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A new method for the prediction of the side force on keel and rudder of a sailing yacht based on the results of the Delft Systematic Yacht Hull Series

by

J.A. Keuning and B. Verwerft

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THE 19th CHESAPEAKE SAILING YACHT SYMPOSIUM

ANNAPOLIS, MARYLAND, MARCH 2009

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A new Method for the Prediction of the Side Force on Keel and Rudder of a Sailing Yacht based on the Results of the Delft Systematic Yacht Hull Series

by:

J. A. Keuning and B. Verwerft

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Abstract

Since the first introduction of an expression for the assessment of the side force production of a sailing yacht as function of leeway and heel, based on the results of the Delft Systematic Yacht Hull Series, in 1981, considerable changes in appendage layouts and planforms have taken place. The side force production as function of the leeway and heel played only a very limited role in the present VPP calculations and remained therefore for many years somewhat undervalued. The last years more attention has been paid to the subject in particular caused by the necessity to asses the yaw balance of (large) sailing yachts and the introduction of maneuvering models for yachts under sail. This report shows the developments and presents a new assessment model which yields far better results for a large variety of appendages. The results of this study are presented in the present paper.

List of symbols

A_{lat}	=	Lateral area
AR	=	Aspect ratio
ARe	=	Effective aspect ratio
b	=	Span of the foil
B_{wl}	=	Waterline beam
c	=	Chord of the foil
c_t	=	Tip chord of the foil
c_r	=	Root chord of the foil
c_{hull}	=	Hull influence coefficient
c_{heel}	=	Heel influence coefficient
C_L	=	Lift coefficient
Fh	=	Side force
Fn	=	Froude Number
q	=	Dynamic pressure
T	=	Total draft
Sc	=	Wetted surface canoe body
Tc	=	Draft canoe body
Vs	=	Speed yacht through the water
α	=	angle of attack
β	=	leeway angle
β_0	=	zero lift drift angle
δ_r	=	rudder angle
Φ	=	down wash angle
Λ	=	sweep back angle of the foil
φ	=	heel angle
ψ	=	yaw angle
ρ	=	Water density

1 Introduction

In the original model as presented by Gerritsma e.a. in 1981 Ref [1], the total side force of the hull and appendages and the separate contributions to this side force originating from the hull, the keel and the rudder, were assessed differently in the upright and the heeled condition.

In the upright condition the so called Extended Keel Method, as formulated by Gerritsma Ref [1], is used to calculate the side force on keel and rudder. The side force generated by the hull is accounted for by the virtually extension of the keel and the rudder inside the canoe body up to the waterline. This is depicted in Figure 1. The downwash angle from the keel on the rudder is approximated as 50% of the leeway angle and the water velocity over the rudder reduced by 10% to account for the wake of the keel.

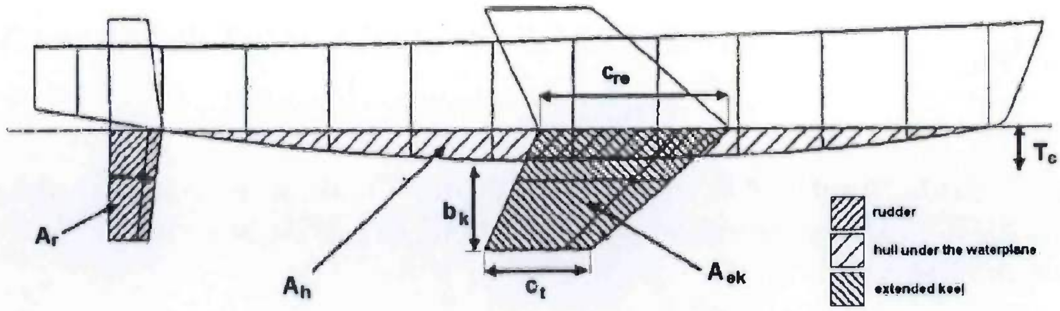

Figure 1: Definitions in the Extended Keel Method

The total side force is calculated as the sum of the force on extended keel and rudder according to:

$$Y_{total} = Y_{ek} + Y_r$$

$$Y_{ek} = 0.5\rho Vs^2 A_{ek}\left(\left(\frac{\partial C_L}{\partial \alpha}\right)_{ek}\beta\right)$$

$$Y_r = 0.5\rho(0.9Vs)^2 A_r\left(\left(\frac{\partial C_L}{\partial \alpha}\right)_r 0.5\beta\right)$$

In which:

Y_{total}	= Total side force
Y_{ek}	= Side force generated by extended keel
Y_r	= Side force generated by rudder
A_r	= Lateral area of rudder
A_h	= Lateral area of hull
A_{ek}	= Lateral area of extended keel
β	= Leeway Angle

