REAL-TIME VELOCITY PREDICTION PROGRAM FOR WIND TUNNEL TESTING OF SAILING YACHTS

H Hansen, The University of Auckland, New Zealand
P S Jackson, The University of Auckland, New Zealand
K Hochkirch, FRIENDSHIP-Systems, Germany

SUMMARY

Wind tunnel testing is an effective design tool in competitive yachting but good trimming of the sails is of paramount importance to obtain accurate results. At present it is common practice to trim the sails by maximising the drive force. In many sailing conditions however this does not result in the maximum boat speed. A VPP is hence developed to predict the boat speed from the wind tunnel measurements in real-time and enable the sails to be trimmed to maximise boat speed rather than drive force.

The real-time VPP (RT-VPP) is implemented in the Twisted Flow Wind Tunnel at The University of Auckland. Initial upwind tests are conducted and the results compared to the performance predicted by employing a semi-empirical aerodynamic force model with trim parameters. This shows the potential of the RT-VPP to investigate aerodynamic forces in a more direct way than was previously possible.

NOMENCLATURE

β_T, β_A, β_{eff}	True, apparent and effective wind angle (°)
ϕ, λ, δ, θ	Heel, leeway, rudder and trim angle (°)
η	Angle of resultant force direction in z-plane (°)
$_A$, $_T$	Indices for absolute and wind tunnel coordinate system
$_m$	Index for wind tunnel model
a	Point on central axis, $\mathbf{a}=(a_x\ a_y\ a_z)^T$ (m)
$\mathbf{C}_F$, $\mathbf{C}_M$	Force and moment coefficient vector, $\mathbf{C}_F=(C_{FX}\ C_{FY}\ C_{FZ})^T$ (-), $\mathbf{C}_M=(C_{MX}\ C_{MY}\ C_{MZ})^T$ (-)
CoE	Centre of effort point, $\mathbf{CoE}=(x_{CoE}\ 0\ z_{CoE})^T$ (m)
F, **M**	Force and moment vector, $\mathbf{F}=(F_X\ F_Y\ F_Z)^T$ (N), $\mathbf{M}=(M_X\ M_Y\ M_Z)^T$ (Nm)
$\mathbf{T}_\phi$	Transformation matrix for rotation through ϕ (-)
A_S, AR	Reference sail area (m^2) and aspect ratio (-)
C_D	Total drag coefficient (-)
C_{Di}, C_{Dvis}	Induced and viscous drag coefficient (-)
C_L, C_{Lopt}	Lift and optimum lift coefficient (-)
c_t, c_s	Twist and separation constant (-)
e	Efficiency factor (-)
q_A, q_{eff}	Apparent and effective dynamic pressure (Nm^{-2})
r, f, t	Trim parameters reef, flat and twist (-)
V_S, V_T, V_{eff}	Ship, true and effective wind speed (m/s)
z	Heeled geometric centre of sail area height (m)
z_{ref}	Reference height (m)
RT-VPP	Real-time velocity prediction program

1. INTRODUCTION

Wind tunnel testing of yacht sails is an effective design tool in competitive yachting. It enables the designer to assess different sail geometries at the design stage and determine the relative performance for any sailing condition in a constant test environment. Many sail force coefficients used in velocity prediction programs (VPPs) have also been derived from wind tunnel tests. For assessing downwind sails wind tunnel testing is particularly useful since significant portions of the flow along the chord of the sails are separated. Hence potential flow methods cannot be used and viscous flow models, e.g. the Reynolds Averaged Navier-Stokes Equations (RANSE), are still computationally too expensive to be used as standard tools and still require intense validation of their results.

For many wind tunnel tests, soft sails of similar material properties to those of the full-scale sails are preferred because their flying shape can be altered as in real life to give the optimal shape for a given sailing condition. This process of trimming the sails is very important both in full-scale and in the wind tunnel. Due to the large number of possible adjustments trimming is also complex and requires a lot of experience. On a real yacht a good guide of how well the sails are trimmed is the ratio between the achieved speed of the yacht and the target speed predicted by a VPP. In the wind tunnel it is common practice to trim the sails by maximising the drive force, which in the wind tunnel is the force acting along the centreline of the model yacht. If the drive force is maximised for a certain test condition, the sails are assumed to have the optimal shape.

Wind tunnel testing is commonly used as a sail design tool for comparative testing of different sails. In many cases sails are judged by simply comparing the maximised drive force coefficients. This however ignores the differences in, for example, the side force and heeling moment produced by the different sails and may not yield the sail that would perform best in real life. Especially the heeling moment (M_X) should not be ignored for the majority of sail types. It can be considered by trying to maximise the drive force and at the same time keep M_X under a certain critical value while trimming the sails. This however increases the complexity of trimming further and it is still difficult to draw accurate conclusions of the relative performance of different sails. It is hence common practice to post process wind tunnel results by entering the data into a VPP and compare the resultant boat speeds for different sails.

Assessing the performance of sails is further complicated by the fact that the optimal shape, at which a sail performs aerodynamically most efficiently and produces the maximum driving force, will not necessarily result in the maximum speed of the yacht. The heeling moment (M_X) generated by the sails can lead to an excessive heel angle of the yacht, which increases the hydrodynamic resistance and reduces the aerodynamic efficiency. In this situation departing from the optimal sail shape by, for example, reducing the angle of attack at the top of the sails to decrease M_X may increase the boat speed. Similarly reducing the aerodynamic side force and consequently the leeway angle (λ) or reducing the yaw moment (M_Z) and hence rudder angle (δ) may be beneficial in certain conditions. Departing from the optimal sail shape to maximise the boat speed is approximated in most VPPs by using optimal aerodynamic force coefficients in conjunction with trim parameters reef (r), flat (f) and more recently twist (t). The trim parameters describe the effect the change in sail shape has on the forces and moments.

The real-time VPP (RT-VPP) aims to change this wind tunnel testing process by enabling the operator to trim the sails to maximise the yacht speed rather than the drive force. The performance of different sails can then be directly compared based on boat speed without having to post process the results. The RT-VPP calculates the yacht's speed directly from the forces measured in the wind tunnel while the sails are trimmed, taking all the constraints mentioned earlier into account. It also eliminates the need to use trim parameters. In addition to making the sail trimming, and the whole comparative testing process, much more like the real life situation, the RT-VPP can be used to assess the accuracy of the assumptions made when using trim parameters.

