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A New Velocity Prediction Method for Post-Processing of Towing Tank Test Results

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ABSTRACT

A velocity prediction program (VPP) has been developed at the UAS Kiel, which implements a new method to model the hydrodynamic forces acting on the hull and appendages of a sailing yacht. Based on linear wing theory the model allows the derivation of a set of hydrodynamic coefficients for the VPP from a limited set of towing tank test runs. This approach makes the new VPP, called *AVPP*, in particular suitable to serve as a towing tank post-processor.

The paper describes *AVPP*, the hydrodynamic model and the math behind the derivation of hydrodynamic coefficients from tank test results. Two examples are shown: a study of the impact of the ACC V4/V5 rule changes and a comparison of a canting keel and a conventional keel yacht.

NOTATION

F_X, F_y	Hydrodynamic force, see Figure 1
$F_{H\beta}$	Heeling force at base rudder and tab angle
$F_{H\delta,\tau}$	Additional heeling force for $\delta \neq \delta_0, \tau \neq \tau_0$
f_{H0}	Side force coefficient at $\beta=0$, $\delta=\delta_0$, $\tau=\tau_0$
h	Righting arm
h_{Crew}	Righting arm of crew
L_{Ref}	Reference length
LCE_β	Longitudinal centre of efficiency at base rudder and tab angle
$LCE_{\delta,\tau}$	Longitudinal centre of efficiency for additional rudder and tab forces
M_x	Hydrodynamic moment, see Figure 1
$M_{x\,R}$	Hydrostatic righting moment
M_Z	Hydrodynamic moment, see Figure 1
m_{Crew}	Mass of crew
R_H	Added resistance due to heel
r_H	Added heeled resistance coefficient
R_I	Induced resistance
$R_{I\beta}$	Induced resistance at base rudder and tab angle
$R_{I\delta,\tau}$	Additional induced resistance for $\delta \neq \delta_0, \tau \neq \tau_0$
R_{PP}	Parasitic profile drag
R_{Tot}	Total hydrodynamic resistance
R_U	Upright resistance
T_R	Reference draft of the yacht
$T_{E\beta}$	Effective draft at base rudder and tab angle
$T_{E\delta,\tau}$	Effective draft for additional rudder and tab side force
t_β	Effective draft coefficient at base rudder and tab angle
U	Boat speed
VCE	Vertical centre of efficiency
β	Leeway angle
β_0	Base leeway angle
δ	Rudder angle
δ_0	Base rudder angle
φ	Heeling angle
ρ_W	Density of water
ρ_A	Density of air
τ	Trim tab angle
τ_0	Base trim tab angle
∇_R, V_R	Reference volume (canoe body immersed volume)
sgn(φ)	1 if $\varphi>0$, -1 if $\varphi<0$, 0 if $\varphi=0$

INTRODUCTION

Today towing tank testing is common practice in the design process of high performance racing yachts. However tank test results by themselves provide only limited information for the evaluation of a yacht design and it's hydrodynamic qualities. A complete analysis of the yacht's performance can only be achieved in conjunction with a velocity prediction, taking into account rig and sail set design as well as hydrostatic properties. Consequently, a strong motivation for towing tank testing of yacht hulls is to derive a set of hydrodynamic coefficients from the results for integration into a velocity prediction program (VPP). The major problem here is that a full description of the hydrodynamic properties including all resistance components of hull and appendages usually requires a large number of towing tank test runs, making these tests very expensive.

AVPP is a new 4-dof VPP that addresses this problem. *AVPP* uses a hydrodynamic model, which is based on linear wing theory in combination with empirical corrections of non-linear phenomena. Using this approach the number of test runs to completely model the hydrodynamic properties of a yacht can be reduced significantly compared to the common method of modelling hydrodynamic properties as arbitrary multidimensional surfaces. Since non-linear empirical corrections are generally small they can be neglected in many cases, further reducing the number of necessary test runs. This is particularly helpful for investigation of design alternatives, where one design parameter is varied while all other parameters remain constant.

The aerodynamic model of *AVPP* calculates aggregate sail force coefficients from wind tunnel derived individual sail force coefficients as common practice within the IMS VPP and others. Additionally windage elements and parasitic drag elements can be taken into account. The solution algorithm calculates equilibrium for four degrees of freedom. An optimisation routine maximizes boat speed adapting two sail trimming parameters, *reef* and *flat*.

For any hydrodynamic coefficient, *AVPP* provides *estimate functions* to calculate individual hydrodynamic coefficients from empirical data. This approach allows using hydrodynamic coefficients from tank test results, from CFD simulations and from empirical methods in any combination.

AVPP has been implemented as an interactive program using C++ and the MFC ©. It has been used at our institute for a couple of investigations ranging from ACC-yachts to Olympic keelboats. Two investigations are shown in this paper: (i) a comparison of two ACC yachts, designed under the V4 and V5 rule set and (ii) a comparison of a canting keel yacht with a conventional yacht.

GENERAL

AVPP is a 4-degrees-of-freedom VPP that calculates equilibrium of longitudinal and heeling forces F_X and F_H as well as yawing and heeling moments M_x and M_Z, see Figure 1 for coordinate system. The following *state variables* describe the current state of the yacht while sailing: velocity U, heeling angle φ, leeway angle β, rudder angle δ, angle of a trimming tab τ and two additional parameters modelling the trimming of the sails done by the sailors: *reef* and *flat*. U, φ, β and δ are calculated from the 4-dof equilibrium condition while *reef* and *flat* are calculated from the optimisation condition U=max.

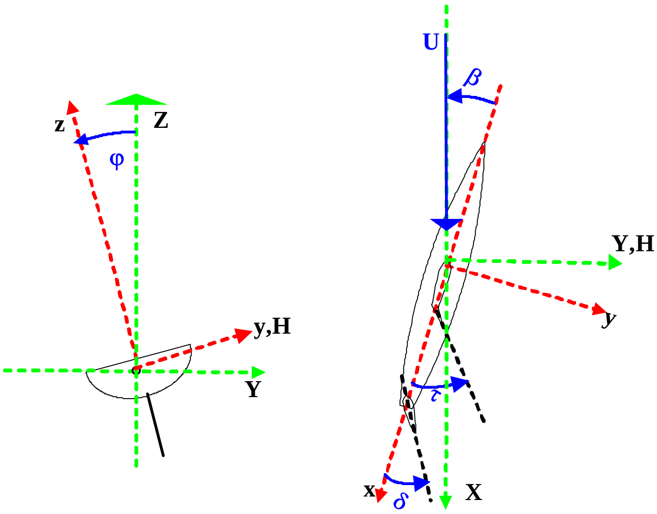

Figure 1 – Coordinate system

HYDRODYNAMIC MODEL

The hydrodynamic model describes the method to calculate forces and moments for the given degrees of freedom for any combination of values of the state variables including *off-equilibrium* states of the yacht to allow proper interpolation within the solution algorithm. The hydrodynamic model is based on dimensionless hydrodynamic coefficients, which can be derived from towing tank tests. Clearly we want these coefficients to be accurate close to realistic ("sailable") state variables of the yacht, however for off-equilibrium states accuracy is less important. Consequently we want a towing tank test matrix (the definition of the test runs carried out in the towing tank) to be dense close to sailable states while sparse at potential off-equilibrium states.

