"The Yaw Balance of Sailing Yachts Upright and Heeled"

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THE 16th CHESAPEAKE SAILING YACHT SYMPOSIUM

ANNAPOLIS, MARYLAND, MARCH 2003

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THE 16^{th} CHESAPEAKE SAILING YACHT SYMPOSIUM

ANNAPOLIS, MARYLAND, MARCH 2003

The Yaw Balance of Sailing Yachts Upright and Heeled

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ABSTRACT

The present paper describes the results of a study carried out to improve the frequently used prediction methods for assessing the longitudinal position of the Center of Lateral Resistance (CLR) of a sailing yacht hull. To formulate these improvements use is being made from the extensive database of the Delft Systematic Yacht Hull Series (DSYHS) containing yaw moment measurements under various conditions with respect to speed, heeling angle and leeway. The data has been used to formulate alternative procedures and formulations for the existing methods for prediction of yaw moment as previously presented by J.Gerritsma (1971) and K.Nomoto (1979). The outcome of this modified procedure is compared with the experimental results obtained both within the DSYHS and the Delft Systematic Keel Series (DSKS). In the DSYHS one keel and rudder have been tested under a variety of hulls and in the DSKS a variety of keels have been tested under one particular hull. Finallly the results are checked against the measured data obtained from two series of tests in the Delft Shiphydromechanics Laboratory with very large sailing yachts with low aspect keels.

By matching these hydrodynamic data with the wind tunnel results on the position of the Center of Effort (CoE) of the sails and it change due to heeling angle a better analysis of the balance of the yacht can be made.

NOTATION

Cl	- lift coefficient
α	- angle of attack
Λ	- sweep back angle
bk	- span of foil
Tc	- draft of canoe body
cre	- root chord of extended keel
ct	- tip chord of keel
Te	- effective depth
ρ	- water density
u	- longitudinal flow velocity
v	- transverse flow velocity
h_m	- maximum cross sectional depth
β	- leeway angle
CLR	- center of lateral resistance
Cm	- midship section coefficient
V	- vessel speed
Amz	- yaw moment area
Afy	- side force area
a22	- added mass in the transverse (Sway) mode
Cmz0	- yaw moment at zero degrees of leeway
φ	- heeling angle
Fh	- heeling force in the heeled plane
Fn	- Froude number

1 - INTRODUCTION

One of the challenges the designer has to deal with in the design process of a sailing yacht is finding the best longitudinal position of the sail plan with respect to the under water body of the ship. The problem is introduced by the fact that from "simple" calculations neither the exact position of the Center of Lateral Resistance (CLR.) of the forces on the under water body nor the exact longitudinal position of the Center of Effort (CoE.) of the aerodynamic forces on the sails is known. The problem is even further aggravated by the fact that both the CLR and the CoE may change considerable under the influence of variations in the forward speed, the heeling angle, the angle of incidence of the sails and the leeway angle of the hull.

In particular the heeling angle has a considerable influence on the yaw equilibrium of the yacht. From the well known picture of the physics and forces involved, as depicted in Figure 1, it is clear that the working lines of the driving force on the sails (F_D) and the resistance force on the hull (R) move away from each other when the yacht is heeled and rotates along a longitudinal and horizontal axis.

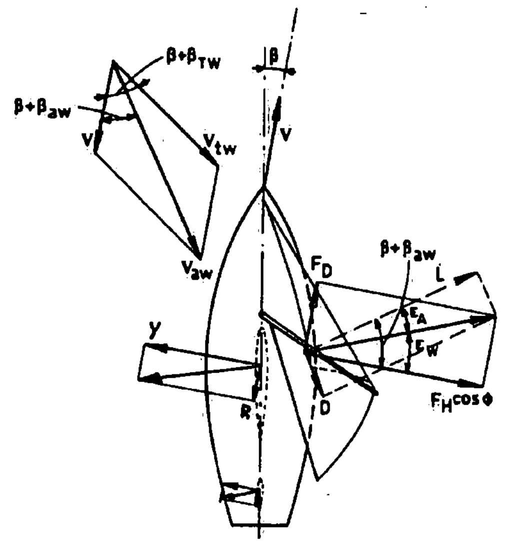


Figure 1. Definition of forces

Through this a considerable yaw moment is introduced. In addition, the CLR and the CoE change due to the asymmetry introduced by the heeling angle, bringing a further increase of the yawing moment. The yaw equilibrium may now only be "restored" by either changing the sail settings (and so most likely introducing loss of propulsive power) or by a controlled (and limited) application of a rudder angle. In the case of "simple" rigs and efficient underwater shapes this generally does not introduce overwhelming problems and yawing equilibrium may be achieved with limited sail and rudder adjustments. With the recent increase of yacht size, the desire for limited draft, and the complexity of rig layouts, the possibilities to counteract these yawing moments with the rudder become more and more limited. This calls for an early assessment of the possible yaw (un)-balance of the sailing yacht under consideration in view of the desired performance (speed) and safety (maneuverability).

Up until now a more or less "exact" determination of the CLR and the CoE can probably best be obtained with the aid of towing tank tests with the hull and wind tunnel tests on the rig. These can be carried out in a large number of different conditions and the resulting driving- and side-forces, and the associated yawing- and heeling-moments, determined. By equating these forces and moments generated by the hull and the sails the final equilibrium situation may be obtained and evaluated for their applicability. These tests, however, will probably only be carried out in a later stage of the design process. An extensive change in appendage design and appendage layout is often carried out during these tests in order to optimize the final design. In particular wind tunnel tests may be necessary for those conditions in which large separation of the airflow over the sails will occur (i.e. broad reaching and running). In other conditions a more theoretical solution may become available through the extensive use of Navier-Stokes solvers, which may yield sufficiently reliable results now or in the foreseeable future. The use of these Navier-Stokes solvers is made necessary by the inevitable and relatively important contribution of the viscous effects involved in determination of both the CLR and the CoE. This approach however is certainly at present not particularly feasible for the earlier stages of the sailing yacht design process, in which a relatively large number of design variations have to be considered in a relatively short time. Probably an experimental validation of the results obtained from these calculations will be necessary or asked for. Both methods are generally time consuming and expensive. So for most designs of competitive or performance-orientated sailboats, frequent use is being made of simpler and easy-to-use assessment methods for both the CLR and the CoE. In using these methods, for instance, the CoE of the complete sailplan may be approximated by calculating the geometric center of a standardized set of simplified sails. For instance often only the 100% fore triangle is used for the headsails. For assessing the CLR, different methods are used. By far the simplest one is taking the geometric center of the underwater profile of the boat. This center will certainly not coincide with the actual CLR. A more sophisticated method is the one introduced by prof. J.Gerritsma in 1971 best known as the Extended Keel Method, in which the foils are isolated and calculated using general wing theory and the contribution of the hull is accounted for by extending the keel to the undisturbed waterline. This yields very good results for the calculation of the sideforce versus leeway relationship but the CLR is less well predicted; in general it tends to be predicted to be too far aft. This was attributed to an improper representation of the yaw moment generated by the hull. So to improve on this calculation of the CLR prof. K.Nomoto introduced in 1979 an improvement on the Gerritsma method in which he separated the forces on the foils (keel and rudder) and the sideforce and yaw moment of the hull. This method showed a significant improvement on the calculation of CLR when compared with measured data. For non-standard hull forms and appendage layouts however, there is still a relevant discrepancy between measured and calculated CLR. In particular, for deeper hulls and shallow drafts the discrepancy still existed. The first challenge therefore lies in a more correct prediction of the CLR or the yaw moment of an arbitrary sailing yacht with arbitrary hull geometry and arbitrary appendage shape and layout in the upright position as function of leeway angle and forward speed.

