measured. By relating the resistance measured behind a keel to the resistance of the rudder measured with no keel present a “change” in resistance could be determined. This “change” has to be attributed to the influence of the wake of the keel on the rudder.

In Figure 6 this “change in the measured rudder resistance” in the upright condition without leeway due to the presence of the keel in front of it is presented for all four different keels.

Although some scatter exists it appears that in general a fraction of $\frac{Rr_{wake}}{Rr_{free}} \approx 0.9$ may be found.

This implies a free flow velocity reduction fraction $\frac{V_{wake}}{V_0} \approx 0.95$, assuming that the rudder

residual resistance has been subtracted and the viscous resistance, by nature, is grossly dependent on the flow velocity squared. If considered in more detail however there appears to be a significant forward speed influence with a peak in the Froude numbers which come close to the so called “hull speed”. This may imply that other effects such as wave generation may also play a role.

However, when the boat has a small leeway angle this “change” in resistance or resistance reduction (and thus the velocity reduction) becomes much smaller or even almost zero. This may be seen from the results as presented in Figure 7 in which the same fraction as in Figure 6 is presented but now with the boat yawed from 3 to 9 degrees. For the larger leeway angles the reduction fraction becomes very close to 1.0.

This implies that in normal sailing conditions the flow velocity over the rudder will not be influenced too much by the presence of the keel.

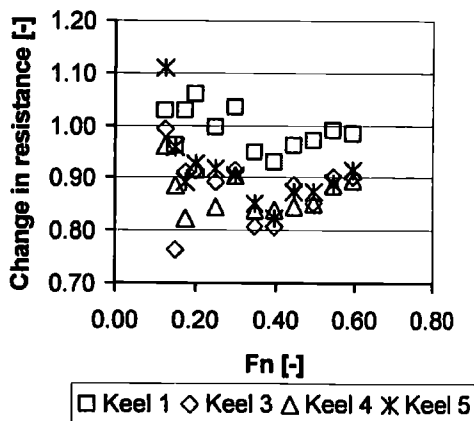


Figure 6: Change in rudder resistance in the upright condition without leeway angle

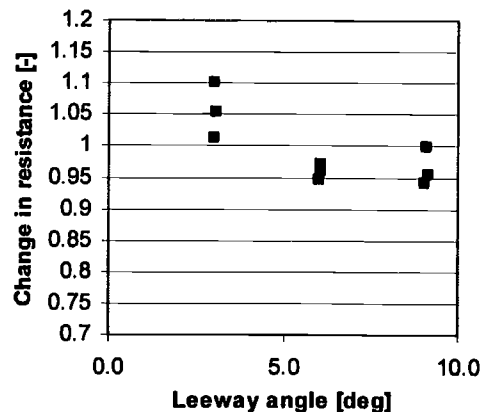


Figure 7: Change in rudder resistance in the upright condition for keel 3 with leeway angle

4.3 The Downwash Angle or Rudder Lift

The keel has another effect on the performance of the rudder as well: the downwash. Keel downwash will cause a change in the effective angle of attack of the rudder. The magnitude of this downwash has been determined by the procedure described in the "approach chapter": i.e. tests have been carried out with the hull in yawed condition, while the rudder angle has been varied. The lift generated by the rudder can then be plotted against the rudder angle δ . The difference between the leeway angle β and the rudder angle at which rudder lift becomes zero δ_0 maybe considered to be equal to the averaged downwash angle Φ . In formula (see Figure 8):

$$\Phi = \beta + \delta_0$$

In Figure 9 the lift curve of the rudder as function of the rudder angle when placed behind the keel, in this figure it is keel #1, is presented for various leeway angles.

This procedure has been applied for all four keels and for both the upright and the heeled condition applied during the tests. For all four keels the downwash angle has been determined.

The resulting downwash angles as a function of the leeway angle and thus of the loading on the keels, are depicted for the four different keel in Figure 10 and Figure 11.