AVPP addresses this by using an *equilibrium state guess* where all towing tank-tests are centred around. The equilibrium state guess (esg) defines rudder angle δ_0 and tab angle τ_0 depending on heeling angle:

$$\delta_0 = f(\varphi),\ \tau_0 = f(\varphi) \qquad (1)$$

esg will be defined as a table and approximated with a spline function during calculations. If no use of esg shall be made, $\delta_0 = \tau_0 = 0$ is set as default.

The total hydrodynamic force in X-direction is the resistance: $F_X = R_{Tot}$. It is calculated using:

$$R_{Tot} = R_U + R_H + R_I + \sum R_{PP} \qquad (2)$$

Here R_{Tot} is total resistance, R_U upright resistance at non-lifting condition, R_H added resistance due to heel, R_I

induced resistance due to production of lift and R_{PP} parasitic profile drag of blade and rudder profile.

R_U is defined as a table R_U=f(U) derived from towing tank results. R_H is defined as a table $r_H=R_H/R_U$=f(U, φ) as a fraction of R_U.

Induced resistance R_I is calculated from base induced resistance $R_{I\beta}$ at rudder angle $\delta=\delta_0$ and tab angle $\tau=\tau_0$ and additional induced resistance components for deviations of rudder and tab angle from esg-values:

$$R_I = R_{I\beta} + R_{I\delta} + R_{I\tau} \quad (3)$$

Simple superposition is sufficient here since $R_{I\delta}$ as well $R_{I\tau}$ can be assumed to be small for proper esg.

$R_{I\beta}$ is calculated using effective draft $T_{E\beta}$ of yacht's canoe body and appendages arranged under the canoe body:

$$R_{I\beta} = \frac{F_{H\beta}^2}{T_{E\beta}^2} \frac{1}{0.5\rho_W U^2 \pi} \quad (4)$$

where $F_{H\beta}$ is the heeling force acting in H-direction (lift perpendicular on flow direction and span). ρ_W is fluid density. $T_{E\beta}$ and $F_{H\beta}$ are effective draft and heeling force at rudder angle $\delta=\delta_0$ and tab angle $\tau=\tau_0$.

The base effective draft $T_{E\beta}$ is derived from towing tank test results, defined as functions $t_{E\beta}=T_{E\beta}/T_R$= f(U, φ), where T_R is the reference draft of the yacht. Linear lifting surface theory says that $T_{E\beta}$ is constant for any heeling angle φ, boat velocity U and leeway angle β. So for general applications in real fluids it can be assumed that deviations of $T_{E\beta}$ from a single value are small.

Heeling force $F_{H\beta}$ is calculated from:

$$F_{H\beta} = (f_{H0} + \frac{\partial f_H}{\partial \beta}\beta)\, 0.5\rho_W U^2 \nabla_R^{2/3} \quad (5)$$

where ∇_R is the reference buoyancy and f_H is the heeling force coefficient:

f_{H0} is heeling force coefficient at zero leeway β=0, $\partial f_H / \partial \beta$ its gradient with respect to β, both at base rudder and tab angle δ_0 and τ_0. A table generated from towing tank data supplies f_{H0}(U,φ) and $\partial f_H / \partial \beta (U, \varphi)$. Again linear wing theory gives constant coefficients $\partial f_H / \partial \beta$ and f_{H0}. Consequently it can be assumed that deviations from a single value are small.

For small deviations of rudder and tab angle from esg-values some heeling force corrections are calculated as follows:

$$F_{H\delta} = \frac{\partial f_H}{\partial \delta}(\delta - \delta_0)\frac{1}{2}\rho_W U^2 \nabla_R^{2/3}$$

$$F_{H\tau} = \frac{\partial f_H}{\partial \tau}(\tau - \tau_0)\frac{1}{2}\rho_W U^2 \nabla_R^{2/3} \quad (6)$$

Derivatives $\partial f_H / \partial \delta$ and $\partial f_H / \partial \tau$ are derived from towing tank test results as function of heeling angle φ only. Total heeling force F_H is calculated from:

$$F_H = F_{H\beta} + F_{H\delta} + F_{H\tau} \quad (7)$$

For deviations of rudder and tab angles from esg-values additional induced resistance is calculated as follows:

$$R_{I\delta} = \frac{F_{H\delta}^2}{T_{E\delta}^2}\frac{1}{0.5\rho U^2 \pi} \quad (8)$$

$$R_{I\tau} = \frac{F_{H\tau}^2}{T_{E\tau}^2}\frac{1}{0.5\rho U^2 \pi} \quad (9)$$

$t_{E\delta}=T_{E\delta}(\varphi)/T_R$ and $t_{E\tau}=T_{E\tau}(\varphi)/T_R$ are given tabulated data, derived from towing tank data or calculated by estimate functions. The decomposition of induced resistance as applied here neglects some non-linearity. In addition, a situation where total side force F_H is lower than base side force $F_{H\beta}$ induced resistance is of rudder and tab are modelled incorrect. However this can be avoided with proper esg-values

Moments are calculated around x- and Z-axis as follows:

$$M_Z = (F_{H\beta} LCE_\beta + F_{H\delta} LCE_\delta + F_{H\tau} LCE_\tau)\cos\varphi \quad (10)$$

LCE_β/L_R and respective values for δ and τ are tabulated functions of φ to be derived from towing tank test data .

$$M_x = F_y VCE = F_H VCE / \cos\beta \quad (11)$$

Here the transformation $F_y = F_H / \cos\beta$ assumes small leeway angles and resistance to be smaller than side forces. It is also assumed that any wing only generates resistance in flow direction and lift perpendicular on flow force direction and span (no flow forces are generated in the direction of span).

The vertical centre of efficiency VCE is assumed to depend on φ only, being independent of distribution of side forces on keel, rudder and tab. It is given as a tabulated function. For total moment around x-axis, the hydrostatic moment $M_{xRighting}$ has to be added:

$$
\begin{aligned}
M_{xR} = -(h(|\varphi|)\nabla_R g\rho \\
+ m_{Crew} g\, h_{Crew} \cos(\varphi) \min(1, \frac{|\varphi|}{6}) \\
+ M_{R\,Dyn}) \operatorname{sgn}(\varphi)
\end{aligned}
\qquad (12)
$$

Here h is hydrostatic righting arm, m_{Crew} and h_{Crew} are crew mass and crew arm respectively. It is assumed that crew righting moment applies fractionally only for heeling angles less than 6°.