The lift curve slope is calculated using the well known formula of Whicker and Fehlner (Ref [2]):

$$\frac{dCl}{d\alpha} = \frac{5.7\text{ARe}}{1.8 + \cos\Lambda\sqrt{\frac{\text{ARe}^2}{\cos^4\Lambda} + 4}}$$

The effective aspect ratio of keel is determined by:

$$\text{ARe} = \frac{2(bk + Tc)}{\left[\frac{c_{re} + c_t}{2}\right]}$$

In which:

Cl	= Lift coefficient
α	= Angle of attack
Λ	= Sweep back angle quarter chord line
ARe	= Effective aspect ratio of foil
bk	= Span of keel
Tc	= Draft of canoe body
c_{re}	= Root chord of extended keel
c_t	= Tip chord of keel

The full yaw moment in this upright condition was now calculated using the side force on keel and rudder with their respective separations to the centre of gravity of the ship.

In general this procedure yields good result for the total side force production with moderate aspect ratio keels. For very low aspect ratio keels the procedure did not work properly, in particular when situated under high draft hulls. Also the yaw moment was not predicted satisfactory.

Under heel this EKM procedure did not work properly. Therefore in these heeled conditions a side force polynomial was derived using the results of the Series 1 of the DSYHS by Gerritsma e.a. in 1981, Ref [1]. Later in 1998 the applicability of this expression was extended by calculating new coefficients using the results of Series1, 2, 3 and 4 (some 50 models) by Keuning and Sonnenberg Ref [3]. The polynomial expression that was formulated accounts for the effects of the heel angle and forward speed on the total side force production of hull, keel and rudder and uses as parameters amongst others the relation between the hull depth and the keel span. Particular parameters related to the geometry of the keel and rudder lack in the expression. This lack of possible input results from the fact that, within the DSYHS for all models one keel and one rudder was used. This implies that the formulation presented is aimed more at defining the influence of different hulls geometries on the keel performance than that different keel and rudder planforms can be taken into account.

The formulation reads:

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

$$+ b_4 \cdot \frac{T_c}{T} \cdot \frac{T^2}{S_c}) \cdot \tfrac{1}{2} \rho V^2 S_c \left(\beta - \beta_{Fh=0}\right)$$

$$\beta_{Fh=0} = B_3 \varphi^2 Fn$$

In which:

$Fh\cos(\varphi)$ = Side force in the horizontal plane [N]
φ = Heel [rad]
β = Leeway [rad]
$\beta_{Fh=0}$ = Zero side force leeway angle [rad]
T = Total draft [m]
S_c = Wetted surface canoe body [m^2]
T_c = Draft canoe body [m]

The coefficients b_1 to b_4 were derived by regression analysis through the results of the DSYHS database and they are presented in a matrix as functions of the heeling angle 0, 10, 20 and 30 degrees of heel.

The results of this assessment formula worked well for hulls and appendages not too much deviating from the layout and plan form as used in the DSYHS models series. For instance the results obtained for high aspect and short chord keels did not match well with available experimental data.

The use of this expression yields also no information on the contribution of the three different components separately, i.e. the lift on the hull, the keel and the rudder and therefore no result for the yaw moment can be found.

To overcome this problem and to facilitate the calculation of the yaw moment in realistic sailing conditions Keuning and Vermeulen, Ref [5], made the assumption that the distribution of the total side force over keel and rudder, as it is found in the upright condition using the EKM, could be used in the heeled condition also. The total side force is considered to originate from the side force on the keel and the rudder, including lift carry over. This corresponds with the findings that a bare hull rarely generates any significant side force when heeled and yawed. To calculate the yaw moment on the hull, both upright and heeled, they formulated the modified "Munk moment" on the hull, which is calculated taking the geometry of the heeled hull in account and they introduced an additional yaw moment under heel at zero leeway angle. This procedure is described in Ref [5]. This whole procedure yields good results for the side force and yaw balance on a sailing yacht hull but is considered less elegant due to the different approaches used upright and heeled.

In 2007 Keuning, Katgert and Vermeulen Ref [6] further improved the prediction of the side force production for higher aspect ratio keels and the associated yaw moment under heel by introducing a new expression for the influence of the downwash of the keel on the rudder into the calculations. In the older assessment methods still assumption of the 50% reduction of the leeway angle was used for the determination of the effective angle of attack on the rudder. The new formulation for the downwash angle is dependent on the keel circulation and the aspect ratio of the keel and reads:

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

with:

φ	0 °	15 °
a_0	0.136	0.137

In which:

Φ = Downwash angle at rudder
C_{Lk} = Lift coefficient of keel
ARe_k = Effective aspect ratio of keel

This improved the calculations significantly for keels different from the DSYHS keel. It should be noted however that the distance between the rudder and the keel is still not taken in account.