So, the present study is aimed at formulating a still-empirical and easy-to-use assessment tool for the CLR or yaw moment, but for a larger variety of underwater hull and appendage shapes -as an extension of or an addition to the already existing methods. In the present paper a short summary of the few of the aforementioned methods is given in combination with some of the results obtained. Then a refinement of this method using the results of the DSYHS is presented. The results will be compared with the measured data of some of the models tested in the DSKS.

2 – CALCULATION METHODS

In 1971 Prof J. Gerritsma presented a method to assess the hydrodynamic efficiency of sailing yacht hulls using the formulations used for lift and lift curve slope arising from airfoil theory. This method is generally referred to as the Extended Keel Method (EKM). Using wing theory as presented among others by Whicker and Fehlner in 1958, Reference [4], this method considered the primary lift generating devices of a sailing yacht to be the keel and the rudder. If these were of a large enough aspect ratio, he proposed to calculate the hydrodynamic effectiveness of the sailing yacht (i.e. the lift generated per degree leeway) using this wing theory concept. To take into account the end plate effect of the hull on the hydrodynamic performance of the fins, the actual planform of the keel and the rudder is mirrored with respect to the endplate to obtain an Effective Aspect Ratio (AR_e) in the lift curve slope formulations. To take into account the side force production of the hull itself Gerritsma;s suggestion was to mirror the foils (keel and rudder) with respect to the waterplane at rest and to take the effective aspect ratio of this new "double" fin into the formulations for the determination of the lift curve slope and the (induced) resistance coefficients. The area of the foils used in the lift calculations is taken to the waterplane, also. By doing so the part of the fin area extended "inside" the hull was considered to take account for the side force production of the hull. In order to be able to account for the downwash (sidewash) effect of the keel on the rudder a correction on the effective angle of attack of the rudder with 60% of the leeway angle was suggested by Gerritsma for the typical appendage lay out of the DSYHS. This correction coefficient was obtained from tests with yacht hulls having a "normal" separation (distance) between the keel and the rudder, as used in the DSYHS. An additional reduction for the rudder lift, due to the wake of the keel, was proposed; this was to use only 90%
of the free stream velocity on the rudder. A more general approach for the effect of the side wash from the keel on the rudder is formulated by S.F.Hoerner in Reference [9] :

$$\Delta\beta = \frac{1.6 * Cl}{\pi * AR_{keel}}$$

In which:

$\Delta\beta$ = leeway angle degradation on the rudder
Cl = lift coefficient of the rudder
AR_{keel} = aspect ratio of keel

When the distance between keel and rudder is sufficiently large to suppose that the sidewash is primarily caused by the now rolled up vortex sheet from the keel.

The actual angle of incidence on the rudder then becomes:

$$\beta_{corr} = \beta\left(1 - \frac{1.6 * Cl}{\pi * AR_{keel}}\right)$$

In which:

β = Leeway angle

The outline of this procedure and the definition of the quantities used in the formulations are indicated below and in Figure 2. The lift curve slope of the two foils is determined using :

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

$$a_e = \frac{2 * (bk + Tc)}{\left[\frac{cre + ct}{2}\right]}$$

In which :

Cl =	*lift coefficient*
α =	*angle of attack*
Λ =	*sweep back angle of quarter chord line*
a_e =	*effective aspect ratio of foil*
bk =	*span of foil*
Tc =	*draft of canoe body*
cre=	*root chord of extended keel*
ct =	*tip chord of keel*
Ar =	*Lateral area of rudder*
Ah =	*Lateral area of hull*
Aek =	*Lateral area of extended keel*

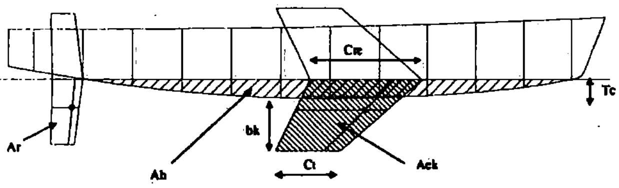


Figure 2. Definitions in the Extended Keel Method

The extension of the keel to the waterline was considered by Gerritsma to be an unrealistic procedure for (very) low aspect ratio keels, i.e. for Tc/T > 0.5. For these keels he suggested the use a correction on the "draft" based on the theoretical work of Newman and Wu (1973) on slender bodies with fins. This correction yields:

$$Te/T = \sqrt{(1 + 0.13\,(Tc/T) - 0.95\,(Tc/T)^2)}$$

In which:

Te	=	effective depth
T	=	total draft
Tc	=	canoe body draft

Or as simplification for values of Tc/T around 0.5:

$$Te/T = \sqrt{1 - 0.62\,Tc/T}$$

The yaw moment is obtained by combining the moments produced by keel and rudder, taking as moment arm the distance between the midship section and the center of effort on both foils, these centers being estimated to be situated on the quarter chord line at 43% of the total draft. A full description of the method is presented in Reference [1].

In general this method yields very good results for the side force production of sailing yachts with a variety of under water body shapes and appendages. The CLR however is generally predicted too far aft even with the 60% reduction applied on the rudder force.

K.Nomoto e.a. (1979) considered this difference in the calculated versus the measured CLR to be primarily caused by the fact that the side force produced by the underwater body of the hull was not properly taken into account. He therefore proposed to add to J.Gerritsma's method the hydrodynamic forces acting on the fore body of the underwater hull. These forces and moment were calculated using the so-called "slender body" theory. In the literature this potential contribution to the yaw moment of a body in an oblique flow is known as the Munk Moment. This Munk Moment arises from the fact that in an ideal (nonviscous) fluid an elongated 3-dimensional body at an angle of attack experiences a pure couple, which tends to increase its angle of attack. This couple is composed of two equal but opposing (i.e. acting in opposite directions) forces acting over the bow half and the stern half of the ship. This implies that in an ideal fluid there is no resulting force (side force in sway) but a significant moment. This situation is depicted in Figure 3.

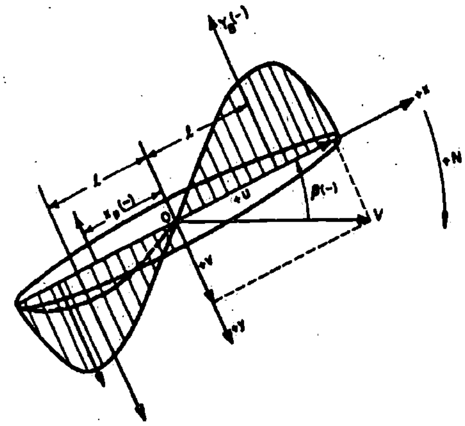


Figure 3. Force distribution on slender body in oblique potential flow. Ref [6]

The physical explanation of this Munk Moment is based on the assumption of an ideal, potential flow calculation and thus with an inviscid fluid. In a real viscous fluid, vortices and a certain amount of flow separation will occur downstream along the body, which will result in a reduction of the pressure on the aft body as also depicted in Figure 3.