COEFFICIENT SET AND ESTIMATE FUNCTIONS

The set of hydrodynamic coefficients is summarized in the following list:

- $R_U = f(U)$ — Upright Resistance
- $r_H = f(U,\varphi)$ — Heeled Resistance Coeff.
- $t_\beta, t_\delta, t_\tau = f(U,\varphi)$ — Effective Draft Coefficients
- $f_{H0} = f(U,\varphi)$ — Side Force Coefficients
- $\partial f_H / \partial\beta = f(U,\varphi)$ — Side Force Coefficients
- $\partial f_H / \partial\delta(,\tau) = f(\varphi)$ — Side Force Coefficients
- $LCE_{\beta,\delta,\tau}/L_R = f(\varphi)$ — Centre of Efficiency Coeffs.
- VCE =f(φ) — Vertical Centre of Efficiency Coefficient

These coefficients can be derived from towing tank test results as shown in the following chapter. However they are generally independent of each other and thus can be determined from different sources, may it be regression methods, CFD calculations and towing tank test results. As an example a common practice for appendage optimisation at our institute is to use canoe body resistance data from towing tank tests, side force generation coefficients from Vortex Lattice Grid CFD calculations and appendage resistance data from RANSE CFD calculations.

If non of the above methods are available for the generation of hydrodynamic coefficients AVPP supplies *estimate functions* providing hydrodynamic coefficients from empirical methods. Upright resistance, effective draft and added resistance due to heel are calculated from *Keuning's* method (Keuning, 1998). Rudder and tab side force coefficients and respective effective draft coefficients and centres of efficiency are estimated using empirical formula derived from CFD-calculations (Graf, 1984). Again these *estimate functions* can be used in any combination with one of the above methods to calculate hydrodynamic coefficients. In the preliminary design phase of a yacht a velocity prediction can be carry out entirely based on *estimate functions*.

DERIVING HYDRODYNAMIC COEFFICIENTS FROM TOWING TANK TEST RESULTS

In order to derive a complete set of hydrodynamic coefficients development of a suitable test matrix needs special attention. The following test matrix (Figure 2) allows to detect any non-linearity of hydrodynamic coefficients, for example the impact of rudder and tab on the effective draft, dependency of side force coefficients on boat speed and heeling angle and so on. It consists of 51 test runs: 7 resistance test runs at non-lifting conditions, 20 leeway tests at esg-values for rudder and tab angles and some rudder and tab angle variations (cross matrices). In many cases one is not interested in yawing balance. In this case the cross-matrices (rudder and tab variations) can be substituted by single tests at esg-values for rudder and tab angle, reducing the number of test runs to 31. Decreasing the number of investigated leeway angles can further shrink the test matrix without sacrificing accuracy too much.

AVPP Test Matrix

Non-lifting test conditions

Fn	
0.25	1
0.30	1
0.35	1
0.40	1
0.45	1
0.50	1
0.55	1

Lift-generation test conditions

Heel Angle	0°			8°			16°			24°	
Leeway Angl	0°	2°	4°	0°	2°	4°	1°	3°	5°	2°	4°
Fn											
0.25											
0.30											
0.35	1			1	1	1		1			1
0.40	1			1	6	1		6			1
0.45	1			1	6	1		6			1
0.50	1			1	1	1		1			1
0.55											

Total Number of Test Runs 51

Pointmatrix: 1 Runs	τ_0+1	τ_0	τ_0-2
δ_0+1			
δ_0		1	
δ_0-1			
δ_0-2			

Crossmatrix: 7 Runs	τ_0+1	τ_0	τ_0-2
δ_0+1		1	
δ_0	1	1	1
δ_0-1		1	
δ_0-2		1	

Equilibrium State Guess						
Heel	φ	[°]	0	8	16	24
Leeway	β_0	[°]	0	2	3	4
Rudder	δ_0	[°]	0	-2	-4	-7
Tab	τ_0	[°]	0	0	-5	-5

Sailing condition: Wind from starboard

Figure 2 - AVPP Towing Tank Test Matrix

The process of towing tank testing is not described in this paper. A description of common procedures and implications is given in *Claughton et.al.(1998).*

Model test results have to be transformed to full scale, applying some Reynolds-correction. For the method presented here, only the resistance test results have to be transferred. The method used here is derived from the ITTC'78 Performance Prediction Method (*Harvald, 1992*).

While upright resistance is integrated into AVPP as a simple table of native values, other hydrodynamic coefficients have to be treated in a different way.

The easiest way to understand derivation of coefficients is to plot some diagrams where flow forces or moments are approximated with some linear function. This is done for any combination of boat velocity and heeling angle (in practice drawing of diagrams can be substituted by some linear regression algorithm, provided by spreadsheet programs).

Leeway tests results are generated with rudder angle δ_0 and tab angle τ_0 as given from esg-table. Plotting heeling force $F_H = F_Y / \cos(\varphi)$ over leeway angle β allows to derive $\partial F_H / \partial \beta$ and F_{H0}, see Figure 3. With canoe body buoyancy V_R, density of fluid ρ_W and velocity U the following coefficients can be calculated:

$$\partial f_H / \partial \beta = \frac{\partial F_H / \partial \beta}{0.5 \rho_W U^2 V_R^{2/3}} \qquad (13)$$

$$f_{H0} = \frac{F_{H0}}{0.5 \rho_W u^2 V_R^{2/3}} \qquad (14)$$

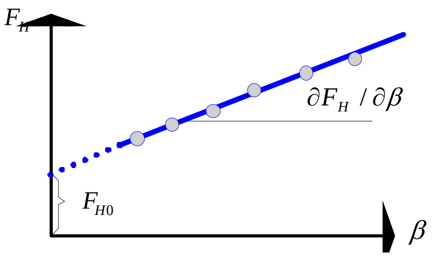

Figure 3 - Leeway Test Result Plot

To derive effective draft ratio $t_{E\beta} = T_E/T_R$ and added resistance due to heel, the results from the leeway tests at base rudder and tab angle, longitudinal flow forces F_X are plotted over F_H squared. The sum of upright resistance and added resistance due to heel R_H+R_U can be derived from an extrapolation of a linear approximation of $F_X = f(F_H^2)$, while effective draft can be derived from slope of linear approximation, see Figure 4.

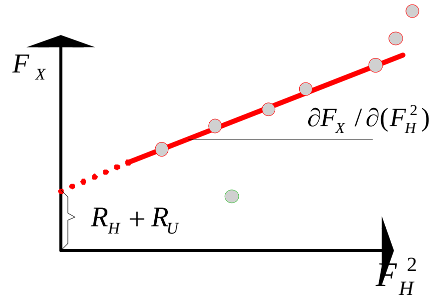

Figure 4- Leeway Test Result Plot for Effective Draft

$$r_H = \frac{R_H}{R_U} = \frac{F_X(\varphi, F_H = 0) - F_X(\varphi = 0, F_H = 0)}{F_X(\varphi = 0, F_H = 0)} \qquad (15)$$

$$t_{E\beta} = \frac{1}{T_R \sqrt{\partial F_X / \partial (F_H^2) 0.5 \rho U^2 \pi}} \qquad (16)$$

Plotting yawing moment M_Z and side force F_Y over leeway angle β allows deriving side force and yawing moment slope, see Figure 5

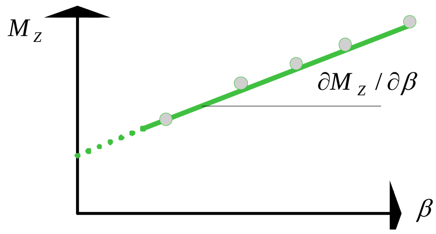

Figure 5- Yawing Moment Slope

Longitudinal centre of efficiency can then be calculated by:

$$LCE_\beta / L_R = \frac{\partial M_Z / \partial \beta}{\partial F_Y / \partial \beta} \frac{1}{L_R} \qquad (17)$$

LCE_β has to be corrected by the distance of longitudinal position of measurement dynamometer from origin.