When trimming sails in the wind tunnel without the RT-VPP the resultant heel angle (ϕ) of the yacht is not known. The aerodynamic models in VPPs use effective angle theory to simulate the heel angle of the yacht. As a result sails are in many cases only tested in the upright condition. The RT-VPP continuously calculates the heel angle of the yacht while the sails are trimmed. It is interfaced with a mechanism which heels the model dynamically in the wind tunnel to the calculated angle. This improves modelling of the real life condition further and allows the validity of the effective angle theory to be assessed.

2. SEMI-EMPIRICAL VELOCITY PREDICTION PROGRAMS

Semi-empirical VPPs are popular tools to predict the speed of a yacht at the design stage. In most cases a steady state analysis approach is taken. The yacht is assumed to operate in a constant wind environment. All forces acting on the yacht need to be in equilibrium for the yacht to move at a constant speed in a constant direction at a constant orientation. In practice not all six degrees of freedom are considered, mainly because of difficulties in modelling all the aerodynamic forces and moments. Usually two equations for the force equilibrium in the plane of the water are set up. The drive force generated by the sails must equal the resistance of the hull, rig and appendages and the side force generated by the keel, hull und rudder must balance the side force of the sails. A third equation is taken from the heel moment and righting moment equilibrium (Figure 1). Some VPPs use a fourth equation to balance the yawing moment. There are different ways to set up the mathematical and computational model for solving the equations. The most common approach is to determine the maximum speed (V_S) of the yacht for a given true wind direction (β_T) and speed (V_T). The force coefficients need to be described in terms of the free variables of ship speed (V_S), heel angle (ϕ), leeway angle (λ), rudder angle (δ) and the trim parameters flat (f) and reef (r). An initial guess for the free variables is required before the solution is started. As shown in Figure 2 the first step for each iteration is to calculate the aerodynamic forces and the centre of effort (**CoE**). From this the remaining free variables can be obtained through the iterative process outlined in Figure 2. Alternatively more advanced optimisation methods can be employed to determine the maximum speed as will be discussed in section 3. Either process is repeated for all true wind speeds and angles of interest.

A second method, less often adhered to, is to assume a value for boat speed and leeway angle from which the hydrodynamic side force and resistance can be calculated. The aerodynamic forces are then determined by solving the equations for equilibrium. This in turn allows the calculation of the true wind speed and angle. The calculations are performed for a series of leeway angles for all points of sail. An interpolation method then yields V_S, ϕ, λ and δ for each true wind speed and angle. This approach is described in more detail by Van Oossanen [1]. With this method it is mathematically simpler to find the aerodynamic and hydrodynamic force equilibrium and the method places the hydrodynamic characteristics of the hull and appendages in a more central role.

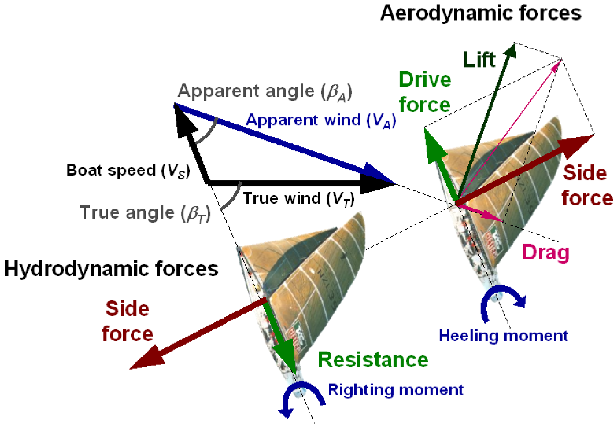


Figure 1: Forces and moments acting on a sailing yacht that are modelled by a three equation VPP

2.1 SEMI-EMPIRICAL AERODYNAMIC SAIL FORCE MODEL

The aerodynamic sail force model of semi-empirical VPPs derives the forces from the optimum lift and viscous drag coefficients (C_{Lopt} and C_{Dvis}) given as functions of the effective wind angle (β_{eff}). Effective angle theory assumes that the sails are insensitive to span-wise flow that results from heeling [2]. The sails are therefore only influenced by the flow component in the heeled z-plane, which is perpendicular to an idealised mast without bend or rake (Figure 3). The apparent angle in the z-plane is called the effective angle (β_{eff}) and the speed in the z-plane is the effective wind speed (V_{eff}). The C_{Lopt} and C_{Dvis} curves in the z-plane are assumed to remain the same for any heel angle (ϕ).

The effective wind angle (β_{eff}) is for simplicity calculated at the geometric centre of sail area height (z_{CoA}) since the centre of effort height is not constant. As the yacht heels the height above the water (z) is $z=z_{CoA}\cos\phi$. From the true wind speed (V_T) at the reference height (z_{ref}) of 10m the true wind speed at height z can be calculated assuming a logarithmic velocity profile [3] from