In the slender body theory, which is used by Nomoto to calculate the Munk Moment, the basic assumption is that of the "dynamic displacement" effect. The "static displacement" produces buoyancy and the "dynamic displacement" induces a change of momentum of the (incoming) fluid, which in turn leads to a force on the body under consideration. The same idea is used by Wagner (Reference [10]) to calculate the hydrodynamic forces (lift) on surfaces penetrating the free surface such as the hydrodynamic lift on planing surfaces and to calculate the lift on very low aspect wings.

Consider now a slender body, i.e. a body of which the beam and draft are many times smaller than it's length, moving in a oblique flow. This makes it possible to simplify the physics, observing a 2-D flow at each cross section of the body. Considering the hydrodynamics involved it can now be stated that the lateral momentum of the fluid in a plane perpendicular to the body axis is equal to : $vA(x)$ in which v is the velocity perpendicular to the body axis and A(x) is the added mass of the cross section at length x of the body. The rate of change of the lateral moment of the fluid then becomes : $uv\frac{d}{dx}A($. This is depicted in Figure 4.

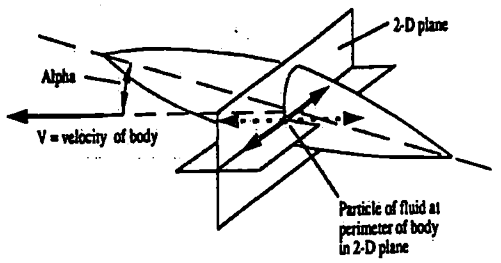


Figure 4. Slender body theory fluid momentum

Nomoto simplifies the formulation for the added mass of each of the cross sections by taking the formulation for an elipsoide, i.e. :

$$A(x) = \pi\rho h^2($$

and so the formulations for the lateral force and the yaw moment become:

$$Y = \pi\rho u \int_{-\frac{l}{2}}^{\frac{l}{2}} v \frac{d}{dx} h^2(x \quad d$$

and $$N = \pi\rho u \int_{-\frac{l}{2}}^{\frac{l}{2}} vx \frac{d}{dx} h^2(x \quad d$$

in which:

$h(x)$ = *depth of section at x*

When these integrations are carried out (over the entire length of the body) no lateral force is found but a significant moment. This moment is the Munk Moment. In a real viscid fluid the flow around the bottom of the body will generate vortices and these will reduce the effect of the cross flow when going more to the after body of the underwater hull and will therefore reduce the transverse velocity component $v = u\beta$. Nomoto adapts this assumption and deals with it by taking both the integrals only to the deepest section of the hull, with maximum cross sectional depth h_m, located probably close to the midship. This results in the following expressions :

$$Y = \pi\rho u^2$$

$$N = -\pi\rho u^2 \beta \left\{ x_m h_m^2 + \int_{x_m}^{\frac{l}{2}} h^2(x) d \quad \right\}$$

The lateral force is now no longer zero and the yaw moment is smaller than the original Munk moment.

The results found with this method showed a good agreement with the towing tank measurements carried out by Nomoto on two models of contemporary yacht hulls.

Similar results were found by McMillan in 1991, Reference [3], who carried out extensive model experiments in the wind tunnels of Auckland University in New Zealand. He concluded that the methods of Gerritsma and Nomoto yielded by far the best results when compared with several others, at least for the geometries he tested. His conclusions were based solely on sideforce production. His restrictive remark on the general conclusions concerned the ratio between the canoe body depth and the total draft of the models he tested, which was rather small, i.e. deep keels with a geometric aspect ratio larger than AR_G > 0.8 placed underneath relatively shallow hulls. McMillan however did not validate the results of the predictions for the yaw moment or the CLR with his measurements. Considering the results obtained by Nomoto himself it is concluded that the yaw moment is under predicted, so CLR is generally predicted to be too far aft; however, the improvement in the prediction in this respect, when compared to the results obtained with the method introduced by Gerritsma, significant.

3 – PRESENT METHOD

3-1 Upright Condition

For the present study it was decided to validate the results obtained with Nomoto's method by comparison with the results obtained in the towing tank for the models of the Delft Systematic Yacht Hull Series. This report deals first with the upright, i.e. zero heel condition, of the models. Then, the situation with heel is considered.

Some twenty models of the DSYHS have been used for this validation. The models used come from Series 1 (Model #1 to #22), Series 2+3 (Model #23 to #39) and Series 4 (Models #42 to #50) of the DSYHS. These three are sub-series within the complete DSYHS, each sub-series having it's own parent model. The selection was based on variation in Beam to Draft ratio, Length-Displacement ratio, Longitudinal Position of the Center of Bouyancy, and Prismatic Coefficient. For a complete reference to the geometry parameters of these models reference is made to Keuning and Sonnenberg, 1998, Reference [5]. Bodyplans of the three different parent models of the sub-series are depicted in Figure 6. It should be noted that each of the models in Series 1 has the same midship section coefficient C_M =0.646. In Series 2+3, C_M varies between 0.67 and 0.69, and in Series 4, Cm varies between 0.71 and 0.77.

When calculating the side force and the yaw moment for these 20 models of the DSYHS using both the Gerritsma method and the Nomoto method and then comparing the calculated with the measured results obtained from the DSYHS tests, it showed that, in general, Gerritsma's method yielded better results for the side force and Nomoto's method yielded better results for the yaw moment. This method, in general, under predicted the yaw moment of the yachts but over predicted the side force production of the yachts. So, a slightly different procedure was adopted, as explained below.

The basic idea, adopted by Nomoto e.a., is to carry out the integrations only over the forebody of the slender body, because the lateral flow at the aft body is considered to be too strongly influenced by shed vortices forward and subsequent flow separation. This assumption is frequently used and it probably originates from experience with maneuvering ships and fully submerged bodies, such as submarines. Maneuvering these vessels operate, in general, at much higher angles of attack (drift angles) than is to be expected in the case of a sailing yacht hull. Within the naval architectural community this is not without debate. Crane, Eda and Landsberg, in Principles of Naval Architecture, Reference [6], point out that a generally accepted simplification in naval hydrodynamics is that the potential flow effects (ideal fluid) and the viscous flow effects, at least in dealing with the maneuvering forces,

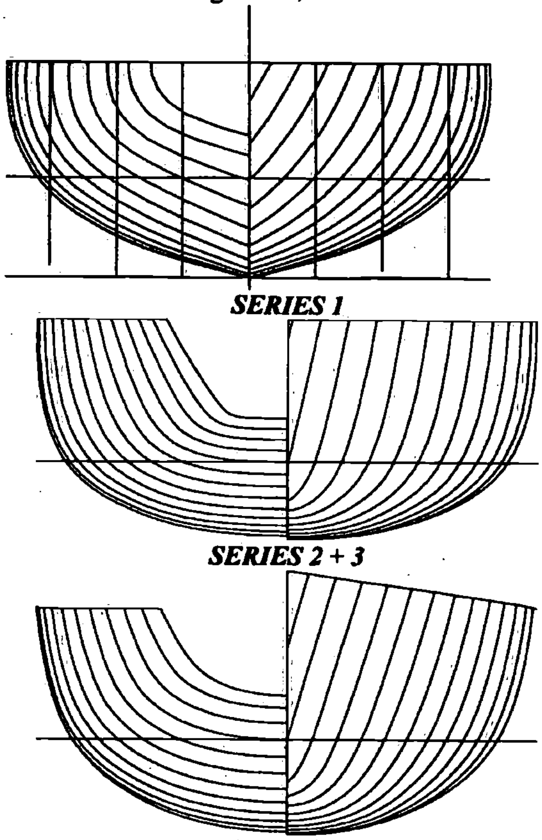


Figure 6. Body plans of the parent hulls of the DSYHS

are to be considered as independent of each other. Hence they assume that the lateral force in the ideal fluid, as approximated by the slender body theory, is independent of the lateral force caused by the vorticity in the real viscous fluid. The total yawing moment on the body in a real fluid is than to be taken as the sum of these two components. The real fluid viscous lateral force is related to the cross flow drag over the under water part of the hull. From the published data on this cross flow drag force it may be considered, as a first approximation, to contribute very little to the side force and the yaw moment on a sailing yacht hull operating at relative small leeway angles. So the following modification is adopted to Nomoto's method:

Modification 1:
In this study we adopted the approach to carry out the integration of the change in lateral fluid momentum over the full underwater length of the hull. The side forces and their contribution to the yaw moment are considered to originate solely from Gerritsma's assumptions in the Extended Keel Method.