2 The approach

This situation of using two different approaches, i.e. one for the upright condition and one for the heeled condition, was considered both undesirable and inconsistent. Also the fact that the regression formulas were only applicable for appendages no to remote in design from those used in the DSYHS was considered undesirable. So a new method has been developed.

In this new method the side force generated by keel and rudder is calculated using as a basis the well known expression for the lift on a foil, i.e.:

$$L = 0.5 \cdot \rho \cdot v^2 \cdot A \cdot C_L \quad \text{and} \quad C_L = \frac{dC_L}{d\alpha} \cdot \alpha$$

By using this expression the actual area of the keel and rudder is now taken in account.

For the lift curve slope the formulation is used as derived by Whicker and Fehlner (W&F) for a thin airfoil see Ref [2]. This expression reads:

$$\frac{dCl}{d\alpha} = \frac{5.7\text{ARe}}{1.8 + \cos\Lambda\sqrt{\frac{\text{ARe}^2}{\cos^4\Lambda} + 4}}$$

In the present calculation the foils are not extended to the free surface, but the foil area is taken as their actual geometrical size.

The effect of the hull on the side force generation is formulated separately.

First the generally supposed end plate effect of the hull on the keel is taken into account by taking for the effective aspect ratio of the wing two times the value of the geometrical aspect ratio of the wing, according to:

$$\text{ARe} = 2AR_{geo} = 2\frac{b}{c_{mean}}$$

In which:

ARe = Effective aspect ratio of foil
AR_{geo} = Geometric aspect ratio of foil
b = Span of foil
c_{mean} = Mean geometric chord

Secondly it is known that this is not the only effect of the hull on the side force production of the appendages. There is also the so called "lift carry over" from the keel to the hull. From earlier measurements it was already found that the lift generated by the bare hull of a sailing yacht with leeway and heeling angle is generally quite small Therefore the main effect of the mutual interaction between keel and hull must be in this "lift carry over" from the keel to the hull.

In an attempt to capture this lift carry over the ratio between the entire lift of the appended hull and the lift generated by the keel and rudder separately, as calculated by using the expression above, is determined for the entire DSYHS. This ratio between the two lift sums is further referred to as the "hull influence coefficient" chull i.e.:

$$c_{hull} = \frac{L_t}{(L_k + L_r)}$$

In which:

c_{hull} = Hull Influence coefficient
L_t = Total hydrodynamic lift of the yacht
L_k = Lift generated by the keel
L_r = Lift generated by the rudder

This c_{hull} is now determined for the hulls of the DSYHS in the upright condition first. As stated before the results of the DSYHS yield a good impression of the influence of the hull parameters on the combined hull and keel side force production. The result of the determination of the c_{hull} is depicted in Figure 1

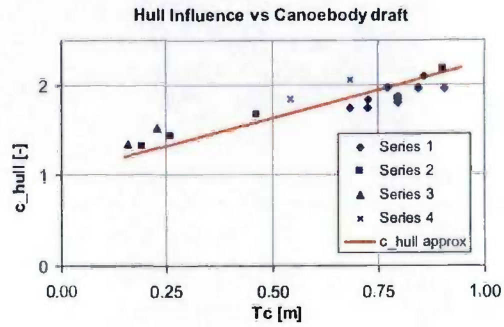

Figure 1: Hull influence coefficient for standard DSYHS appendages

As may be seen from this plot there is a strong linear relationship between this lift carry over and the canoe body draft for all four Series with different parent hull forms within the DSYHS using this approach.

Based on these results the following expression has been formulated for the keels and hulls in the DSYHS:

$$c_{hull} = a_0 Tc + 1 \quad \text{with: } a_0 = 1.25$$

To extend the range of application of this expression to keels with quite different plan forms (i.e. aspect ratios) the results of two other research projects are used, i.e. the Delft Various Keel Series (DVKS), in which quite a few different keels have been tested underneath one particular model, and the Delft Systematic Keel Series (DSKS), in which a series of modern keels has been tested underneath two similar models with different Beam to Draft (B/T) ratio. These tests have been previously described by Keuning and Binkhorst in Ref [4] and Keuning and Sonnenberg in Ref [3].

When these data are incorporated in the analysis of the lift carry over in the upright condition the following relation has been found and the following formulation for the hull influence coefficient in the upright condition can be found (Figure 2).