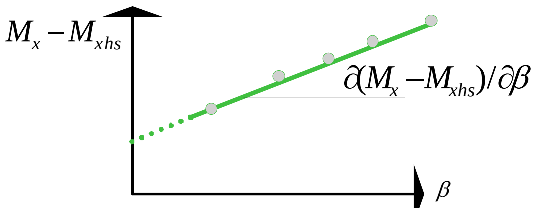

Figure 6 - Heeling Moment Slope

For vertical centre of efficiency, it is assumed that it does not vary with velocity. For VCE_β plot M_x-$M_{x\ hs}$ over heeling angle β, Figure 6. Assuming $F_y=F_H/\cos\beta$, VCE will be derived from:

$$\frac{VCE}{T_R} = \frac{\partial(M_x - M_{x\,hs})/\partial\beta}{\partial F_y/\partial\beta}\frac{1}{T_R} \quad (18)$$

Here $M_{x\ hs}$ is the righting moment at U=0, the hydrostatic righting moment of model, which can be derived from an additional heeling test at U=0. It has to be subtracted to separate hydrodynamic from hydrostatic heeling moment. VCE is calculated for esg-values of rudder and tab angles. It is assumed that VCE does not change if side forces change due to non-esg-values of rudder and tab angles. VCE has to be corrected by the distance of the dynamometer centre of heeling rotation to origin.

Rudder and tab side force coefficients, effective span and longitudinal centre of efficiency are derived similar. To derive rudder and tab side force coefficients, plots of side forces $F_{H\delta}$ $(F_{H\tau})$ against rudder angle δ (tab angle τ) at leeway angle $\beta=\beta_0$ are used:

$$\partial f_H/\partial\delta = \frac{\partial F_H/\partial\delta}{0.5\rho_W U^2 V_R^{2/3}} \quad (19)$$

$$\partial f_H/\partial\tau = \frac{\partial F_H/\partial\tau}{0.5\rho_W U^2 V_R^{2/3}} \quad (20)$$

For effective span, heeling force $F_{H\delta}$ $(F_{H\tau})$ squared are plotted against F_X. Effective span coefficients for rudder and tab can then be calculated using:

$$t_{E\delta} = \frac{1}{T_R\sqrt{\partial F_X/\partial(F_{H\delta}^2)0.5\rho_W U^2\pi}} \quad (21)$$

$$t_{E\tau} = \frac{1}{T_R\sqrt{\partial F_X/\partial(F_{H\tau}^2)0.5\rho_W U^2\pi}} \quad (22)$$

For longitudinal centre of efficiency of rudder and tab the following equations are used:

$$LCE_\delta/L_R = \frac{\partial M_Z/\partial\beta}{\partial F_{Y\delta}/\partial\beta}\frac{1}{L_R} \quad (23)$$

$$LCE_\tau/L_R = \frac{\partial M_Z/\partial\beta}{\partial F_{Y\tau}/\partial\beta}\frac{1}{L_R} \quad (24)$$

All coefficients derived so far are dimensionless and can be transferred to full scale without further corrections, as long as geometric values of reference volume V_R, length L_R and draft T_R are used corresponding to model scale.

AERODYNAMIC MODEL AND SOLUTION ALGORITHM

The aerodynamic model is responsible for the calculation of aerodynamic forces. *AVPP* uses the method that has been implemented in the *IMS* velocity prediction program. It is based on individual sail force coefficients for mainsails, jibs and spinnakers, derived from wind tunnel coefficients. Aggregate lift and drag coefficients c_{Ltotal} and c_{Dtotal} for a sail set are calculated from:

$$c_{DTotal} = c_D\, reef^2 + CE\, c_L^2\, flat^2\, reef^2 \quad (25)$$

$$c_{LTotal} = flat\ reef^2\ c_L \quad (26)$$

Here c_D and c_L are weighted sums of the drag and lift coefficient of all sails in the sail set while *CE* is an *efficiency coefficient*, taking into account the quadratic parasite profile drag and the effective span of the sail set. *reef* and *flat* are trimming parameters for the sail to obtain maximum boat velocity via depowering the sail or reducing sail area. *flat* is a linear reduction of lift and respective squared reduction of induced and parasite drag at constant span, corresponding to a sail chord or traveller angle trimming action of the sailor. *reef* is a factor taking into account a reduction of sail area as the name implies, with corresponding impact on lift, drag and effective span.

For details of this method see *Claughton et.al.(1998)* or the *IMS* documentation from the *Offshore Racing Council*.

An additional aerodynamic model calculates sail forces from a vortex lattice grid CFD method. While inherently restricted to non-separated flow and thus for upwind sailing conditions, this method allows the definition of sails of arbitrary shape to study impact of sail trimming on the performance of the yacht. For further information see *Graf, 1996.*

A full description of all forces and moments acting on a sail yacht has to include the wind resistance of so called windage elements – any part of the yacht generating aerodynamic resistance that is not taken into account by the sail forces model as above. *AVPP* allows defining additional windage drag areas for an unlimited number of windage elements. Also a table of righting arms $h=f(\varphi)$ has to be supplied by the user in order to define righting moments as in (12).

The general solution algorithm calculates equilibrium of aerodynamic and hydrodynamic forces applying Newton-Rawson iteration. For estimated values of the velocity $\hat{U}$, heeling angle $\hat{\varphi}$, leeway angle $\hat{\beta}$ and rudder angle $\hat{\delta}$ the aerodynamic and hydrodynamic forces and moments $F_{X,H}^A, M_{x,Z}^A, F_{X,H}^W, M_{x,Z}^W$ are calculated. A correction of estimated state variables is then calculated solving:

$$\begin{bmatrix} \frac{\partial F_X}{\partial U} & \frac{\partial F_X}{\partial \beta} & \frac{\partial F_X}{\partial \varphi} & \frac{\partial F_X}{\partial \delta} \\ \frac{\partial F_H}{\partial U} & \frac{\partial F_H}{\partial \beta} & \frac{\partial F_H}{\partial \varphi} & \frac{\partial F_H}{\partial \delta} \\ \frac{\partial M_x}{\partial U} & \frac{\partial M_x}{\partial \beta} & \frac{\partial M_x}{\partial \varphi} & \frac{\partial M_x}{\partial \delta} \\ \frac{\partial M_Z}{\partial U} & \frac{\partial M_Z}{\partial \beta} & \frac{\partial M_Z}{\partial \varphi} & \frac{\partial M_Z}{\partial \delta} \end{bmatrix} \begin{Bmatrix} U' \\ \beta' \\ \varphi' \\ \delta' \end{Bmatrix} = - \begin{Bmatrix} F_X^A(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) + F_X^W(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) \\ F_Y^A(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) + F_Y^W(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) \\ M_x^A(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) + M_x^W(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) + M_{xRighting}(\hat{\varphi}) \\ M_Z^A(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) + M_Z^W(\hat{U},\hat{\varphi},\hat{\beta},\hat{\delta}) \end{Bmatrix} \quad (27)$$

Derivatives $\partial F_X / \partial U$ … can be developed from wing theory or calculated as finite differences.