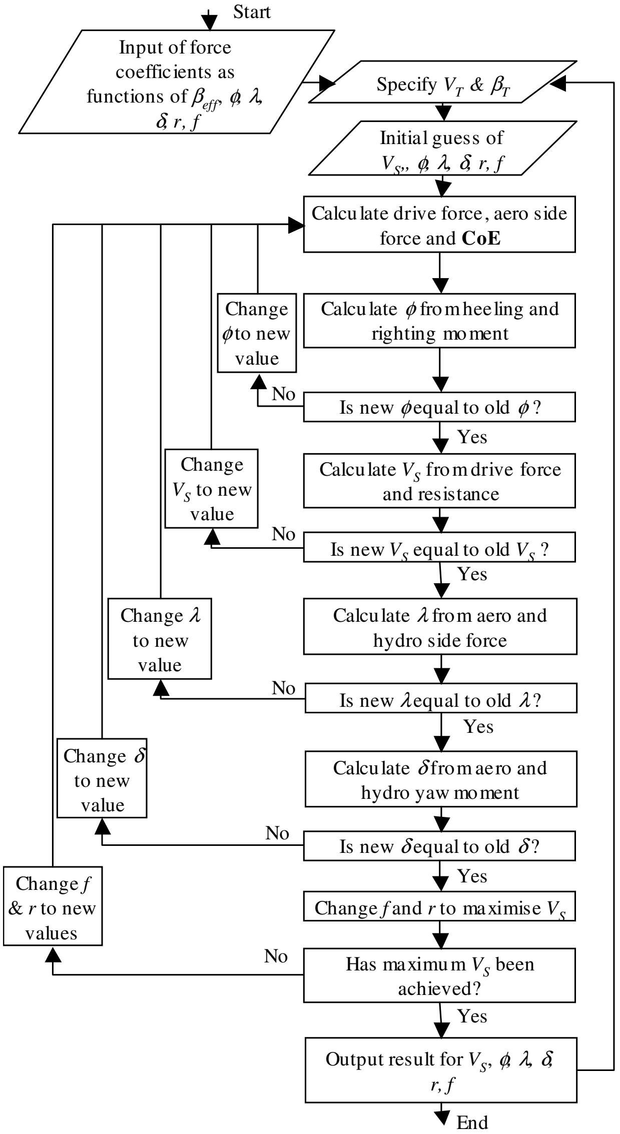


Figure 2: Generic semi-empirical VPP with flat and reef as trim parameters

$$V_T(z) = V_T(z_{ref})\frac{\log(z/z_0)}{\log(z_{ref}/z_0)}, \tag{1}$$

where the surface roughness (z_0) is taken as 0.001m from the International Measurement System (IMS) formulation [3]. The effective angle (β_{eff}) at height z can be expressed as a function of $V_T(z)$, the true wind angle (β_T), ϕ and V_S as

$$\beta_{eff} = \tan^{-1}\frac{V_T(z)\sin\beta_T\cos\phi}{V_T(z)\cos\beta_T + V_s}, \quad \beta_{eff}\in\left[0{,}180^\circ\right]. \tag{2}$$

For β_{eff} the lift coefficient can be determined from C_{Lopt} as

$$C_L = C_{Lopt}(\beta_{eff})r^2 f, \quad r \le 1, \quad f \le 1, \tag{3}$$

where reef (r) and flat (f) are trim parameters. The total drag coefficient is the sum of the skin friction drag coefficient (C_{D0}), the induced drag coefficient (C_{Di}) and the separation drag coefficient (C_{Ds}). C_{Ds} can be expressed as a function of C_L^2 *by*

$$C_{Ds} = C_L^2 c_s, \tag{4}$$

where the separation drag constant (c_s) is 0.019 for main with spinnaker and 0.016 for main with jib [3]. C_{D0} and C_{Ds} are often not separated but are combined in the viscous drag coefficient (C_{Dvis}). The total drag coefficient (C_D) is then

$$C_D = C_{Dvis}(\beta_{eff})r^2 + C_{Di}. \tag{5}$$

C_{Di} is ideally a function of C_L^2 and depends on the aspect ratio (AR) and the efficiency (e) of the rig. To account for non-elliptical loading the trim parameter twist (t) is introduced so that

$$C_{Di} = \frac{C_{Lopt}^2(\beta_{eff})r^2 f^2}{\pi e AR}(1 + c_t t^2), \quad t \in [0{,}1], \tag{6}$$

where the twist constant (c_t) is often taken as the theoretical value of 8 following Jones [4]. From C_L and C_D the drive

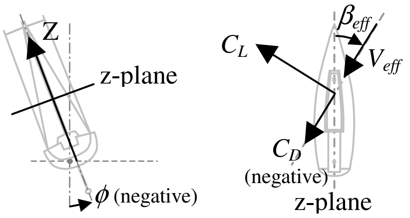


Figure 3: Lift and drag coefficient and effective angle are defined in the heeled z-plane.

force (C_{FX}) and side force (C_{FY}) coefficients in the z-plane are calculated as

$$\begin{pmatrix} C_{FX} \\ C_{FY} \end{pmatrix} = \begin{bmatrix} \cos\beta_{eff} & \sin\beta_{eff} \\ -\sin\beta_{eff} & \cos\beta_{eff} \end{bmatrix} \begin{pmatrix} C_D \\ C_L \end{pmatrix}, \tag{7}$$

where C_D has a negative value since it is acting in the negative x-direction for β_{eff} smaller than 90° (Figure 3). The drive force (F_X) and side force (F_Y) in the heeled z-plane can now be calculated by multiplying the coefficients by the reference sail area (A_S) and the effective dynamic pressure (q_{eff}) as

$$F_X = C_{FX} A_S q_{eff} = C_{FX} A_S \frac{\rho_{air}}{2} V_{eff}^2, \tag{8}$$

$$F_Y = C_{FY} A_S q_{eff} = C_{FX} A_S \frac{\rho_{air}}{2} V_{eff}^2, \tag{9}$$

where V_{eff} is the effective wind speed in the z-plane described by

$$V_{eff} = \sqrt{(V_T(z)\sin\beta_T \cos\phi)^2 + (V_T(z)\cos\beta_T + V_S)^2}\,. \tag{10}$$

The heel moment (M_X) and yaw moment (M_Z) are obtained from the centre of effort position in the y-plane, which is aligned with the centreline of the yacht (x-axis) and the z-axis. The x-position of the centre of effort (x_{CoE}) and z-position (z_{CoE}) are described as functions of the resultant force direction (η) in the z-plane [5]. η is defined as

$$\eta = \tan^{-1}\frac{F_Y}{F_X}. \tag{11}$$

The **CoE** can hence be described as the point

$$\mathbf{CoE} = (x_{CoE}, 0, (z_{boom} + (z_{CoE} - z_{boom}) r(1-t)))^T, \tag{12}$$

where z_{boom} is the boom height in the body fixed coordinate system (coordinate system B) and the centre of effort height (z_{CoE}) is dependent on the trim parameters r and t. The forces $\mathbf{F}=(F_X\ F_Y\ F_Z)^T$ and **CoE** are transformed by rotating through the heel angle (ϕ) to obtain $\mathbf{F}_A$ and $\mathbf{CoE}_A$ in the absolute coordinate system, in which the z_A-plane is horizontal, with

$$\mathbf{F}_A = \mathbf{T}_\phi \mathbf{F}, \tag{13}$$

$$\mathbf{CoE}_A = \mathbf{T}_\phi \mathbf{CoE}, \tag{14}$$

where the transformation matrix ($\mathbf{T}_\phi$) is

$$\mathbf{T}_\phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}. \tag{15}$$