As a result this yields very little change in the side force, actually zero, but a significant change in the yaw moment. To compare the results of the calculations with the measurements of the DSYHS, the following procedure was used:

- *The forces on the keel and the rudder were determined using Gerritsma's Extended Keel Method. In the calculation a correction factor on the rudder force due to downwash and wake effects was applied of 0.4.*
- *The resulting yaw moment was calculated from the fins, taking the CE on the quarter chord line on 0.43 times the draft of the (extended) fins.*
- *The resulting side force and yaw moment were subtracted from the measurements carried out in the DSYHS yielding the side force and yaw moment contribution of the hulls.*
- *The yaw moment was calculated using Nomoto's method but with the integration of the sway 2-D added mass carried out over the entire waterline length.*

The results obtained with this procedure have been plotted as side force divided by the dynamic pressure

$$q = \tfrac{1}{2} \rho V^2$$

and as yaw moment divided by

$$q^* Lwl = \tfrac{1}{2} \rho V^2 {}^* Lwl.$$

In which:

Lwl = Waterline length
V = Forward speed

The comparison showed that the side force was very well predicted for almost all hulls with Bwl/Tc ranging from 2.5 (DSYHS hull number 27) to 11 (DSYHS hull number 24).

It also showed that for Series 2+3 and Series 4 the results for the yaw moment were worse than those obtained for Series 1. This lead to an investigation into validity of the approximation of the yaw added mass as used by Nomoto. To investigate this a little further, all DSYHS hulls were checked to determine their sectional sway added mass and it's distribution over the length of the hull, with the aid of a 2-D strip theory computer program. The computer program used for these calculations was SEAWAY, as developed by Journee, Reference [7]. The sectional sway added mass was obtained using various methods, including several Lewis transformations and a Close-Fit procedure.

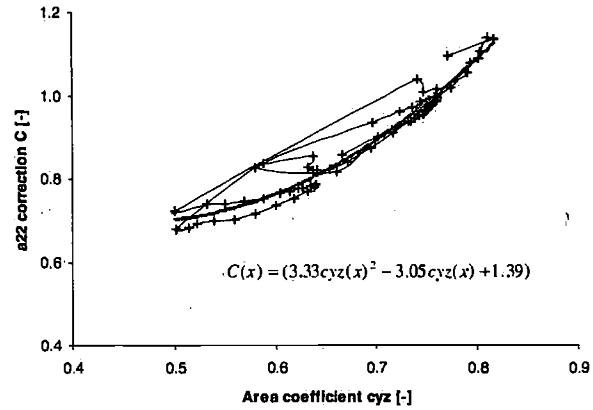
The results so obtained have been compared with the same results using Nomoto's original assumption. From this comparison between the two calculations it turned out that the assumption made by Nomoto for the calculation of the yaw added mass, based on the ellipsoidal body, was an oversimplification. It was shown that the sway added mass was strongly dependent on the area coefficient of the section under consideration. For a sailing yacht hull this may vary considerably over the length of the yachts hull. So an additional modification was adopted.

Modification 2:
A correction coefficient, as function of the sectional area coefficient (which is a function of the sectional area coefficient), applied to the assumed "canoe-body-draft-squared" assumption for the sway added mass, was adopted.

This correction coefficient was established by regression of the relationship between the calculated results for the sway added mass with SEAWAY and Nomoto's approximation. This coefficient is shown in figure 7.

Figure 7 Sway added mass correction coefficient:

This type of approach was chosen for the current study because the goal was to deliver a designer's tool. Using a correction on the depth-squared assumption makes it possible for the designer to use the proposed method



without the necessity to run a 2-D strip theory computer program. The formulation for the yaw moment now becomes:

$$N = \frac{\pi}{2} \rho V s^2 \beta \int_{\frac{-L}{2}}^{\frac{L}{2}} h^2(x) * C(x) dx$$

$$C(x) = (3.33 c_{yz}(x)^2 - 3.05 c_{yz}(x) + 1.39)$$

In which:

$h(x)$ =*The local depth of the hull*
Vs =*Forward speed of the yacht*
$c_{yz}(x)$ =*The local area coefficient*

For the approximately twenty models selected from the DSYHS, the calculations according to this adopted procedure have been carried out. The results of the calculations have been compared against the measurements of the DSYHS. Due to the limited space available in this paper not all of these results can be presented, but a few characteristic results are shown in figure 8 for four models with different section shapes and Beam to Draft Ratios. The main form parameters of these models are presented in the table below.

SYSSER	Lwl/Bwl	Bwl/Tc	LCB %	LCF %
15	3.165	3.683	-2.29	-3.45
24	3.497	10.958	-2.09	-5.84
25	4.000	5.388	-1.99	-5.54
27	4.496	2.46	-1.88	-5.24

In general, it may be stated that both the side force and the yaw moment are rather well predicted by this new approach and that it yields more accurate results than the original Nomoto method.

To check the applicability of the method to other hulls and appendages, a calculation was performed for three of the keels tested in the Delft Systematic Keel Series (DSKS). In the series, a variety of keels have been tested under the same hull. The hull was that of the "Yonder", a yacht from Dutch designer Jac. de Ridder. The main particulars may be found in the report of J.Gerritsma and J.A.Keuning from 1985, Reference [8]. The three keels selected for the present comparison were:

- The standard IOR Keel
- A Shallow draft keel (without a centerboard)
- A shallow draft keel according to a design by H.Scheel

The main particulars of these keels are presented in the Figure 9.

In addition, calculations were compared with the results of the model tests on a very large yacht with a very low aspect ratio keel. The main particulars of this yacht are presented in Figure 10.