Boat speed is optimised using *Brents Method*, a multi-step minimization search method with free parameters *flat* and *reef*.

For yawing balance a special treatment of longitudinal centre of effort has to be used, because IMS sail force coefficients do not include information about the longitudinal position of the centre of effort. In the approach presented here rudder angles for a small heeling angle have to be estimated. *AVPP* calculates the change of rudder angle due to additional heel. This method allows to take into account additional rudder resistance for larger heeling angles, where the rudder angle has to be increased to maintain lateral balance.

IMPLEMENTATION

AVPP has been implemented as a 'Point and Click' interactive program using C++, the Microsoft Foundation Classes© and OpenGL©. The set of hydrodynamic coefficients has to be provided as tabular data, which is interpolated with the help of some Spline functions.

For practical reasons *AVPP* implements the concept of *trial horse comparisons*, found in many VPPs. This simplifies the investigation of design alternatives.

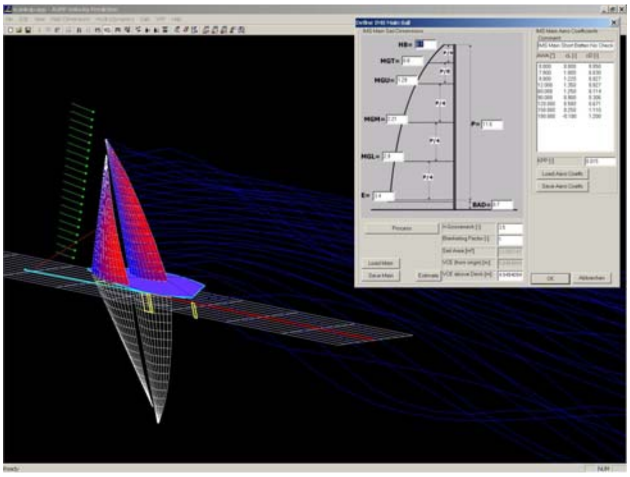

Figure 7 - *AVPP* user interface

EXAMPLES

IACC-Rules V4 / V5 Comparison

Since the last *Americas Cup* races spring 2003 the rules governing the design of the *Americas Cup Class (ACC)* yachts has changed from V4 to V5. In this example *AVPP* is used to study the impact of the rule changes on the performance of the yachts.

The V4/V5 rule changes can be summarized as follows:

- Maximum displacement has been decreased by 1 ton to 24 tons.
- Maximum draft has been increased by 10 cm to 4.1 m.
- Maximum spinnaker area has been increased from 1.5 to 1.6 times the sum of mainsail and 100% jib area.
- The design frame for the rating length has been narrowed.

While taking into account the first three changes of the rules in a comparison of V4 and V5-yachts seems to be quite straight forward, the last rule change concerning the measurement length needs some attention. The ACC rule in general allows trading sail area against length, however the V4 rule does this to a much higher degree than the V5 rule. The comparison presented here is based on max-displacement ACC designs with minimum girth corrections and length between girth of LBG=20.28m giving a sail area of S_M=319.4 m² for the V4 design and LBG=20.18m giving S_M=321.4m² for the V5 design. This is based on the assumption that a generation 2003 – boat with a reduced displacement is measured under the V5-rules with the consequence that the length LBG changes by approximately 0.1m.

Towing tank test results have been available for a generation 2000 spoon-bow ACC yacht with a beam of

B=3.6m, see Figure 8. While not completely replicating design details of generation 2003 boats, for a V4/V5 comparison the tank test results are sufficient.

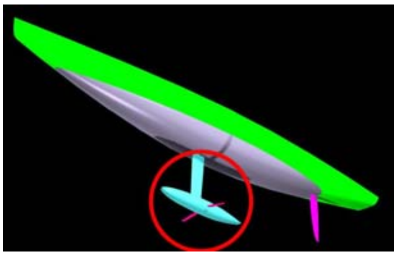

Figure 8 - ACC generation 2000 yacht

Analysing the tank test results as described in the previous chapters, the following results arise. Figure 9 shows effective draft coefficient $t_{E\beta}$, added heeled resistance coefficient r_H and side force coefficient $\partial f_H / \partial \beta$ over heeling angle φ for boat speed *U=9.75 kts*. While side force coefficient does not vary much with heeling angle added resistance due to heel is negative for larger heeling angles as expected. Effective draft coefficient varies with heeling angle somewhat implausible. A benefit of the proposed analysis is the amplification of any measurement errors and data noise, simplifying the detection of inaccuracy of the measurement results. However as a trend it can be derived that effective draft slightly increases with heeling angle. This is a typical phenomenon that can be observed for winged keel configurations.

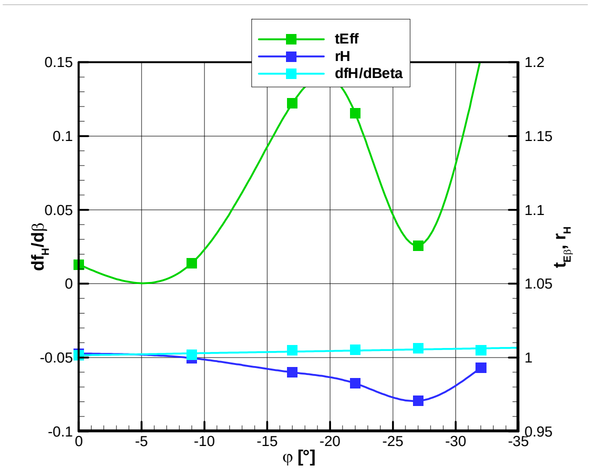

Figure 9 - Effective draft, heeling force coefficient and added heeled resistance coefficient

Hydrodynamic coefficients for the V5-design have been derived from the V4-design coefficients using the following procedure:

- For the righting arm it is assumed that the 1-ton weight reduction is realized by lowering the weight of the ballast bulb only. The resulting righting arm of the V5-design does not vary much from the V4-design.
- The resistance curve of the V5 design has been developed from the resistance curve of the V4-design and derivatives $\partial R_U / \partial \nabla$ and $\partial R_U / \partial LBG$ derived from Keunings regression method (Keuning, 1998).
- Effective draft ratio and added heeling resistance ratio are assumed to be the same for both V4- and V5-design.
- Rudder- and tab-coefficients do not change at all.