The influence of the aspect ratio of the keel on the downwash on the rudder is obvious from these results. The higher aspect ratio keels, i.e. #1 and #5, produce the least downwash. In general the assumption that the downwash is half the leeway seems only valid for the lower aspect ratio keels, i.e. the keels #3 and #4. What is also evident from these results is that the absolute magnitude of the downwash angle related to the leeway angle on the keel diminishes with increasing leeway angle. This may be due to the fact that at the higher leeway angles the flow is relatively more diverted past the rudder in those conditions. It should be remembered that the separation between the keels and the rudder on this particular model is reasonably large for all the keels tested. It would therefore be of interest to gather some additional experimental results from lower aspect keels and smaller keel-rudder separations also.

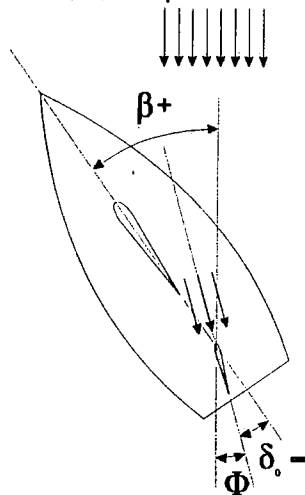


Figure 8: Determination of the downwash angle Φ

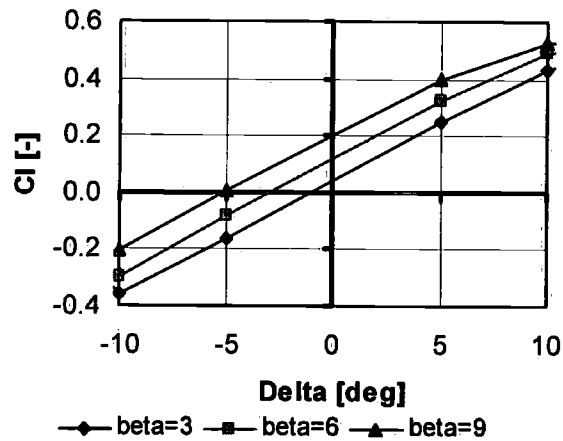


Figure 9: Lift curve of the rudder behind keel #1 for various leeway angles at heel = 0°

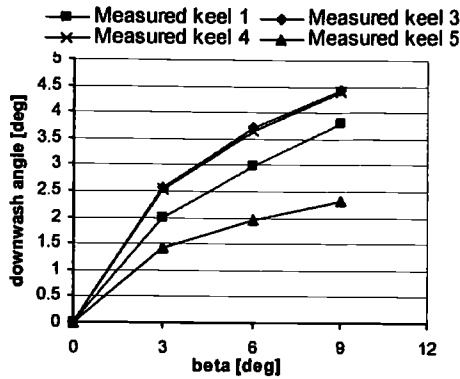


Figure 10: Downwash angle versus leeway angle for heel = 0°

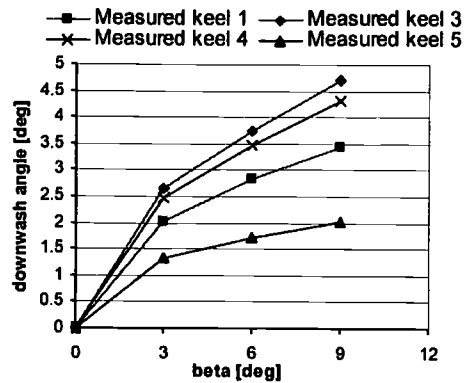


Figure 11: Downwash angle versus leeway angle for heel = 15°

4.4 The Free Flow Velocity Reduction over the Rudder Due to the Hull Presence

The measured lift on the rudder has been compared with the available theoretical predictions for the lift. To this aim use has been made of the well known formulations as presented by Whicker and Fehner, Ref [8] for the lift curve slope, i.e.:

$$\frac{dC_L}{d\beta} = \frac{5.7 \cdot ARe}{1.8 + \cos \Lambda \sqrt{\frac{ARe^2}{\cos^4 \Lambda} + 4}}$$

in which:

$\frac{dC_L}{d\beta}$ = Lift curve slope

ARe = Effective Aspect Ratio = 2 * Geometric Aspect Ratio for the keel and rudder