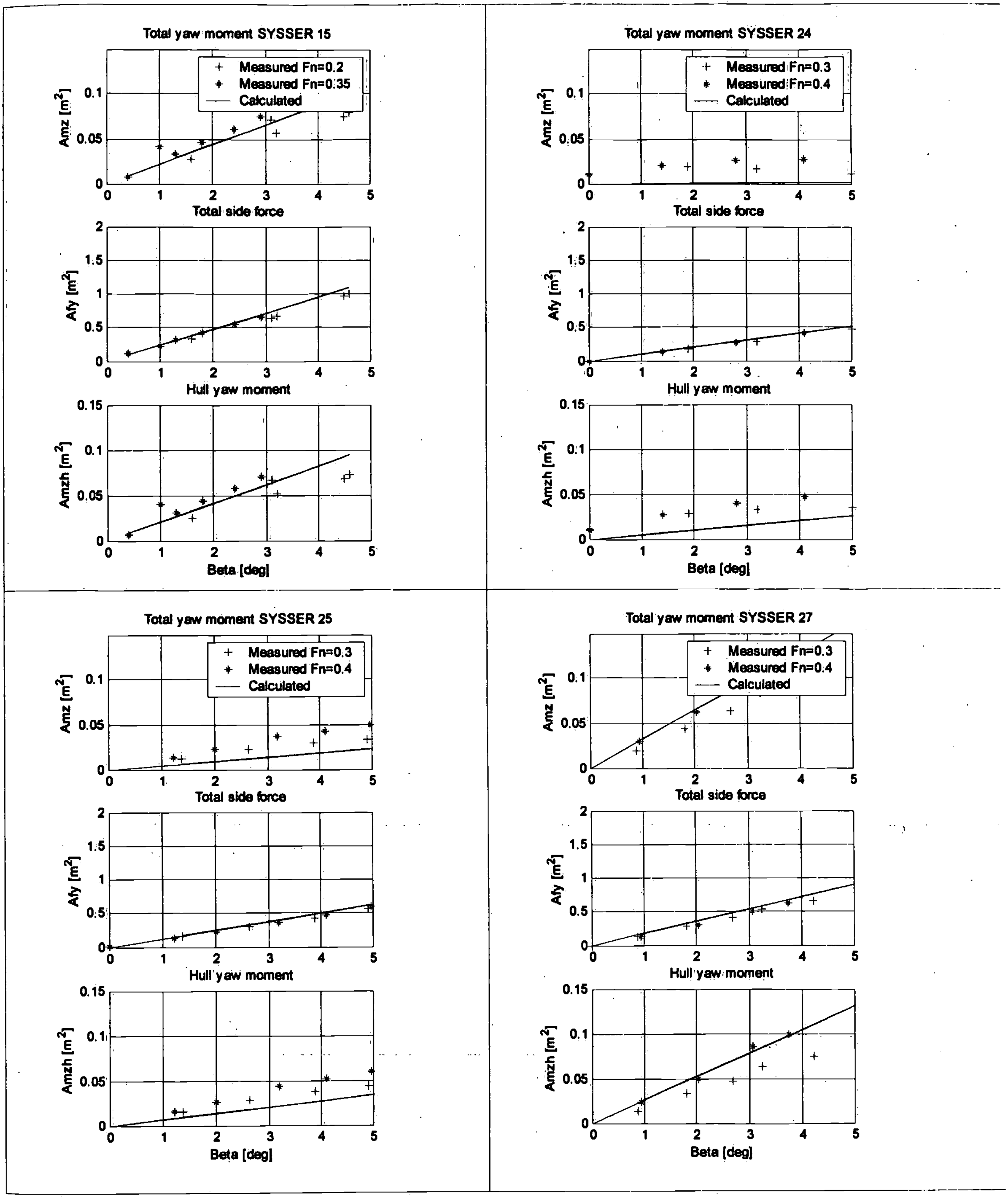


Figure 8 Side Force and Yaw Moment of DSYHS Models 15,24,25 and 27

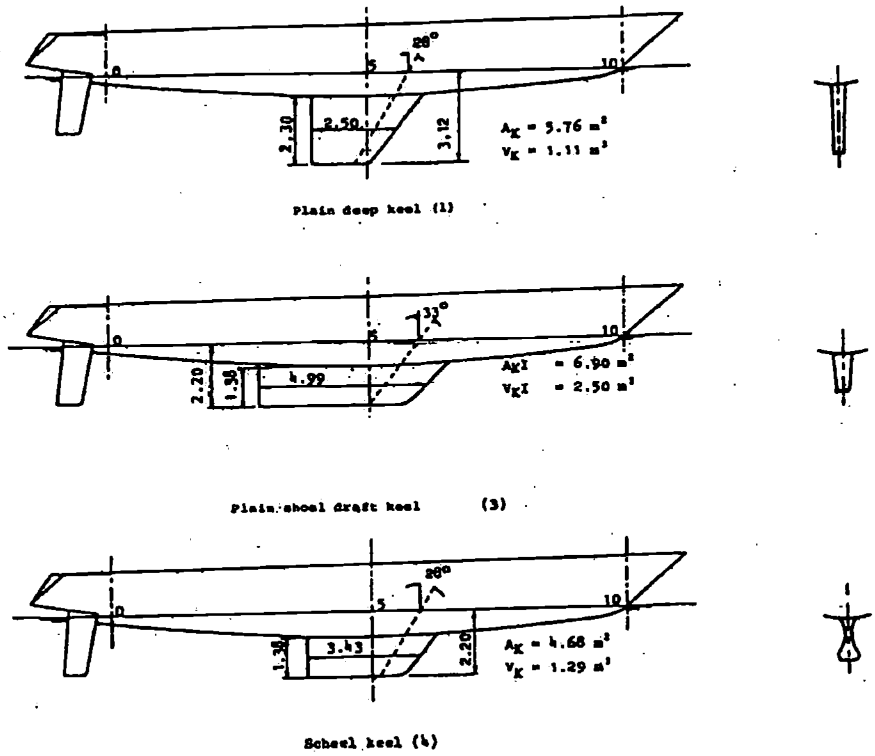
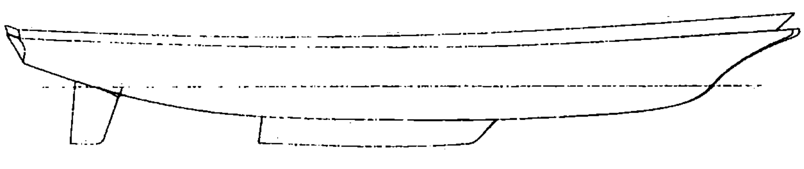