Figure 10 shows righting arm versus heeling angle for both designs, showing small differences only. This might be the desired result of the inventors of the rule change. Figure 11 shows a comparison of the V4-design and V5-design resistance curves. While for boat speed of 5 m/s and below the resistance difference is almost negligible, for larger boat speed the resistance delta increases to a value of about 5%.

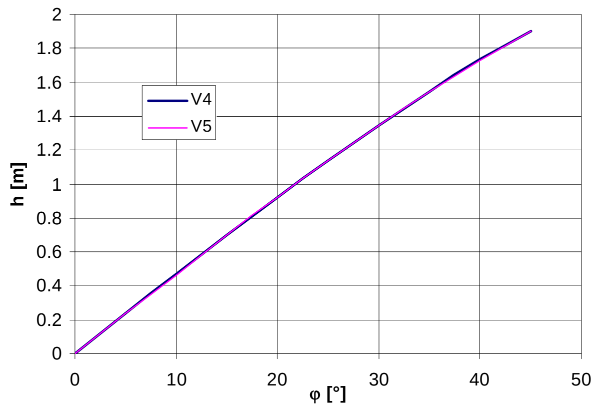

Figure 10 – Righting arm IACC V4 and V5 design

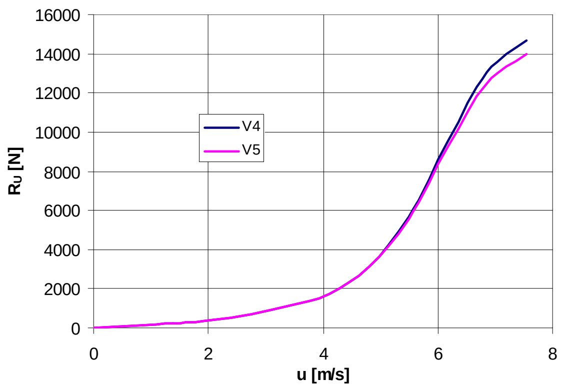

Figure 11 – Upright resistance comparison ACC yacht V4/V5

Figure 12 shows the velocity polar for the two ACC designs. For the upwind sailing condition the velocity difference is quite small and can almost be neglected. For the downwind sailing condition the V5-yachts show better performance, which is primary a result of the increased spinnaker sail area.

In general the performance difference of the ACC yachts measured under the V4 and V5 rule are quite small. The differences are large enough to enforce a complete new design cycle and additional optimisation effort for the next generation of the boats. However for the outside observer the new V5 yachts will be neither less nor more exciting and spectacular to observe than they are currently.

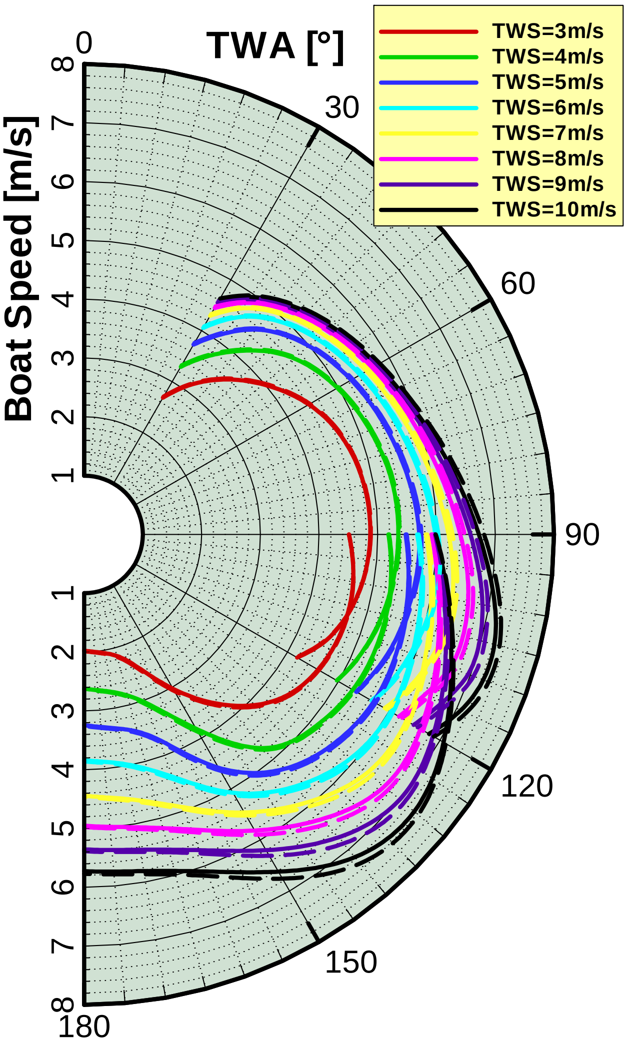

Figure 12 - Velocity Polar ACC V4/V5 Yacht

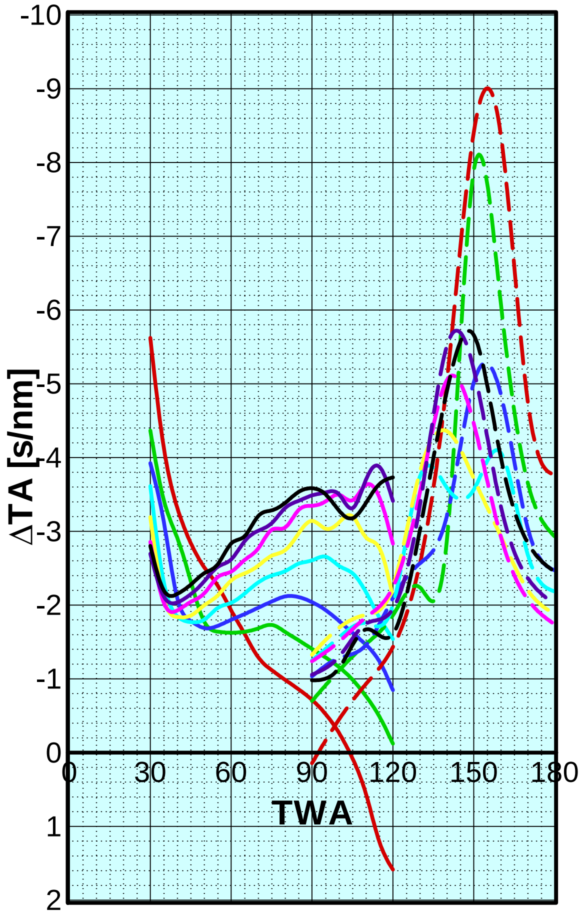

Figure 13 – Time Allowance Deltas for V5-ACC yacht compared to V4 design

Canting Ballast X-Foil Yacht

The second example shows *AVPPs* ability to treat sailing yachts with a canting ballast keel (CBK). CBK appendage concepts are getting more popular for many modern performance yachts because they promise significant performance benefits. The general idea is to rotate the keel around a longitudinal axis in order to swing the ballast to windward, increasing the righting moment significantly. For side force production additional wings are necessary, commonly realized by a pair of additional asymmetric sideboards arranged at some distance exterior of the centreline. This can be seen as a separation and subdivision of the functionality of a conventional keel – producing side forces and righting moment – with two separate wings, each optimised for it's particular purpose.