The moments $\mathbf{M}_A=(M_{XA}\ \ M_{YA}\ \ M_{ZA})^T$ in the horizontal absolute coordinate system are then obtained from

$$\mathbf{M}_A = \mathbf{CoE}_A \times \mathbf{F}_A. \tag{16}$$

2.1(a) Position of Centre of Effort

In order to calculate the moments the distances x_{CoE} and z_{CoE} in the y-plane are required as functions of η. The forces (**F**) and moments (**M**) obtained from wind tunnel or full-scale tests can be transferred into a central axis coordinate system[5]. The line through which **F** is now acting is called the central axis. The point (**a**) on the central axis that is closest to the origin can be determined from

$$\mathbf{a} = \frac{\mathbf{F} \times \mathbf{M}}{|\mathbf{F}|^2}. \tag{17}$$

Since **F** is aligned with the central axis any point along the central axis can be seen as the point through which the force is acting. The intersection of the central axis and the y-plane can hence be defined as the **CoE** and its position is determined from

$$x_{CoE} = a_x - \frac{a_y}{F_Y} F_X, \tag{18}$$

$$z_{CoE} = a_z - \frac{a_y}{F_Y} F_Z. \tag{19}$$

2.1(b) Trim Parameters Reef, Flat and Twist

Trim parameters are used to account for departure from the optimal sail shape to de-power the sails. They can be adjusted from 0 to 1 to maximise the speed of the yacht. Flat (f) <1 represents a linear reduction in lift (Equation 3) due to reducing the camber of the sails. C_{Di} is hence reduced by f^2 (Equation 6). Reef (r) <1 represents a linear reduction in span and chord of the sails. The sail area is therefore reduced by r^2, which affects C_L and C_D as shown in Equations 3, 5 and 6. The centre of effort height (z_{CoE}) is linearly affected by r as shown in Equation 12. Reef was originally intended as a geometric rather than an aerodynamic factor to model the physical reefing of a sail, but it has become thought of as representing any change to the sail trim that reduces z_{CoE} [2]. Twist (t) >0 is intended to model a linear reduction in z_{CoE} through twisting the sails (Equation 12). As a result the induced drag increases proportional to t^2 (Equation 6) due to departing from the ideal loading condition [2]. It is however not trivial to determine the twist constant (c_t) and t is not widely used in VPPs yet.

3. REAL-TIME VPP FOR WIND TUNNEL TESTING

The RT-VPP for wind tunnel testing has been developed for the Twisted Flow Wind Tunnel (TFWT) at The University of Auckland. It is designed as an additional module for FRIENDSHIP-Equilibrium, a semi-empirical

VPP developed by FRIENDSHIP-Systems and the Technical University of Berlin in Germany [5]. FRIENDSHIP-Equilibrium solves for the steady state equilibrium for up to 6 degrees of freedom using a Newton-Raphson solver and optimises V_S in an outer loop by varying the trim parameters using the Hooke-Jeeves-Algorithm as shown in Figure 4. In contrast to the sequential configuration of many other VPPs (Figure 2) the simultaneous solution procedure allows it to satisfy the equilibrium condition in up to 6 degrees of freedom in a reasonable time. Within FRIENDSHIP-Equilibrium the components of the yacht are abstracted by so called 'force modules' which can easily be added or removed and combined in any number and thus the program allows investigating of the influence of different models. Figure 4 shows how FRIENDSHIP-Equilibrium can be used with either a semi-empirical rig force module that uses trim parameters as described in section 2.1 or with the wind tunnel rig force module. Trim parameters are not required when the wind tunnel module is used and the outer optimisation loop is disabled (Figure 4).

The forces and moments acting on the wind tunnel model are measured with a six-component force balance located under the wind tunnel floor. The force balance can be rotated together with the floor above (turntable) to change the apparent wind angle. The turntable has a recess so that the waterline of the model coincides with the tunnel floor. The recess is filled with water to prevent any flow of air under the hull. The model sits in a cradle, which is attached to the force balance and allows the model to heel (Figure 5). A system to dynamically heel the model to the angle calculated by FRIENDSHIP-Equilibrium has been developed. A computer-controlled electric motor heels the model and accelerometers measure the heel angle (ϕ_m). A program written in LabVIEW acquires the wind tunnel data, performs some of the calculations and communicates the relevant data via a shared memory link with FRIENDSHIP-Equilibrium, which is running as a separate application independently in the background. The LabVIEW program also acts as the front end of the RT-VPP. It displays and saves the results (Figure 6) and controls the heel motor.

3.1 AERODYNAMIC WIND TUNNEL FORCE MODEL

The wind tunnel coordinate system, in which the forces ($\mathbf{F}_T$) and moments ($\mathbf{M}_T$) are measured, is aligned with the centreline of the model and the horizontal plane (coordinate system T). $\mathbf{F}_T$ and $\mathbf{M}_T$ are corrected for the change in the position of the centre of gravity and the change in the hydrostatic force, due to the water in the turntable recess, as the model heels. $\mathbf{F}_T$ and $\mathbf{M}_T$ are expressed in coefficient form and transformed to the body fixed coordinate system of the yacht (coordinate system B) by rotating through ϕ_m and translating through the distance between the coordinate systems origins ($\overrightarrow{\mathbf{BT}}$) so that

$$\mathbf{C}_F = \frac{1}{q_{effm} A_{Sm}} \mathbf{T}_{\phi m}^{-1} \mathbf{F}_T, \tag{20}$$

$$\mathbf{C}_M = \frac{1}{q_{effm} A_{Sm}^{1.5}} \mathbf{T}_{\phi m}^{-1} \left(\mathbf{M}_T + \overrightarrow{\mathbf{BT}} \times \mathbf{F}_T \right), \tag{21}$$

where $\mathbf{C}_F$ and $\mathbf{C}_M$ are the force and moment coefficient vectors in the heeled z-plane (coordinate system B), A_{Sm} is the reference sail area of the model and q_{effm} is the effective