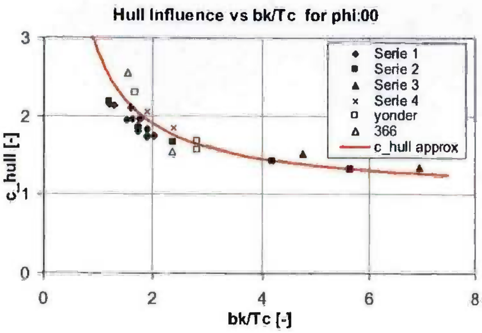

Figure 2: Hull influence coefficient for different keel series

The new relationship for the lift carry over for a large variety of keels may now best be approximated with:

$$c_{hull} = a_0 \frac{Tc}{b_k} + 1 \quad \text{with: } a_0 = 1.80$$

Thirdly the influence of the heeling angle on the lift has to be taken into account.

The influence of the heel angle on the lift production is captured by two mechanisms: one is the lift curve slope reduction due to the fact that the foils are brought closer to the free surface expressed as heel influence coefficient c_{heel}, the second one is the zero lift drift angle βo, which originates from the asymmetry of the hull when heeled.

At first, based on the results of the DSYHS, the DVKS and the DSKS a linear relation between the reduction of the lift curve slope and the heel angle due to the presence of the free surface effect is assumed. This dependency has been calculated and plotted and the results show a moderate dependency on the B/T ratio and the forward speed. In the present study these effects have been neglected and incorporation into the side force assessment method shifted to future research. So in the present study for this effect of heel the following expression is used:

$$c_{heel} = 1 - b_0 \varphi$$

with: $b_0 = 0.382$ for $\varphi : [rad]$

The asymmetry of the hull when heeling over may be captured by the introduction of a seemingly "negative" angle of attack on the appendages, which increases with heel angle and the Beam to Draft ratio in particular. This implies that the effective angle of attack on the appendages is reduced with this βo. An attempt to demonstrate this effect reference is made to Figure 3 in which a somewhat extreme hull is shown under heel.

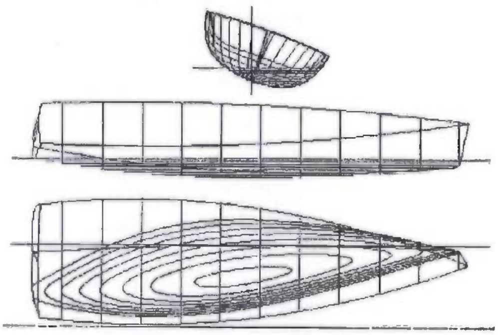

Figure 3: Underwater asymmetry of a heeled hull

The effect of the Beam to Draft ratio on the zero lift drift angle βo is also clearly demonstrated in Figure 4 presenting the measured lift coefficients for three different models of the DSYHS with distinctly different Beam to Draft ratios of the hull. Depicted is the lift coefficient as function of the leeway angle at zero and 30 degree angle of heel. It clearly shows that the higher B/T ratio hulls have a considerable offset with increasing heeling angle.

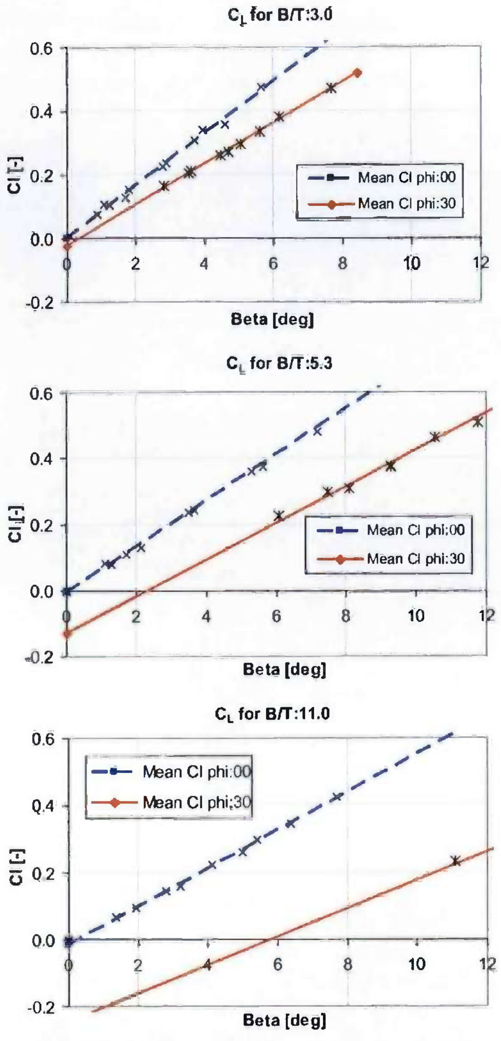

Figure 4: Lift coefficients for zero and 30° heel

Also using the results of the DSYHS, DSKS and DVKS an expression has been found for this zero lift drift angle, which shows reasonable agreement with the measured results. This expression reads:

$$\beta_0 = \left(c_0 \frac{B_{wl}}{Tc} \varphi \right)^2$$

with: $c_0 = 0.405$ for $\varphi : [rad]$

For the present research the forward speed influence on the lift curve slope has been neglected.