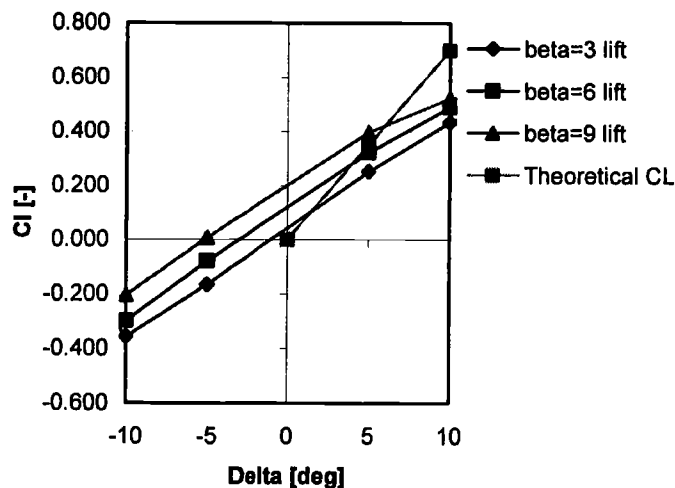


Figure 12: Theoretical lift coefficient curve of the rudder versus the measured one

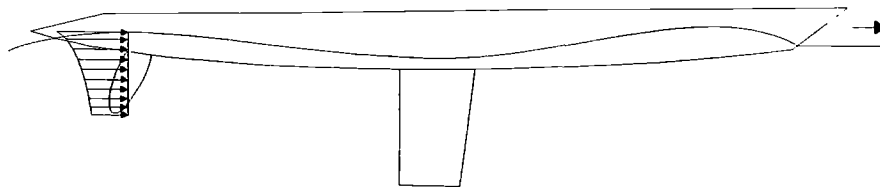


Figure 13: Wave generated velocity component near rudder

In Figure 12 the theoretical derived lift coefficient of the rudder is presented together with the lift coefficients as derived from the measured lift results. There is an apparent deviation between these lift coefficients. A possible explanation for this difference may be found in the difference between the supposed water flow velocity in the rudder plane (as used to calculate the measured lift coefficient) and the actual flow velocity. If this difference really exists, this supposed water velocity appears to be taken too high.

Different from the earlier analysis about the free flow reduction factor this speed difference can not be caused by the wake of the keel. This is so because the results of the lift on the rudder are compared in absence of the keel. The only constant factor in all these measurements on the rudder forces (both with and without the keel present) is the presence of the hull. So the difference should originate from the hull's presence. This leads to the wave system generated by the hull. The orbital velocity of the stern wave generated by the hull generates a velocity component opposite to the boat's forward direction and leads to a reduction of the free flow velocity also. If the properties of this bow wave are known, this velocity component could be calculated using regular deep water wave theory to assess the validity of this assumption.

Using the results as obtained by K. Audenaert in the framework of his master's thesis research, the wave height at the required speed is known; in addition the wave crest is visually confirmed to be at the rudder position. The wave length follows from the boat speed.

For the horizontal orbital velocity in the wave crest the formulation is:

$$u = \zeta \frac{g}{c} e^{kz}$$

in which:	ζ	=	wave amplitude
	g	=	9,81 m/s ²
	c	=	wave speed (here equal to the boat speed)
	k	=	wave number = $\frac{2\pi}{\lambda}$
	λ	=	wave length
	z	=	distance from (below) the free surface

Calculating this horizontal velocity for the tip and the root of the rudder and subsequently integrating this velocity over the depth (span) of the rudder yields a mean velocity reduction in the rudder plane of some 20%. The reduction of the velocity required to fit the measured lift curve slope to the theoretical lift curve slope is 22%.

The orbital velocity in the stern wave may therefore very well be the cause of the decrease in rudder performance. It should be noticed that this velocity reduction determined for these calculations is only valid for this particular hull.