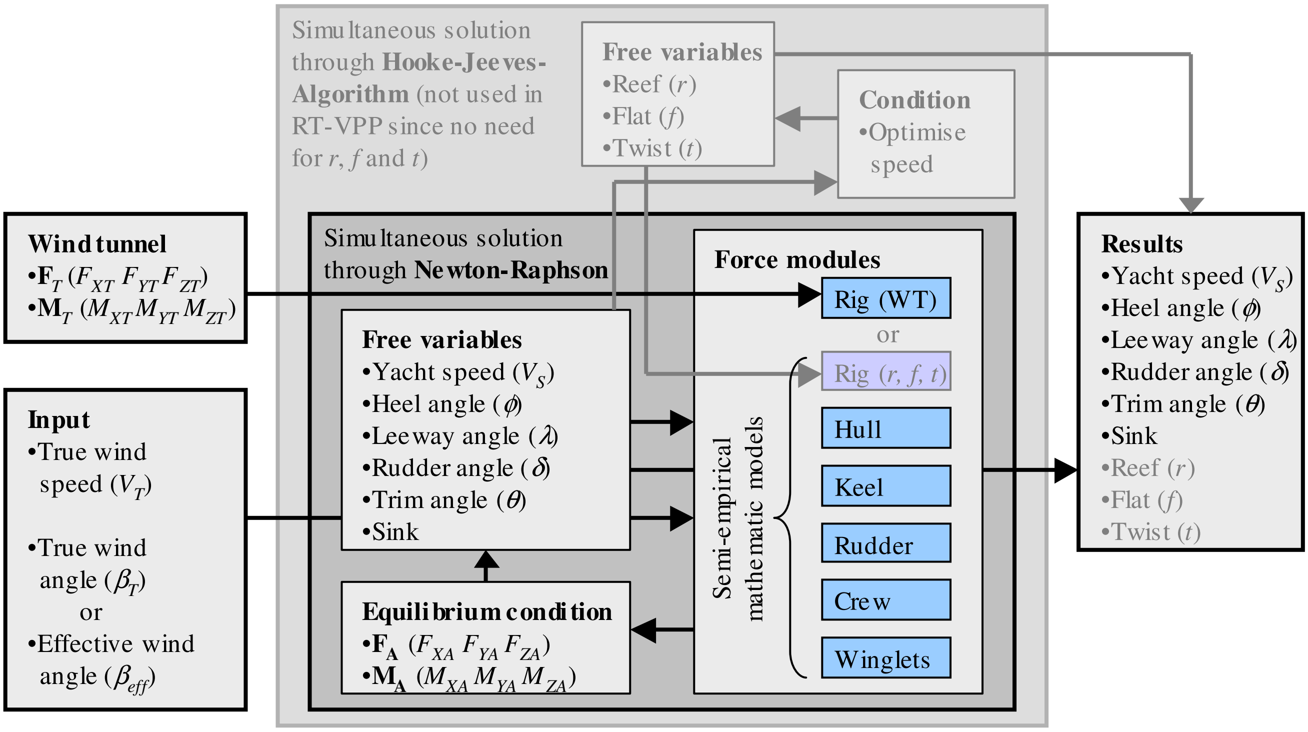


Figure 4: Schematic description of FRIENDSHIP-Equilibrium and the RT-VPP module for wind tunnel testing

dynamic pressure obtained from

$$q_{effm} = q_{Am}(1 - \sin^2 \beta_{Am} \sin^2 \phi_m)\ . \tag{22}$$

q_{Am} is the dynamic pressure at the wind tunnel test section. Since the onset flow is not uniform q_{Am} is dependent on height and is calculated from the tunnel reference pressure at the model geometric centre of sail area height (z_m), which is $z_m = z_{CoAm}\cos\phi_m$. If the flow in the tunnel is twisted, the apparent wind angle (β_{Am}) is dependent on height as well and hence also calculated at z_m.

C_{FX} and C_{FY} can be transformed to C_L and C_D with the inverse of Equation 7. C_L and C_D are equivalent to the coefficients obtained by the semi-empirical model from Equations 3 and 5. Assuming the effective angle theory holds these coefficients are independent of the heel angle. Tests can hence be conducted at any heel angle but the influence of the effective angle theory assumptions is reduced as the heel angle in the tunnel (ϕ_m) gets closer to the heel angle calculate by the RT-VPP (ϕ). If the wind tunnel model is dynamically heeled to the calculated angle, the effective angle theory has no influence on the results.

The full-scale forces and moments are obtained from C_L and C_D. A rotational transformation (Equation 7) is applied to find C_{FX} and C_{FY}. C_{FZ} can be set to zero as in the semi-empirical model or given the value measured in the wind tunnel. The forces ($\mathbf{F}_A$) and moments ($\mathbf{M}_A$) in the horizontal absolute coordinate system can then be calculated with

Figure 5: Wind tunnel model of the 10-metre IMS cruiser/racer DYNA

$$\mathbf{F}_A = A_S \frac{\rho_{air}}{2} V_{eff}^2 \left(\mathbf{T}_\phi \mathbf{C}_F\right), \tag{23}$$

$$\mathbf{M}_A = A_S^{1.5} \frac{\rho_{air}}{2} V_{eff}^2 \left(\mathbf{T}_\phi \mathbf{C}_M\right), \tag{24}$$

where A_S is the reference sail area of the yacht as in the semi-empirical model, V_{eff} is the effective wind speed calculated from Equation 10 and ϕ is the heel angle calculated by the RT-VPP.