Finally the downwash angle of the keel on the rudder is approximated using the expression as formulated by Keuning, Katgert and Vermeulen in Ref [6], i.e.:

$$\Phi = a_0 \cdot \sqrt{\frac{C_{Lk}}{A\mathrm{Re}_k}}$$

with:

φ	0 °	15 °
a_0	0.136	0.137

In which:

Φ = Downwash angle at rudder
C_{Lk} = Lift coefficient of keel
ARe_k = Effective aspect ratio of keel

Using all the various effects described and the approximations formulated the side force production of the keel is now calculated as follows:

$$Lc_{keel} = Lk_{W\&F} \; c_{hull} \; c_{heel}$$

$$Lk_{W\&F} = \left(\frac{dC_L}{d\alpha} \right)_{(W\&F)} \alpha_{e\,keel} \; \frac{1}{2} \; \rho \; V_{e\,keel}^2 \; A_{lat\,keel}$$

in which:

$$V_{ekeel} = Vs$$

$$\alpha_{ekeel} = \beta - \beta_0$$

Along the same lines the lift production on the rudder is calculated using the following formula, now including the effect of the downwash of the keel:

$$Lc_{rudder} = Lr_{W\&F} \; c_{hull} \; c_{heel}$$

$$Lr_{W\&F} = \left(\frac{dC_L}{d\alpha} \right)_{(W\&F)} \alpha_{e\,rudder} \; \frac{1}{2} \; \rho \; V_{e\,rudder}^2 \; A_{lat\,rudder}$$

in which:

$$V_{erudder} = 0.9Vs$$

$$\alpha_{erudder} = \beta - \beta_0 - \Phi - \delta_r$$

The yaw moment is calculated using the side forces generated by the individual components and multiplying it with the distance of the corresponding centre of effort to the centre of gravity of the yacht. The yaw moment of the hull is calculated by taking the Munk moment over the entire length of the hull both upright and heeled as described by Keuning and Vermeulen in Ref [5].

3 Results

The results of this new approach for assessment of the side force production and the yaw moment calculation of the appended hull have now been compared with the results using the previous method as formulated by Keuning and Vermeulen Ref [5]. The results of the new and previous method are plotted against the measured data for the DSYHS database. In the graphs in Figure 7 to Figure 10 the results for a narrow, deep (SYSSER 27) and a shallow, wide hull (SYSSER 33) fitted with the standard DSYHS appendages (Ref [3]) are presented. The main particulars of SYSSER 27 and 33 are shown in Table 1.

	Lwl/Bwl [-]	Bwl/Tc [-]	LCB [%]	LCF [%]
SYSSER 27	4.50	2.46	-1.88	-5.24
SYSSER 33	4.00	10.87	-6.55	-8.73

Table 1: Main particulars of SYSSER 27 and SYSSER 33

In general it was found that the computed results using the new method show good agreement with the measured results. So the accuracy of the new method is comparable with that of the previous method as far as applications within the DSYHS are concerned.

The big advantage however is found in the fact that the new method is consistent over the heel angle range between 0 and 30 degrees of heel. An important improvement is also found in the fact that now in both the upright and the heeled condition the actual area and plan form of both the keel and the rudder is used in the side force calculations, while in the earlier expression only the effective draft of the keel was considered. Changes in the keel area, the span, the chord length and the sweep angle are all taken into account, all of which were not considered in the previous method.

This is best demonstrated when the method is applied and compared with the results of the more modern, high aspect ratio keels underneath the model #366, which is a lower Beam to Draft ratio version of parent hull IACC model #329. The lines plan of this hull is presented in Figure 5.

The dimensions and plan view of the three keels with the same lateral area but varied aspect ratios are presented in Table 2 and Figure 6. For more information on the presented models and keels reference is made to Ref [6].

	Keel 1	Keel 3	Keel 5	Rudder
Lateral Area [m^2]	0.086	0.086	0.086	0.066
Aspect Ratio [-]	1.62	0.70	3.77	0.12
Span [m]	0.37	0.25	0.57	0.32
Mean chord [m]	0.23	0.35	0.15	0.12
Sweepback [°]	9.9	14.4	3.0	18.0

Table 2: Main particulars of the various keels and the rudder

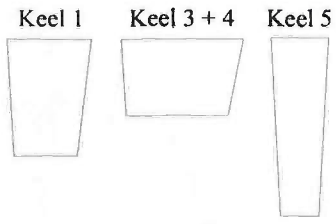

Figure 6: Lateral plan view of the three keels used in the calculations

The results of this comparison for 0 and 15 degrees of heel are depicted in the graphs in Figure 11. In particular the results for the high aspect ratio small chord length keel have improved considerably over the results obtained with the previously used method, as may be seen from the comparison between the measured and computed results for keel #5.