Figure 9. Layout and Main Parameters of Three Keels Tested in the DSKS

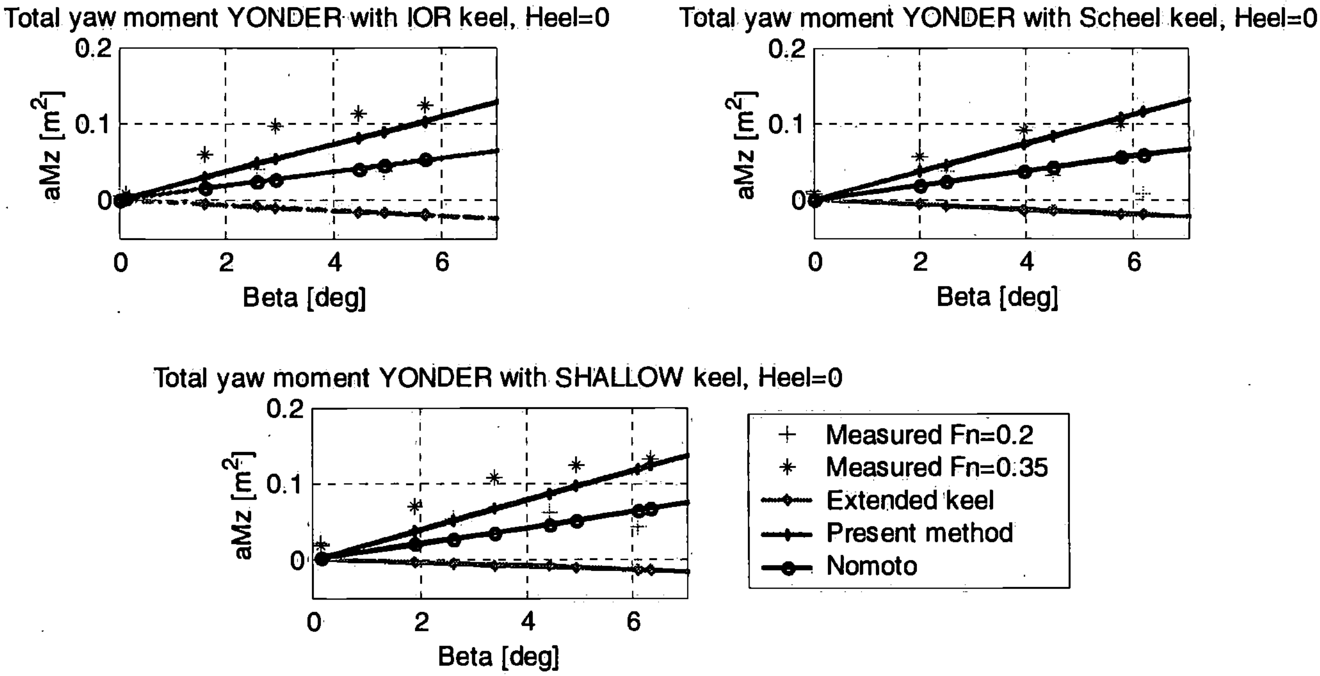


Lwl= 41.61m, Bwl=9.93m, bk=1.75m, Ck=15.14, Tc=2.25m

Figure 10. Layout and Main Parameters of Large Yacht with a Very Low Aspect Ratio Keel

In Figure 11 the results of the calculations for the yaw moment are presented and compared with the measurements for the DSKS. In Figure 12, the results of the calculations for the yaw moment are presented and compared with the measurements of the large yacht with the very low aspect ratio keel. For the sake of the comparison between the respective calculation methods, the results using Gerritsma's and Nomoto's method are presented together with the results using the present method. From these results it may be concluded that the correlation between the calculations and the measurements is significantly improved by applying the proposed modifications to Nomoto's method. In general the yaw moment is predicted to be considerably larger while the predicted total side force remains almost unchanged, yielding a position of the Lateral Resistance much further forward, and therefore, much more "in agreement" with the towing tank measurements. It should be noted however, that the calculations still do not account for the differences in yaw moment at different forward speeds which are found in the measurements.

Figure 11 Measured and Calculated Yaw Moment, for the Yacht Yonder with the three different Keels:



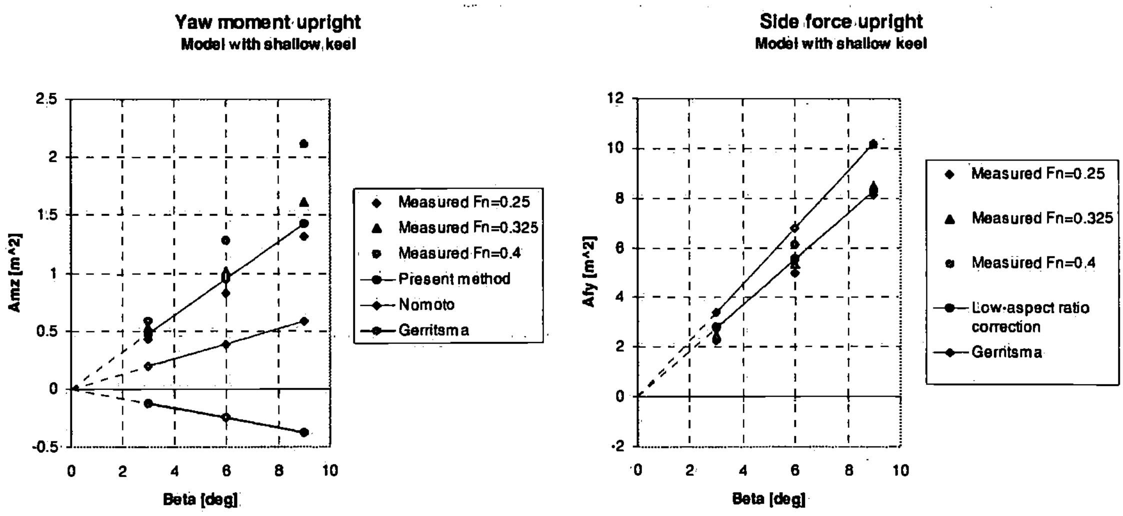


Figure 12 Side Force and Yaw Moment of a Very Large Yacht with Very Low Aspect Ratio Keel in the Upright Condition

3 – 2 Heeled Condition

A similar approach to that described above for the upright condition was applied to find an assessment method for the influence on the yaw moment due to the heeling angle of the yacht.
The proposed approach is as follows:

- *First, the side force production of the hull, keel and rudder, with heel, is predicted.*
- *A distribution between the side force on the (extended) keel and the rudder is assumed, similar to that used in the upright case. Using this distribution, the side force on keel and rudder is separately determined.*
- *The draft of each of the sections of the hull at the specific heel angle under consideration is determined and used in the Nomoto method for estimating the sway sectional added mass of the hull.*
- *The Munk Moment is now calculated, as in the upright condition, by taking the integration over the full waterline length of the hull and by using the area coefficient correction for the sway added mass, as depicted in Figure 4.*

The side force production of the yacht hull, with keel and rudder, in the heeled and yawed condition, is calculated using the well-established formulations obtained from the Delft Systematic Yacht Hull Series. These formulations, presented in Ref. [5], asses the side force production of the hull, keel and rudder combination, as function of the heeling angle, the forward speed, the canoe body draft, and the total draft of the boat. These formulations are as follows:

$$Fh * \cos(\varphi) = \left\{ b_1 * \frac{T^2}{Sc} + b_2 * \left(\frac{T^2}{Sc} \right) + b_3 * \frac{Tc}{T} + b_4 * \frac{Tc}{T} * \frac{T^2}{Sc} \right\} * \tfrac{1}{2} * \rho * V^2 * Sc * (\beta - \beta_{Fh=0})$$

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

In which:

φ	*helling angle*	*rad*
β	*leeway angle*	*rad*
T	*total draft of hull with keel*	*m*
Sc	*wetted surface of canoe body*	*m²*
Tc	*draft of canoe body*	*m*
Fh	*side force in the heelde plane*	*kN*
Fn	*Froude number*	-

The coefficients b_1 through b_4 have been determined for four heeling angles and are presented in the following Table.

φ	0	10	20	30
b1	2.025	1.989	1.980	1.762
b2	9.551	6.729	0.633	-4.957
b3	0.631	0.494	0.194	-0.087
b4	-6.575	-4.745	-0.792	2.766

The coefficient B3 has been determined from the experimental results as:

$$B_3 = 0.0092 * (Bwl / Tc) * (Tc/T)$$

Applying this approach to the yachts in the DSYHS indicated that, in particular for the higher Beam-to-Draft ratio models, there was a considerable yaw moment even at zero leeway angle. It should be noted that this measured side force at zero leeway for most models within the DSYHS is obtained by extrapolation of the measured data of the heeled and yawed tests. This yaw moment is considered to originate from the considerable asymmetry of the underwater part of the hull, when heeled. When the results of the yaw moment obtained from the heeled and yawed model tests were "extrapolated" to zero leeway angle, the following "yaw moment at zero leeway angle" could be determined for all models:

$$Mzo = CMzo * \tfrac{1}{2} * \rho * V^2 * Lwl * Alat$$

In which:

Alat = actual lateral area hull.