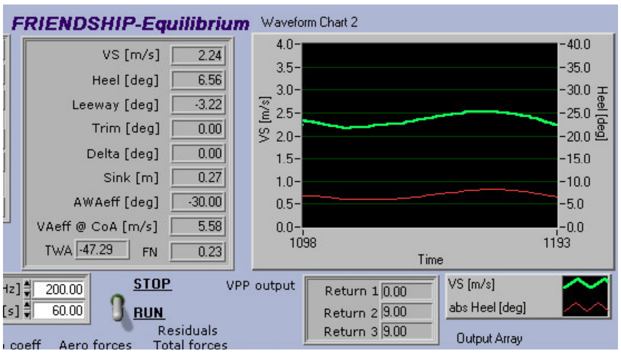
3.2 WIND TUNNEL CONSTRAINTS

In the wind tunnel measurements are traditionally made for different apparent wind angles and heel angles. Combining these angles means that measurements are made for different effective angles. Semi-empirical VPPs define the aerodynamic forces in terms of effective angles but on the other hand maximise the speed of the yacht for true wind angles. For a constant true wind speed and angle, the effective angle changes as the speed of the yacht and the heel angle vary while the solution is optimised. For a constant true wind speed and angle, the effective angle in the RT-VPP therefore also changes while the sails are trimmed in the wind tunnel.

Ideally the apparent wind angle in the wind tunnel should be adjusted dynamically together with the heel angle so that the correct effective angle can be achieved when trimming the sails to maximise the speed for a specified true wind angle. However, the automatic control of the turntable has not yet been implemented so, for the time being, an alternative method needs to be used.

3.2(a) Maximising Speed with Respect to Effective Angle

It is important to maximise the speed of a yacht with respect to the true wind speed because it is a physical condition that the yacht operates in. Usually the speed is also maximised with respect to the true wind angle since this is also an important real life parameter when sailing. A yacht is to sail from one point to another as fast as possible in a certain wind strength. From a sail design point it can however be argued that sails are designed for specific effective angles since they relate best to the aerodynamic behaviour. Hence optimising the yacht's speed with respect to the true wind



VS [m/s] 2.24
Heel [deg] 6.56
Leeway [deg] -3.22
Trim [deg] 0.00
Delta [deg] 0.00
Sink [m] 0.27
AWAeff [deg] -30.00
VAeff @ CoA [m/s] 5.58
TWA -47.29
FN 0.23
Hz] 200.00
[s] 60.00
Return 1 0.00
Return 2 9.00
Return 3 9.00

Figure 6: Detail of the RT-VPP graphical user interface in LabVIEW

speed and the effective angle might be possible for the RT-VPP. In order for this method to be meaningful the results must translate to the maximum speed with respect to the true wind angle so that they describe the real life situation. This question cannot easily be answered and FRIENSHIP-Equilibrium is enhanced to solve for effective or true wind angle as input parameters so that this can be assessed further.

To explore this idea, the validity of using the effective angle to optimise the speed of the yacht is investigated using the semi-empirical model. The trim parameters provide the effect of trimming the sails. This allows a more systematic variation of the 'sail trim' compared to using the RT-VPP. The VPP calculations are carried out for a 10-metre IMS cruiser/racer using r and f as trim parameters. A high true wind speed of 12m/s is chosen since variation of the trim parameters is necessary to simulate trimming of the sails. Trim parameters only de-power the sails. In light winds the trim parameters are not altered by the VPP and for this test case the sails would not be trimmed. Figure 7 shows V_S optimised using r and f and plotted against β_T from 0° to 180°. One curve shows V_S optimised for each β_T. The second curve is generated from optimising V_S for each β_{eff} and plotting the result against the resultant β_T. As long as the same values of the trim parameters are chosen the curves lie on top of each other. It can be seen that the speed optimised for β_{eff} is up to approximately 1% lower for true wind angles between 50° and 85°.

Figure 8 shows in more detail the range of true wind angles where the speed optimised for β_{eff} is lower than the maximum speed for β_T. For β_{eff} = 40° and 65° a set of achievable V_S is shown. The points are obtained by varying the trim parameters r and f systematically between 1 and 0.75 in increments of 0.05 and plotting the resulting boat speeds against β_T. One point in each set results in the maximum V_s for that β_{eff} and represents one point of the V_S curve optimised for β_{eff}. Similarly sets of achievable speeds for β_T could be plotted. The points in each set would form a vertical line since β_T is constant for each set. The curve of V_S optimised for β_T is shown in Figure 8. It represents the best performance and therefore best trim for this condition.

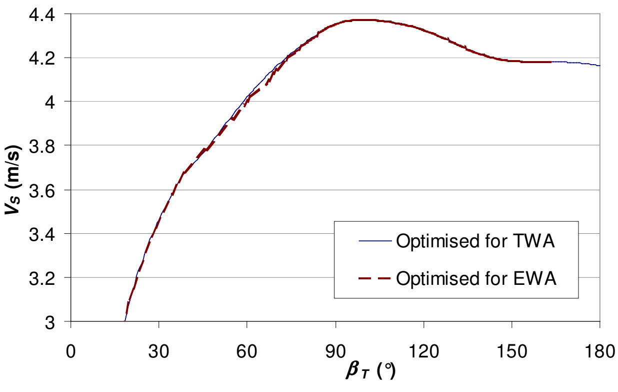


Figure 7: V_S optimised at V_T = 12m/s using r and f for either β_T or β_{eff}

The maximum V_S at β_{eff} = 65° falls on the best performance curve. The best trim is found by optimising V_S for β_{eff} in this case. At β_{eff} = 40° on the other hand the maximum V_S does not lie on the best performance curve and a different trim results in the best performance. The maximum V_S at β_{eff} = 40° does not therefore represent the best sail trim for this condition. It can be illustrated why this is the case. Increasing the heel angle at a constant β_{eff} results in a larger β_T. For courses close to the wind the drive force increases with β_T, which outweighs the added resistance due to heel and results in an increase in V_S. But for the resultant β_T the V_S could be increased by reducing the heel angle and hence increasing β_{eff}.

This shows why maximising V_S with respect to β_{eff} does not necessarily result in the optimum performance. The range of β_T in which maximising V_S for β_{eff} does not result in the best trim depends on the aerodynamic, hydrodynamic and stability characteristics and V_T, but is most strongly influenced by β_T. At β_T where the heeling moment is important and changes in ϕ result in large changes of β_{eff} an under prediction of V_S can be expected. The left side of the polar plot in Figure 9 shows curves of achievable speeds for β_T. The curves are developed by systematically varying r and f as before for β_T from 10° to 180° in 5° increments. The curves are straight lines and if extended run through the origin since each curve represents achievable V_S for a constant β_T. The best performance curve is obtained from the maximum V_S points from each constant β_T line. Equivalently the right side of the polar plot shows curves developed for β_{eff} from 10° to 150° in 5° increments and plotted against β_T. The curves are close to tangential to the best performance curve for β_T between 50° and 85°. It follows that the maximum V_S does not represent the best trim. For β_T larger than 90° the curves are at a larger angle to the optimal performance curve and the maximum V_S results in the best trim.