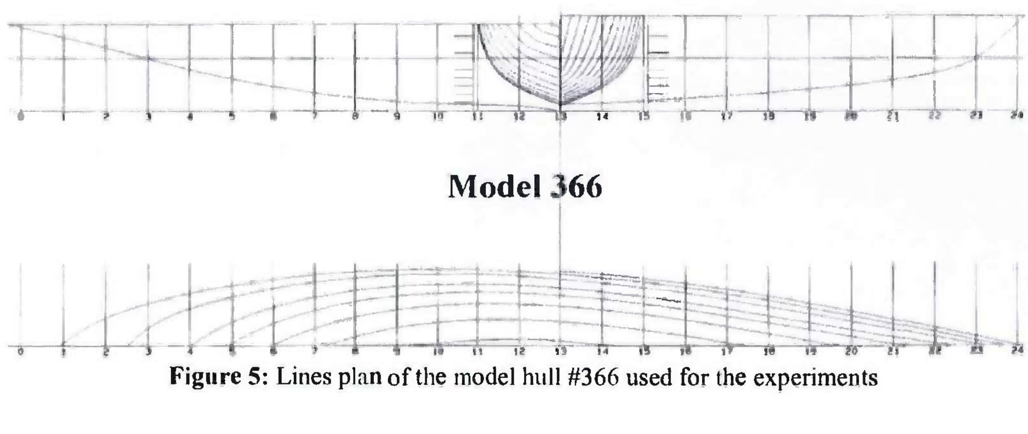

Figure 5: Lines plan of the model hull #366 used for the experiments

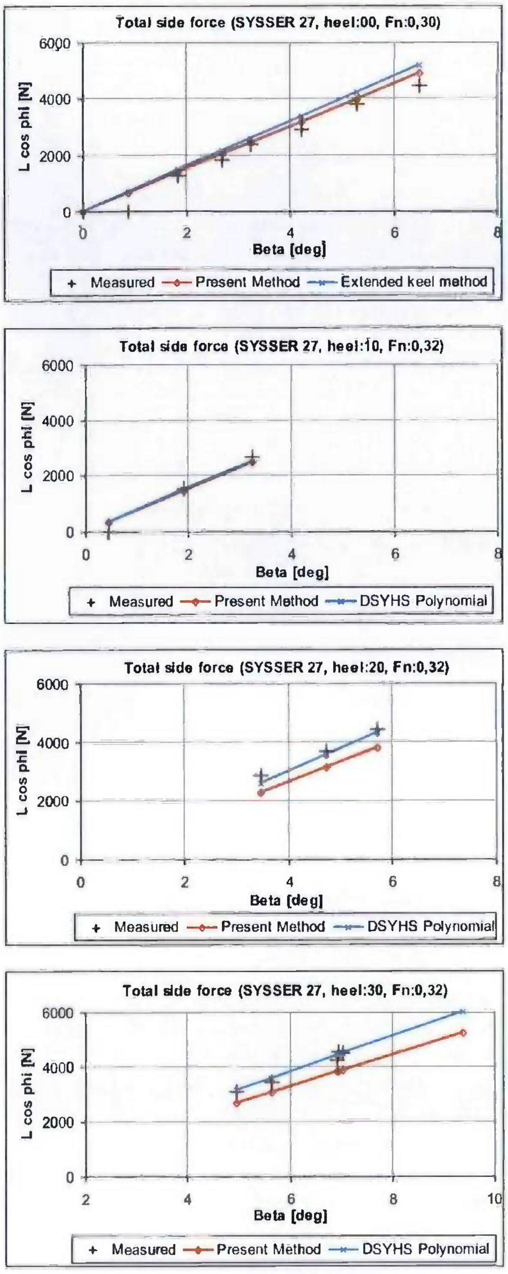

Figure 7: Measured and Calculated total hydrodynamic side force vs. leeway angle for SYSSER 27