SailOvation is a new design of a CBK-yacht, developed by yacht designer M.v. Ahlen for a German sailing magazine. The design concept resembles some of the design characteristics of *Open60* yachts, namely small length to beam ratio, a large transom beam and twin rudders. However *SailOvation* is a yacht of 9 m length supposed to be sailed by a very small crew. Therefore the concept of a pair of sideboards has been abandoned in order to simplify manoeuvring, in particular tacking. An additional swivelling keel blade has been placed at the centreline, which will be canted to leeward while the ballast moves to weather, see Figure 14. This is called the X-keel.

Towing tank tests have been carried out at University of Applied Sciences' open water circulation tank at Reynolds-numbers of approx. $Rn=2.5*10^6$. Leeway tests have been carried out with an X-keel configuration with canted blade and ballast keel as shown in Figure 14 and with both blade and ballast keel non-canted.

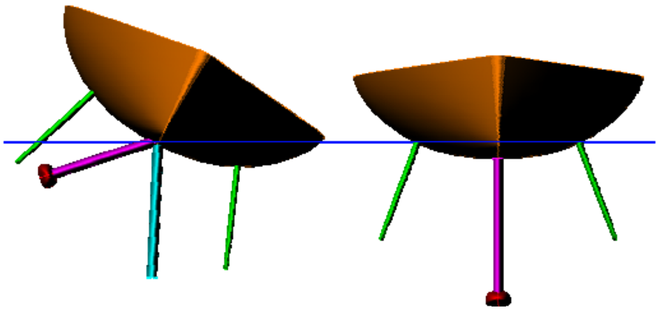

Figure 14 - SailOvation X-keel Arrangement

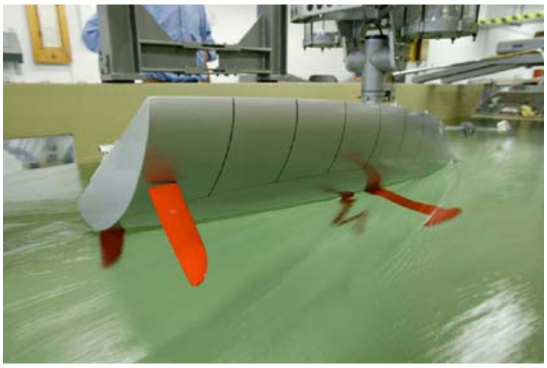

Figure 15 - SailOvation Canting Ballast Keel Yacht

Figure 16 shows a comparison of righting arms for the canted and non-canted appendage configuration, clearly verifying the strong increase of righting moment by canting of ballast. *AVPP* assumes continuous heeling arm derivatives which makes it necessary to smooth the change of righting arm due to canting ballast over a range of heeling angles.

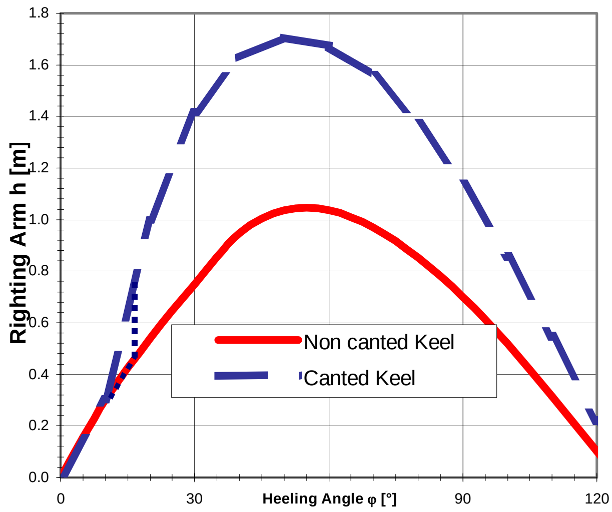

Figure 16 - SailOvation Righting Arm over Heeling Angle for canted and non-canted appendage configuration

Figure 17 shows a comparison of side force coefficient $\partial f_H / \partial \beta$ over boat speed and heeling angle. Generally $\partial f_H / \partial \beta$ is larger for the non-canted keel configuration, however while the non-canted keel looses efficiency with increasing heeling angle the side force for the canted configuration remains almost constant.

Figure 18 shows a comparison of the normalized resistance of the heeled hull for both keel variants, indicating an increase of added heeled resistance of the non-canted keel configuration. The probable reason here is the additional resistance of the ballast bulb and the blade of the ballast keel close to the free surface as well as some additional resistance at the root of the keel blades.

Figure 19 shows a comparison of effective draft coefficient for both keel configurations. The result is somewhat surprising. Compared to the non-canted keel the effective span of canted keel is smaller for small heeling angles but larger for large heeling angles. To understand this, it has to be recalled that the effective span is a measure for any resistance bound to the production of lift. The blade of the X-keel has a symmetric profile. It thus needs some yawing angle to produce lift. As a consequence the canted ballast keel will produce lift as well even though this is not desired. The canted ballast-keel is a far less effective wing when swung to windward. The windward canted blade of the ballast keel by its own has a very small effective span, thus producing some additional induced drag.

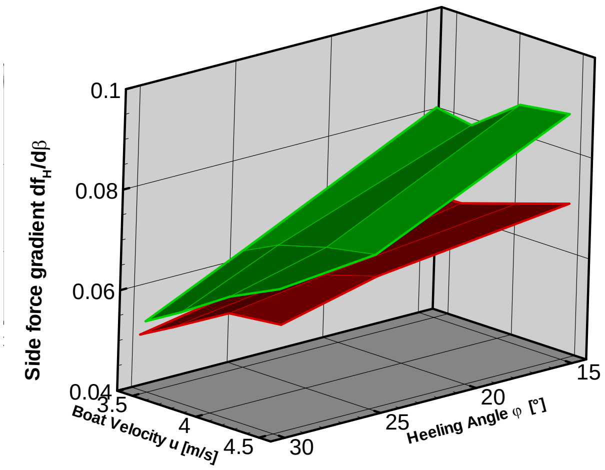

Figure 17 - SailOvation Comparison of Side Force Coefficient (RED: canted, GREEN: non-canted)

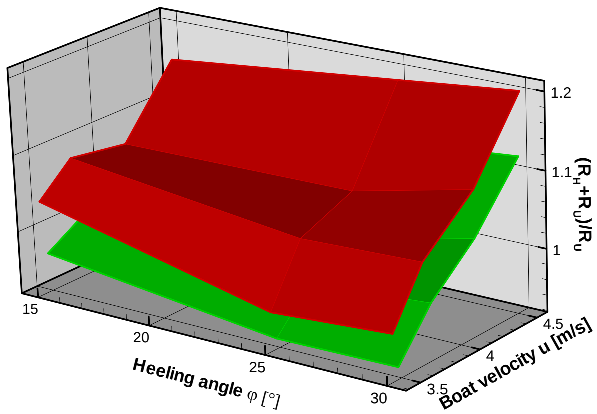

Figure 18 - SailOvation Comparison of Added Heeling Resistance Coefficient (RED: canted, GREEN: non-canted)