For this test configuration, it seems feasible to maximise V_S with respect to β_{eff} for downwind sail testing. But for many

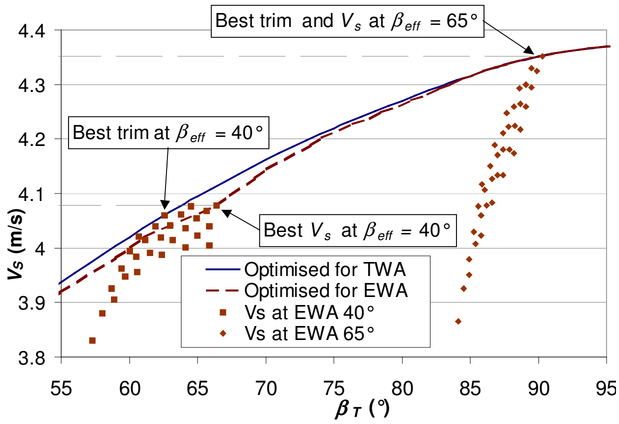


Figure 8: Set of achievable V_S at β_{eff} = 40° and 65° for V_T = 12m/s using r and f between 1 and 0.75 in increments of 0.05

upwind and reaching conditions this method incurs errors.

3.2(b) Effective Angle Correction

Section 3.2(a) shows that it is important to maximise the speed of the yacht with respect to the true wind speed and the true wind angle in certain conditions. With these two parameters fixed the effective wind angle changes as the sails are trimmed. The apparent wind angle in the wind tunnel (β_{Am}) can be selected so that the resulting effective angle in the tunnel (β_{effm}) is close to the β_{eff} calculated by the RT-VPP for this condition. C_L and C_D are directly dependent on the effective angle and need to be corrected for the difference between β_{effm} and β_{eff}. If the corrections are small theoretical methods or generic C_{Lopt} and C_{Dvis} versus β_{eff} curves can be used to approximate the lift and drag curve slope at β_{eff}. The corrected lift coefficient is then obtained from the C_L measured in the tunnel at β_{effm}, the optimum lift coefficient curve slope and the change in effective angle ($\Delta\beta_{eff}$) with

$$C_{L\ at\ \beta_{eff}} = C_{L\ at\ \beta_{effm}} + \frac{\mathrm{d}C_{Lopt}}{\mathrm{d}\beta_{eff}} \Delta\beta_{eff} \cdot \qquad (25)$$

For larger and more accurate corrections the C_{Lopt} and C_{Dvis} versus β_{eff} curves should be developed first for each sail combination and then used to make the corrections. Equation 25 is then rewritten to obtain the corrected C_L from the C_L measured in the tunnel and the optimum lift coefficient curve $C_{Lopt}(\beta_{eff})$ as

$$C_{L\ at\ \beta_{eff}} = C_{L\ at\ \beta_{effm}} + C_{Lopt}(\beta_{eff}) - C_{Lopt}(\beta_{effm}) \cdot \qquad (26)$$

C_D can be corrected in a similar manner. At present the moments are not corrected since they are not directly dependent on β_{eff} but on η as described in section 2.1.

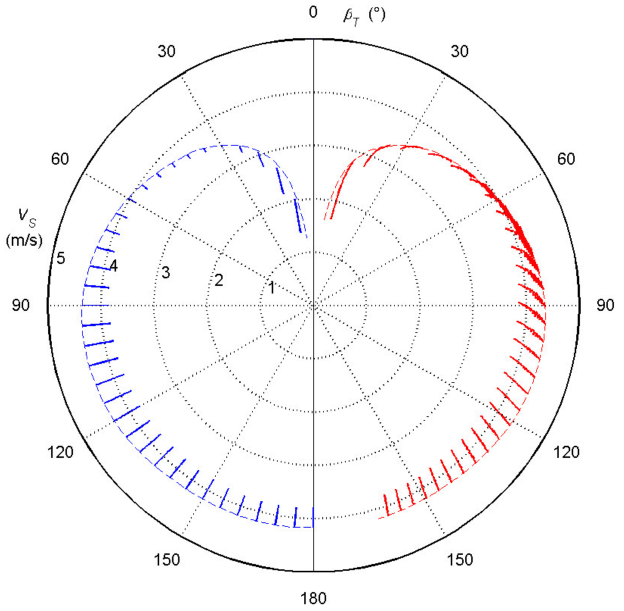


Figure 9: Polar plot of V_S optimised at V_T = 12m/s using r and f for either β_T (left) and β_{eff} (right)

The drawbacks of this method are that corrections need to be applied to the measurements. The corrections can be kept relatively small but do not account for changes of the C_L and C_D curves' slope due to de-powering and changes in the moments. One of the main aims of the RT-VPP is to investigate the forces on sails without the need for empirical descriptions. Additional testing may also be required if C_{Lopt} and C_{Dvis} curves need to be developed to ensure an accurate correction. For upwind testing this method is currently nevertheless the most feasible solution.

3.3 RT-VPP MEASUREMENTS

Initial wind tunnel tests using the RT-VPP are carried out with a 15% scale model of the sail force dynamometer DYNA (Figure 5), a 10-metre IMS cruiser/racer, to show how RT-VPP results compare to predictions using a semi-empirical VPP with trim parameters r and f. Trim parameters are based on assumptions relating to upwind conditions. Hence upwind tests using effective angle correction are carried out to investigate three β_T (40°, 50° and 60°) for different true wind speeds. The model in the tunnel is kept at 0° heel during this initial study and β_{Am} hence equals β_{effm}. Firstly the sails are trimmed to the optimal shape without the RT-VPP for a range of β_{effm}. For each β_{effm} a number of measurements with different trims are made to find the best F_{XT}. Particular attention is paid to β_{effm} = 25°, 30° and 40° since the β_T of interest result in similar β_{effm}. From these measurements the C_{Lopt}, C_{Dvis} and z_{CoE} curves are developed as input for the semi-empirical VPP. The C_{Lopt} and C_{Dvis} curves are also used for the effective angle correction in the RT-VPP.