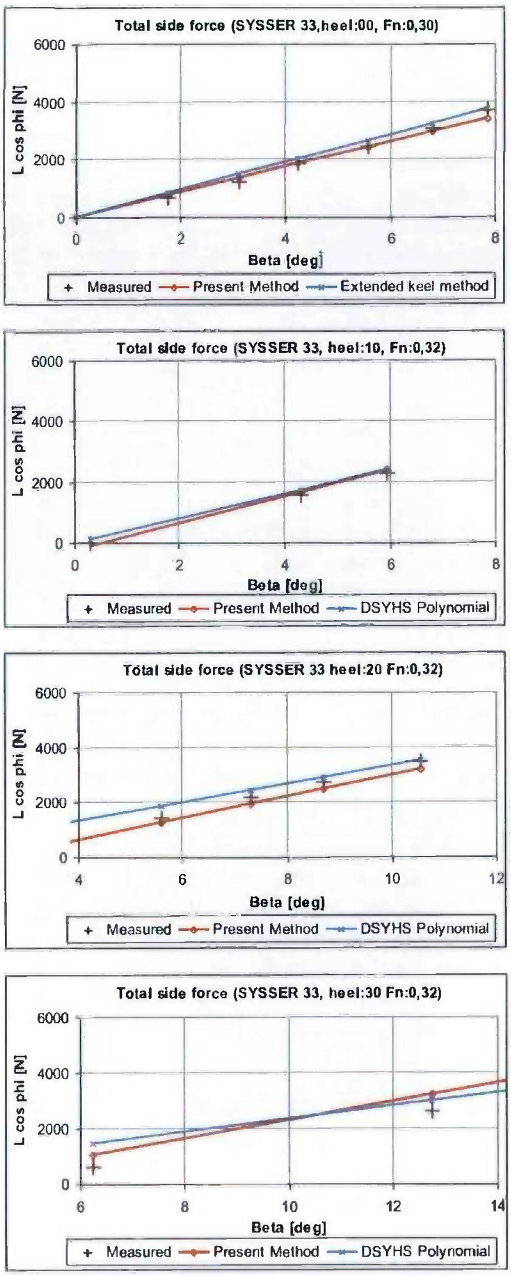

Figure 8: Measured and Calculated total hydrodynamic side force vs. leeway angle for SYSSER 33

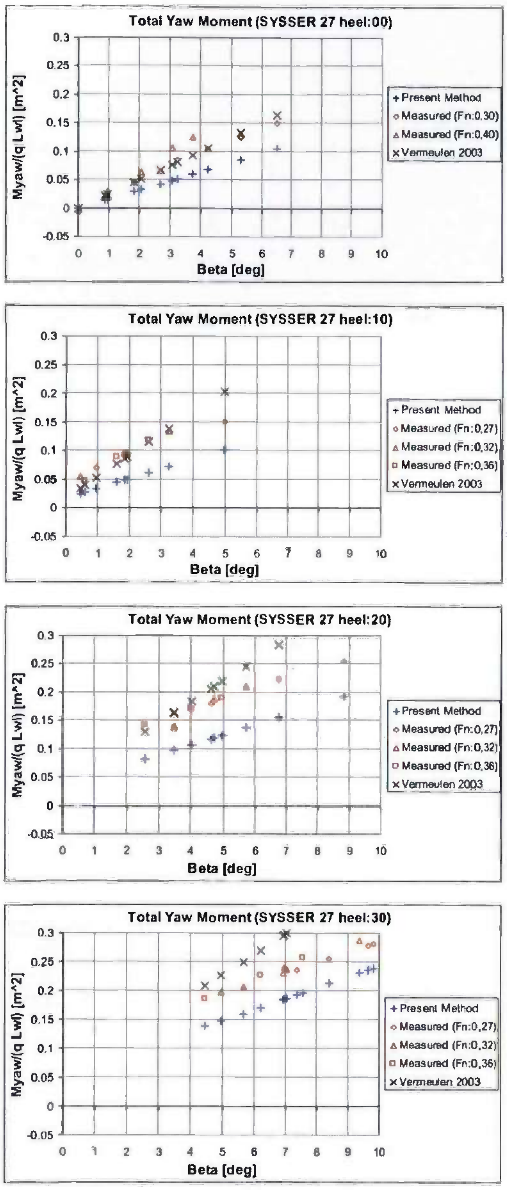

Figure 9: Measured and Calculated total hydrodynamic yaw moment vs. leeway angle for SYSSER 27