5 Downwash formulations

Hoerner, Ref [5] presented a formulation for the angle of downwash behind an arbitrary wing:

$$\Phi = \frac{1.6 \cdot C_L}{\pi \cdot A Re_k}$$

This formulation has been compared with the present measurements. This comparison is presented in Figure 14. This comparison revealed a significant difference between measured and calculated values.

Regression analysis of the new data as presented in the Figures 10 and 11 has therefore been applied to yield new formulations for the downwash angle for an arbitrary keel. Important parameters for the magnitude of this downwash angle are the lift coefficient and the aspect ratio of the keel. Another variable which has been assessed also in the present measurements is the thickness/chord length ratio of sections of the keel. This variable however also makes itself felt in the loading or the lift coefficient of the keel so it has been implicitly incorporated in the formulation.

The following formulation for the total downwash angle yielded the best fit through the available data:

$$\Phi = a_0 \cdot \sqrt{\frac{C_{Lk}}{A Re_k}}$$

with:

φ	0 °	15 °
a_0	0.136	0.137

The fit of this regression formulation through the original measured data is presented in the Figure 15 and 16.

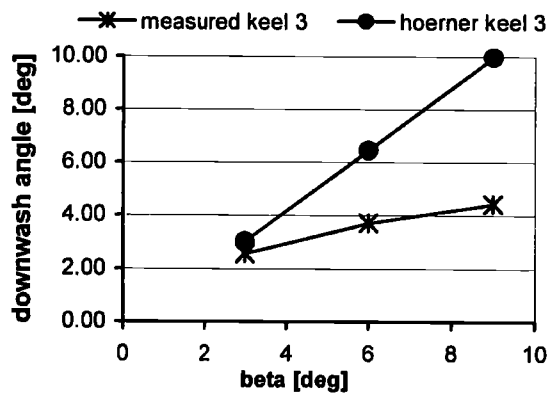


Figure 14: Downwash angle for keel #3 measured and calculated with Hoerner

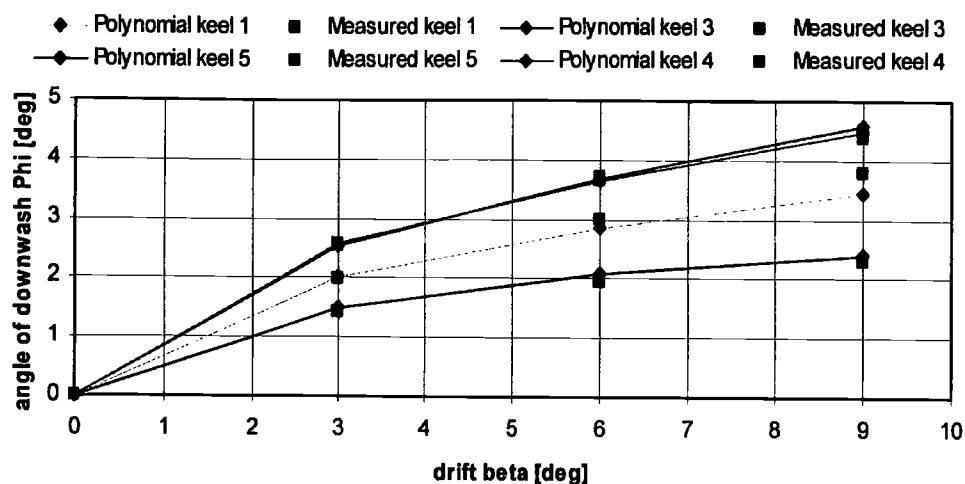


Figure 15: Downwash angle measured and approximated at heeling angle $\phi = 0^\circ$