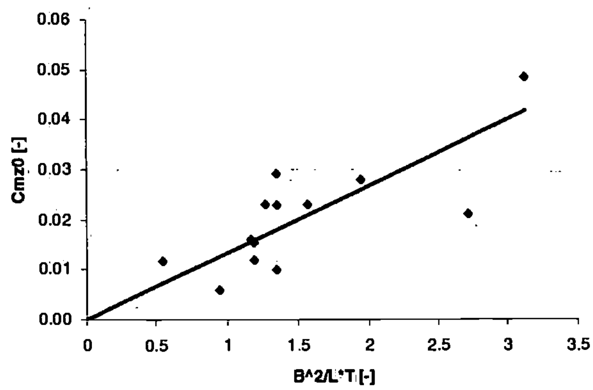
From an analysis of the DSYHS data it became evident that this asymmetry and therefore the offset (yaw moment at zero leeway angle) depended largely on the Beam-to-Draft ratio (B/T) and the Length-to-Beam ratio (L/B) of the hull under consideration. The asymmetry appeared to increase with increasing B/T ratio and to decrease with increasing L/B ratio. Other possible effects on the asymmetry due to aft LCF or LCB seemed less significant. It should be noted however, that due to the fact that all models within each sub-series of the DSYHS are derived by affined transformation a certain similarity in that respect does exist. After some manipulation the following expressions seemed to fit the data reasonably well:

$Cmz_0 = 0.01 \ Bwl^2 / Lwl * Tc$

In which:

Lwl = Waterline length
T_c = Canoe body draft
Bwl = Waterline Beam

Figure 12 Offset Coefficient at 20 Degrees of Heel.



The offset may be expressed as an "*effective additional leeway angle*" to be introduced in the Munk Moment calculation according to Nomoto, as follows:

$$\beta_{eff} = \frac{Mzo}{V^2 * \frac{\pi}{180} * a_{22}}$$

and

$$Mz = V^2 * (\beta + \beta_{eff}) * \frac{\pi}{180} * a_{22}$$

Although this relationship shows some scatter when compared with the original measured data, it produced, in general, a significant improvement in the calculated yaw moment when compared with the measurements.
In the following Figures 13 and 14 the results obtained for the side force and the yaw moment for a limited number of models of the DSYHS are shown and compared with the measured data. The main form parameters of these models are presented in the table below.

SYSSER	Lwl/Bwl	Bwl/Tc	LCB	LCF
			%	%
3	2.747	5.345	-2.30	-3.32
6	3.155	2.979	-2.40	-3.42
24	3.497	10.958	-2.09	-5.84
25	4.000	5.388	-1.99	-5.54
27	4.496	2.460	-1.88	-5.24
33	4.000	10.870	-6.55	-8.73

All data refer to one heeling angle, i.e. 20 degrees.

In figure 16 a comparison between the calculated and measured side force and yaw moment is made for the previously described large sailing yacht, also for 20 degrees of heel. For the DSYHS hulls and for the large yacht, the side force is adequately predicted, as was to be expected because this was already concluded by Gerritsma, 1985. The prediction of the yaw moment is significantly improved, at least when compared with the two earlier methods as proposed by Nomoto e.a., although discrepancies still do exist. This seems particularly so for the "deepest" models with the lower beam to draft ratio's.

Figure 13 Side force production and yaw moment of DSYHS models 3, 6 and 24 at 20 degrees of heel:

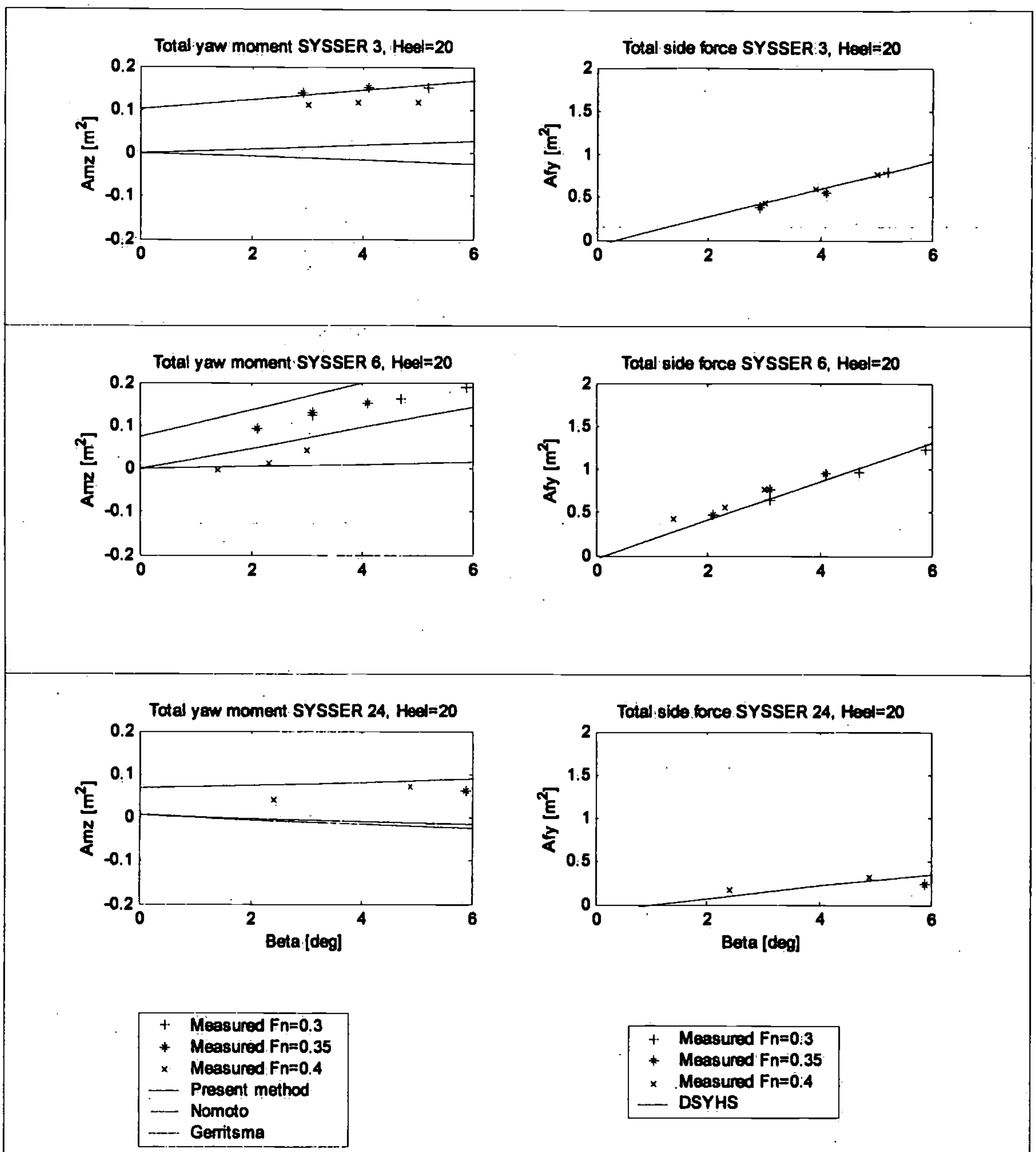


Figure 14 Side force production and yaw moment of DSYHS models 25, 27 and 33 at 20 degrees of heel:

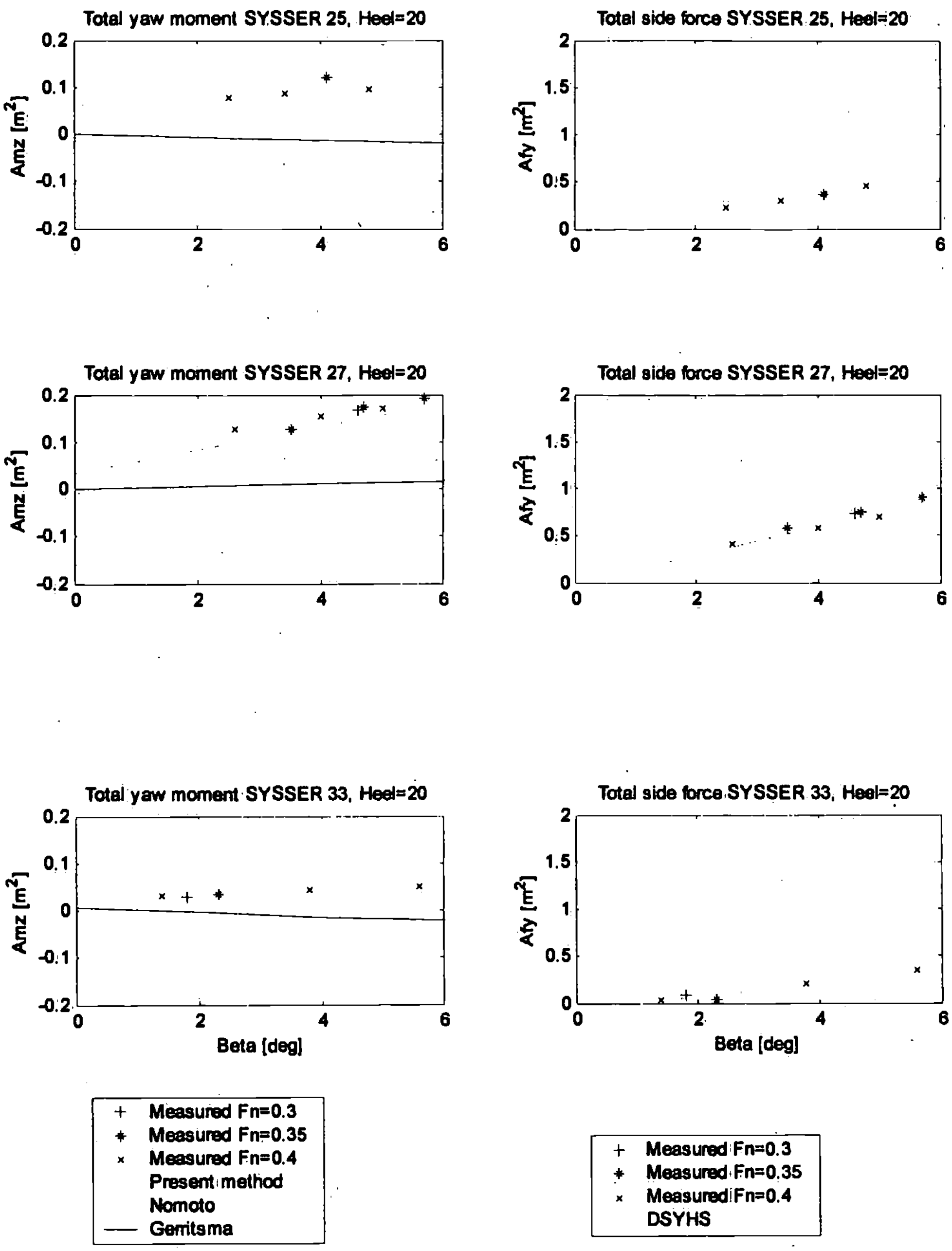
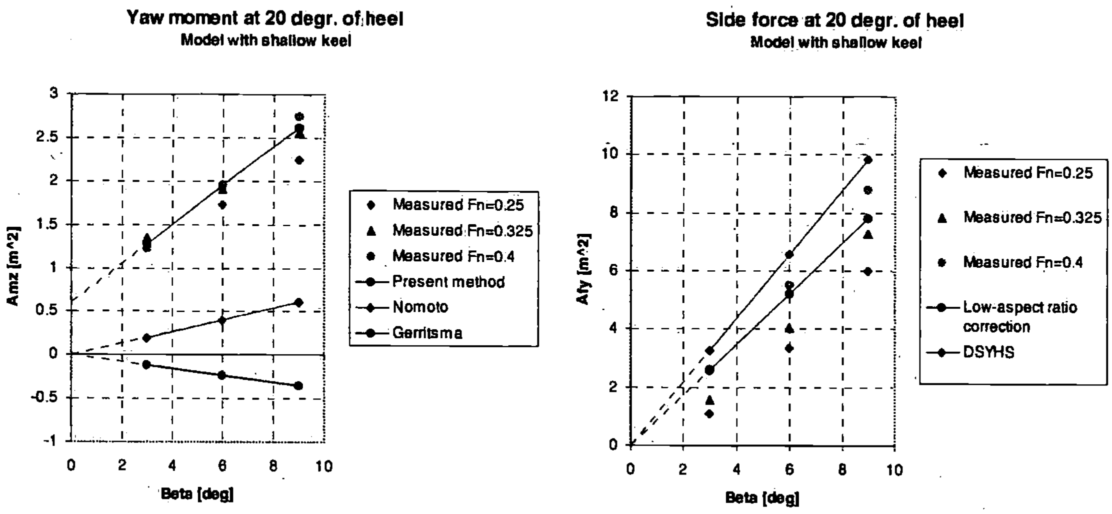


Figure 15 Side force and yaw moment of very large yacht with Very low aspect ratio keel at 20 degrees of heel



4 – CONCLUSIONS.

A comparison is made between two existing methods to calculate the side force production and yaw moment of a sailing yacht. Based on a comparison with measured results in the DSYHS an addition to these methods is formulated.

From a comparison of the results of these two existing methods, it may be concluded that, for the variety of keels presented in this study, the suggested changes in the calculation procedure, yield an improvement in the prediction of the yaw moment.
In the present study, the comparisons with the measurements are restricted to leeway angles of about 6 degrees. Since the comparisons could only be made for the upright condition is (or small heel angles) this seems a justifiable restriction, so far.

For the assessment of the yaw moment at heel angles, an additional approach has been formulated. Here, too, the proposed approach yields a rather usable assessment of the yaw moment of the appended hull. The proposed design tool seems particularly valuable for the assessment of the yaw balance of large hulls with low aspect ratio keels.

A further assessment of the influence of flow separation at larger leeway angles and the effects of forward speed on yaw moment seems to be a valuable addition on the proposed approach.

In the foreseeable future an extension to a maneuvering model including the terms due to rotation is foreseen in order to be able to predict the maneuverability of large sailing vessels under sail.

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