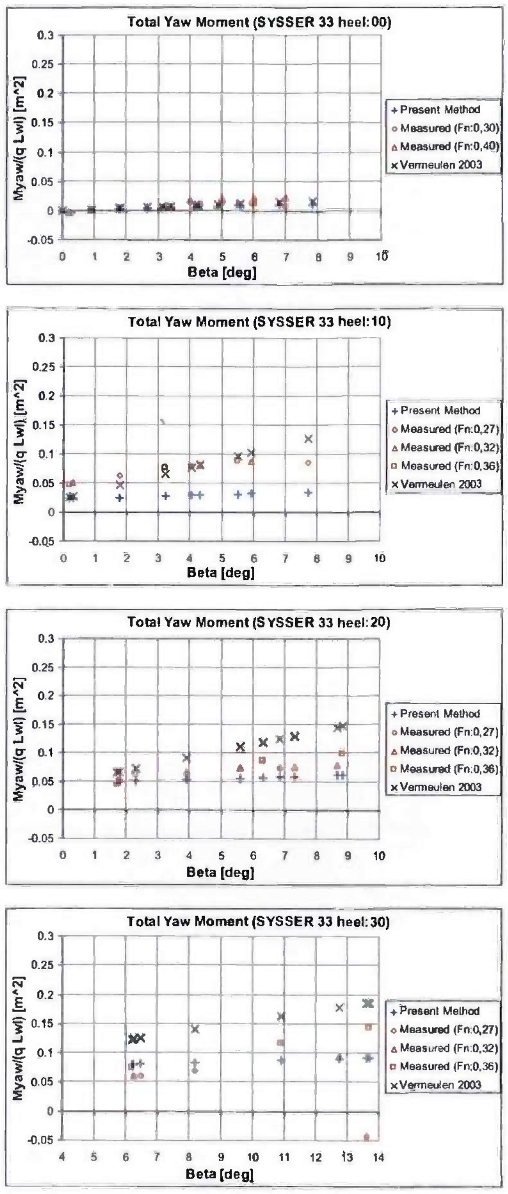

Figure 10: Measured and Calculated total hydrodynamic yaw moment vs. leeway angle for SYSSER 33

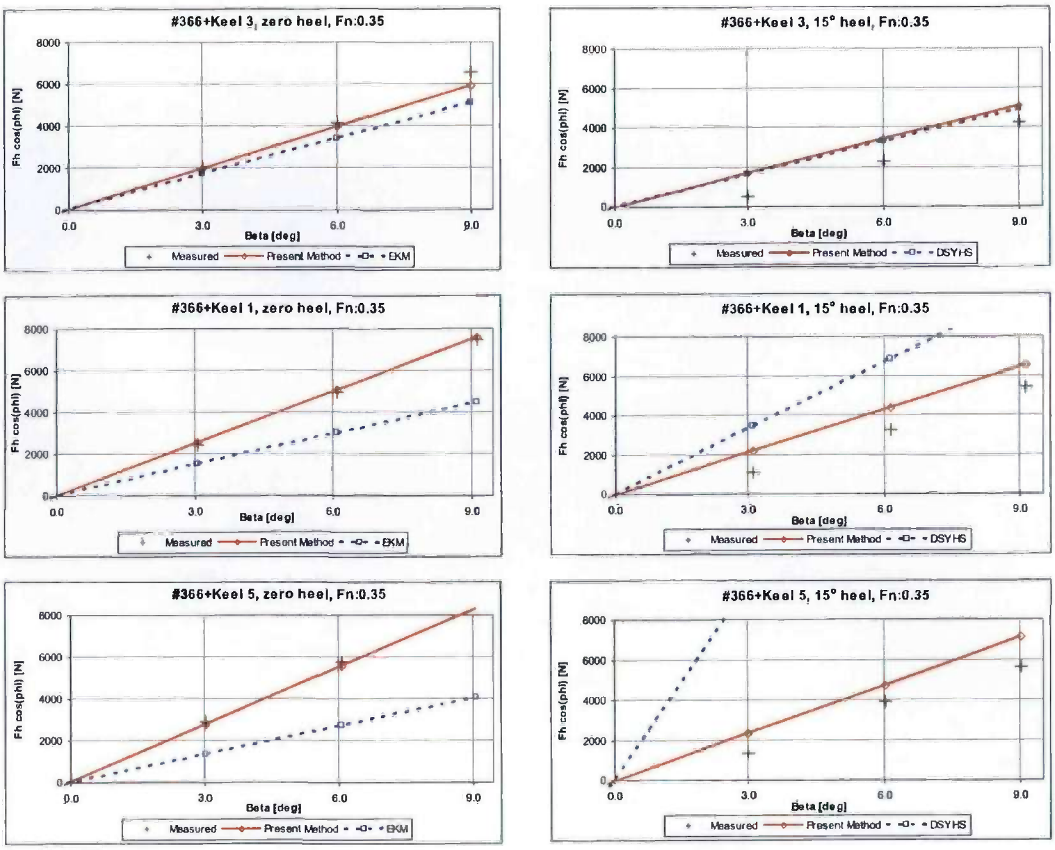

Figure 11; Measured and calculated side force for zero and 15 degrees heel for model #366 fitted with keel 3, 1 and 5

4 Conclusions

From the results of this study it may be concluded that an improved method for assessing the side force production of the hull, the keel and the rudder has been formulated. The most important improvements, when compared with the previously used methods, lie in the fact that now the actual geometry is taken into account and that the formulations used for the upright and the heeled conditions are fully consistent. There is still room for improvements, which may certainly be achieved by taking more data into account. The adopted approach for the lift production of the keel and the rudder using the Wickers & Fehlner lift curve slope formulation, the hull- and heel influence coefficient and the zero leeway angle under heel as well as the lift carry over on the hull as the basic parameters appears to be a valid approach so far.

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