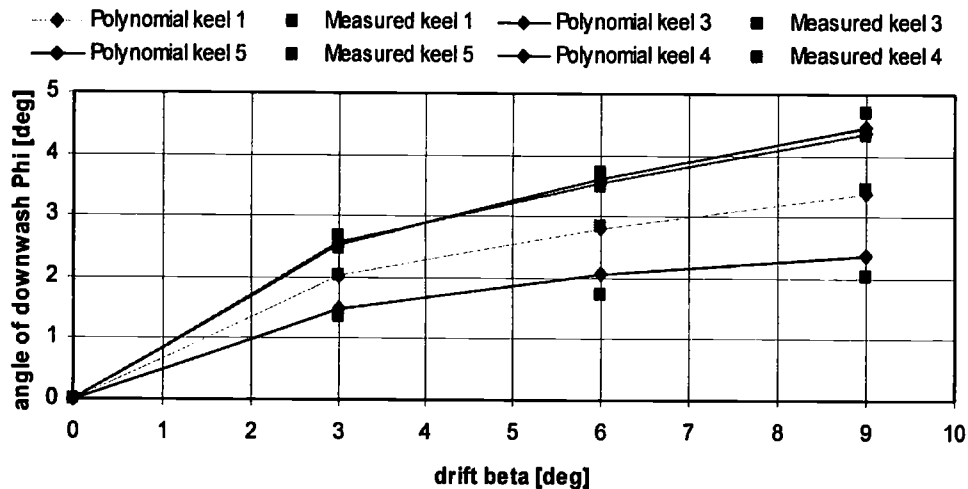


Figure 16: Downwash angle measured and approximated at heeling angle $\phi = 15^\circ$

6 Side force production

The side force measurements carried out within the scope of the present study on a wide variety of keels made it possible to re-assess the polynomial expression formulated with the DSYHS results on the side force production of a sailing yacht upright. The polynomial for the heeled side force is still under scrutiny because the heeling angles used in the DSYHS and the earlier DSKS tests were different. It was known from comparison with measured data that this expression lacked sufficient accuracy for keels with high aspect ratios.

This formulation is also of importance for the assessment of the yaw balance. For the yaw balance the distribution of the side force over the keel and rudder is determined using a procedure as described in Ref [1] making use of both the polynomial expression for the side force as of the EKM. In the maneuvering model of a sailing yacht (as presented by Keuning, Vermeulen and De Ridder, Ref [2]) use is also being made of this polynomial expression. So improvement on any flaws in this expression would mean a significant benefit in many applications.

The previous expression was derived for the side force production for the hull, keel and rudder together and based on the results of the DSYHS and the Delft Systematic Keel Series (DSKS). But the results within the DSKS were only used as available at that time. This implies that no really high aspect ratio results were present in the data base used for the regression. The formulation was presented in various publications about the Delft Systematic Yacht Hull Series (DSYHS), by amongst others by Gerritsma, Keuning and Onnink in 1993, Ref [10] and by Keuning and Sonnenberg in 1998, Ref [11].

Due to the fact that the polynomial expression is based on measurement data from mainly the standard keel used within the DSYHS and a limited number of different keels at that time available within the DSKS, the lower aspect ratio keels dominate the data base.

With the current set of measurement data on higher aspect ratio keels the data base is significantly extended and a new regression using the same polynomial expression for the side force production at zero heeling angle can be carried out now.

The original polynomial expression reads:

$$\frac{Fh \cdot \cos(\varphi)}{\beta \cdot \frac{1}{2} \cdot \rho V^2 S_c} = b_1 \cdot \frac{T^2}{S_c} + b_2 \cdot \left(\frac{T^2}{S_c}\right)^2 + b_3 \cdot \frac{T_c}{T} + b_4 \cdot \frac{T_c}{T} \cdot \frac{T^2}{S_c}$$

In which:

- Fh = Side force [N]
- φ = Heel [rad]
- β = Leeway [rad]
- T = Total draft [m]
- S_c = Wetted surface canoe body [m²]
- T_c = Draft canoe body [m]

The coefficients for this polynomial have now been recalculated based on original DSYHS measurements augmented with the results of the extended DSKS obtained from the present measurements. The new coefficients for the polynomial for side force production at zero heeling angle are presented in Table 2:

φ	0°
b_1	3.213
b_2	-3.462
b_3	0.438
b_4	-2.790

Table 2: New coefficients for the side force polynomial

In figure 17 and figure 18 a comparison of the polynomial using both the old and the new coefficients versus the measured values for keel 1 and 5 are presented.