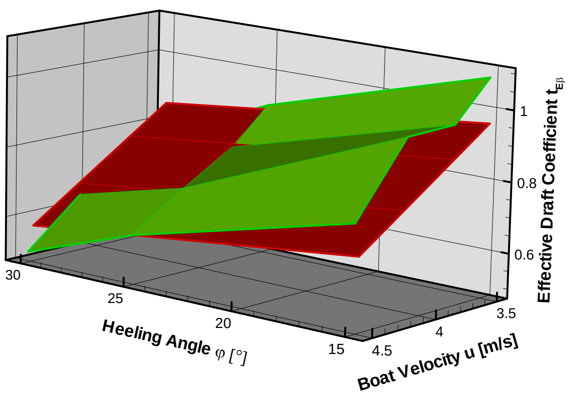

Figure 19 - SailOvation Comparison of Effective Draft Coefficient (RED: canted, GREEN: non-canted)

Figure 20 and Figure 21 show the velocity polar of both keel configurations for true wind velocities of 3 m/s to 9 m/s.

Although the canted keel configuration generates some additional resistance the performance is generally superior to the non-canted keel configuration as expected. In particular for strong wind conditions the large righting moment of the canting keel increases velocity significantly, proving that this keel-concept promises performance gains conventional yacht cannot achieve.

For lower wind velocities the pattern changes. For very light wind and for deep downwind courses – sailing conditions where hydrostatic stability is not the limiting factor for yacht performance – additional resistance of the canted keel configuration decreases boat speed. Here the ballast keel should be fixed to the mid-ship position. The crossover heeling angles and wind velocities can be derived from the polar diagrams.

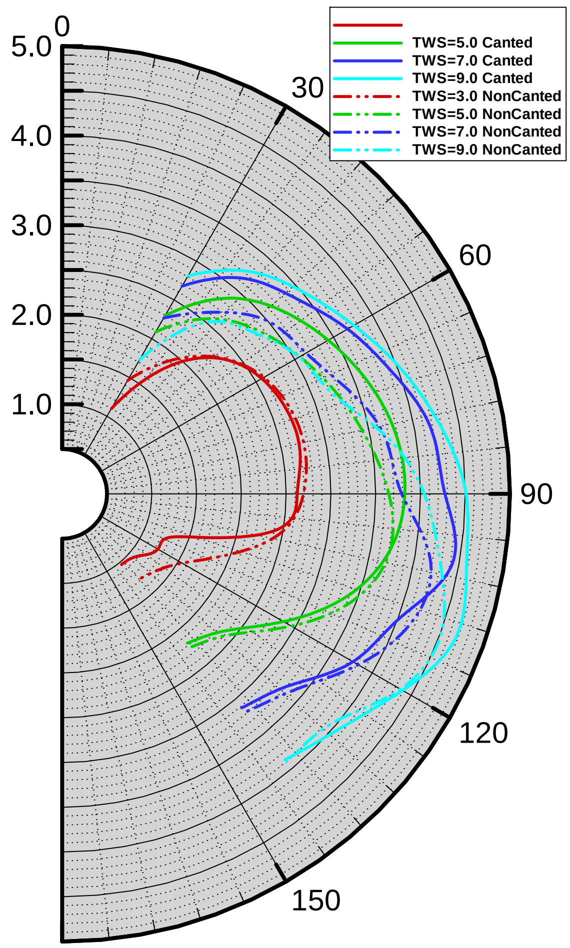

Figure 20 - Velocity Polar SailOvation Canted and Non-canted Configuration UPWIND

It has to be pointed out that a conventional keel is a more efficient keel design than the tested keel in non-canting condition, which might be the reason for the quite poor upwind performance of the yacht with non-canted keel configuration. A comparison based on a conventional keel rather than a canting keel in non-canting condition would probably push the crossover heeling angles and wind velocities to larger values.

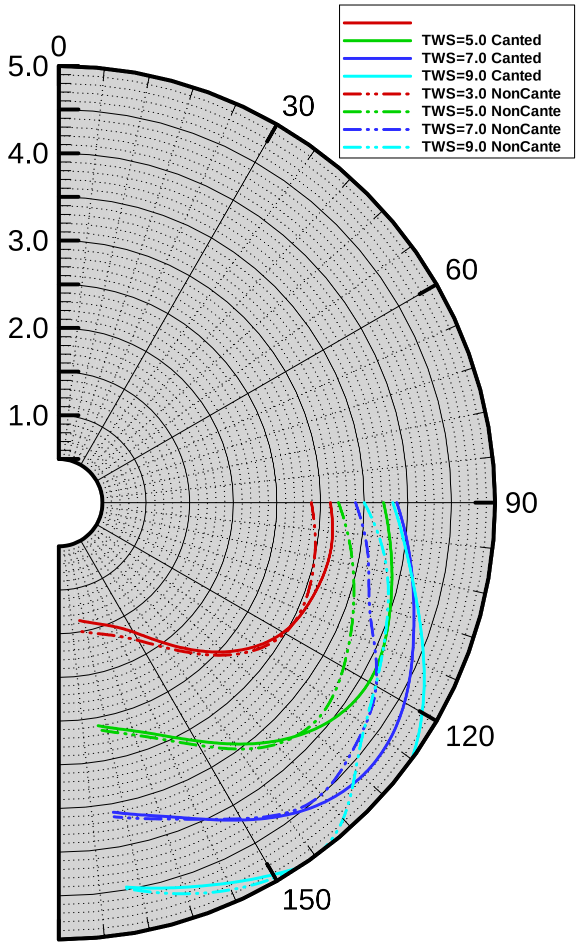

Figure 21 - Velocity Polar SailOvation Canted and Non-canted Configuration DOWNWIND

CONCLUSION

In this paper a new velocity prediction method has been introduced which has been developed to simplify the post-processing of towing tank test results. The hydrodynamic model of the method is based on linear wing theory allowing empirical corrections for non-linear phenomena. A complete set of hydrodynamic coefficients can be derived from restricted number of towing tank test runs. The program implementation of the method, called *AVPP*, allows the integration of hydrodynamic coefficients from different sources, may it be towing tank test results, CFD results or empirical data in any combination.

The paper shows two examples of VPP investigations: a comparison of ACC yachts measured under the V4 and V5 version of the rating rules and a Canting Ballast keel yacht.

In the first example it has been shown that *AVPP* simplifies the investigation of design alternatives, namely variations of buoyancy and draft. The ACC V4/V5 comparison shows that the rule changes only have a minor impact on boat performance.

The second example shows *AVPPs* ability to investigate canting ballast keel yachts. The analysis of towing tank test result indicates, that a canted-keel configuration will generate some additional resistance elements, however at strong wind conditions the performance of such a keel configuration is superior to a conventional keel by a quite remarkable margin.

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