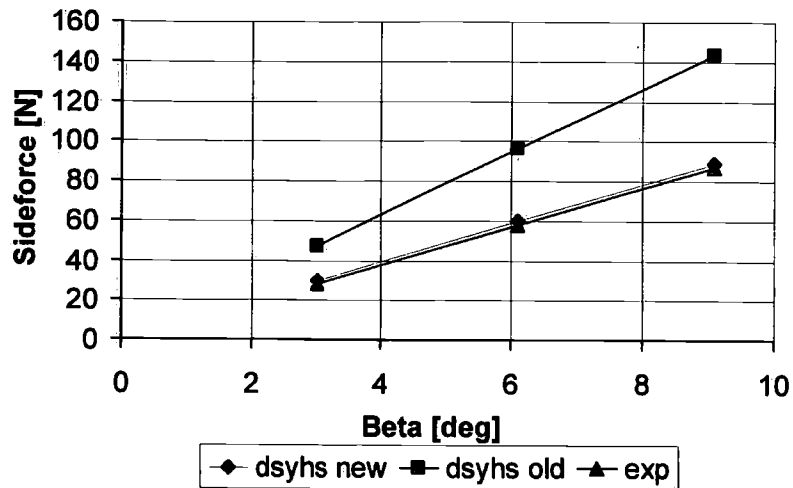


Figure 17: Comparison of old and new polynomial versus experiments for keel 1

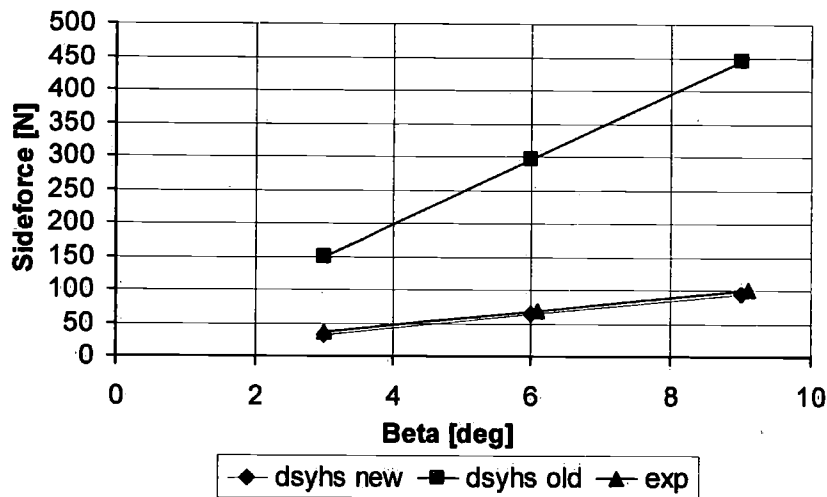


Figure 18: Comparison of old and new polynomial versus experiments for keel 5

7 Conclusions

Based on the results of the present study the following conclusions may be drawn:

- The aspect ratio of the keel has a significant influence on the downwash angle as experienced by the rudder.
- The downwash angle on the rudder does not increase linearly with the loading (C_L) on the keel but it depends also on the leeway angle. This is probably due to the change in the keel-rudder positioning with respect to each other with increasing leeway.
- A better formulation than the one presented by Hoerner for the downwash angle behind a keel with variable aspect ratio and leeway angle has been found which takes these effects into account. This should make the assessment of the yaw balance more reliable.
- On a straight course and without leeway the resistance of the rudder is influenced by the wake of the keel and the wave forming around the stern of the ship.
- At present in the DSYHS results the change in the rudder resistance between the upright condition with no leeway and the heeled and yawed condition is assessed as "induced resistance" although from this study that is not entirely correct.
- New regression through an extended data base yields a better fit of the polynomial expression for the side force production of a sailing yacht in the upright condition with the measured data for high aspect ratio keels. This is of importance when dealing with the yaw balance of a sailing yacht.

Recommendations:

- Similar tests as described in the present report should be carried out with low aspect ratio keels and should include variable keel-rudder separation.
- The tests should be repeated with more heeling angles to suit the DSKS data base.

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