The RT-VPP is then used to obtain the best sail trim by optimising the speed for β_T = 40°, 50° and 60° for V_T = 4, 8, 10, 12, 14m/s based on the previous measurements. Figure 10 shows V_S plotted against V_T for the three β_T. The lines show V_S calculated using the semi-empirical VPP and the points are obtained with the RT-VPP. The secondary axis shows the value for r used by the semi-empirical VPP. f remains at 1 for all cases. For β_T = 50° and 60° no de-

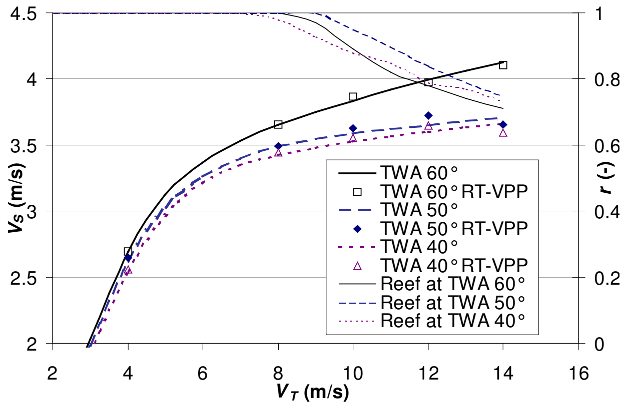


Figure 10: Yacht speed for different β_T calculated with a semi-empirical VPP and the RT-VPP

powering is necessary for $V_T = 4$ and 8m/s. For $\beta_T = 40°$ the trim remains the same only for $V_T = 4$m/s. The agreement of the data is very good for these points. This is not surprising since any differences can only originate from the modelling of C_{Lopt}, C_{Dvis} and z_{CoE}. Results that agree as well as those shown in Figure 10 are however only obtained if the curve of z_{CoE} is very smooth and has very little slope. The RT-VPP corrects C_L and C_D with the same curves used by the semi-empirical VPP but does not correct z_{CoE}. In the future a correction of z_{CoE} should be considered. While the agreement is also good for $\beta_T = 60°$ at higher V_T, for $\beta_T = 30°$ and 40° V_S from the RT-VPP is slightly higher for $V_T = 10$ and 12m/s and lower for 14m/s. This could indicate that the sails can be trimmed more efficiently than the trim parameters assume close to the wind. At V_T=14m/s the sails are back winding or even flapping when trimming in the wind tunnel and should be reefed. The semi-empirical VPP on the other hand 'reefs' by reducing r, which is more efficient in this condition and hence results in a higher V_S. The RT-VPP will be developed further with the goal of investigating this in more detail.

In an investigation into the heel effects on downwind sails by Le Pelley [6] the RT-VPP has already been shown to significantly improve the ease and efficiency of trimming the sails and highlighted the importance of considering the heel angle of the model in the wind tunnel.

4. CONCLUSIONS

The RT-VPP for wind tunnel testing of sailing yachts has been developed and successfully implemented. The integration in the modular structure of FRIENDSHIP-Equilibrium results in a flexible application package.

The concept of optimising boat speed for an effective angle seems feasible for downwind testing but introduces errors for upwind tests. The boat speed in upwind tests should be optimised for true wind angles. Constraints in the wind tunnel set-up require an effective angle correction to allow the optimisation at true wind angles. An initial study on upwind performance does not attempt to be conclusive but shows that the RT-VPP has the potential to investigate aerodynamic forces in a more direct way than was previously possible since trim parameters are no longer required, all six-degrees of freedom can be considered and the model can be tested at the correct heel angle.

5. ACKNOWLEDGEMENTS

The authors thank their colleagues at The University of Auckland and FRIENDSHIP-Systems who contributed to this paper for their support, especially David Le Pelley.

6. REFERENCES

1. Van Oossanen, P. 'Predicting the Speed of Sailing Yachts' (93-004). Van Oossanen & Associates, Wageningen, The Netherlands, 1993.

2. Jackson, P.S. 'An Improved Upwind Sail Model for VPPs'. In *The 15th Chesapeake Sailing Yacht Symposium*. SNAME, Annapolis, 2001.

3. Kerwin, J.E. 'A Velocity Prediction Program for Ocean Racing Yachts revised to February 1978' (78-11). Massachusetts Institute of Technology, Cambridge, 1978.

4. Jones, R.T. 'The Spanwise Distribution of Lift for Minimum Induced Drag of Wings Having a Given Lift and a Given Bending Moment', Technical Note (2249). National Advisory Committee for Aeronautics (NACA), Washington, 1950.

5. Hochkirch, K. 'Entwicklung einer Meßyacht zur Analyse der Segelleistung im Orginalmaßstab (Design and Construction of a Full-Scale Measurement System for the Analysis of Sailing Performance)'. PhD-Thesis, Technische Universität Berlin, Berlin, 2000.

6. Le Pelley, D.J. and Hansen, H. 'An Investigation into the Effects of Heel on Downwind Sails'. In *The Modern Yacht*. RINA, Southampton, 2003.

7. AUTHORS BIOGRAPHY

Heikki Hansen is a PhD candidate at the Yacht Research Unit within the Mechanical Engineering Department of The University of Auckland. His research focuses on improving wind tunnel testing and aerodynamic force modelling of yacht sails. He has previously published on comparing wind tunnel and full-scale sail forces and is a graduate of the Southampton Institute in BEng (Honours) Yacht & Powercraft Design.

Peter Jackson is Professor of Mechanical Engineering at The University of Auckland. His research interest is in theoretical, experimental and numerical low speed aerodynamics, in particular membrane wings. He established the Yacht Research Unit 15 years ago and has since used wind tunnel testing, panel methods, CFD and FEA for developing aerodynamic sail force models for VPPs and aero-elastic models for membrane wings.

Karsten Hochkirch is managing director and co-founder of FRIENDSHIP-Systems, an independent engineering company that offers services in naval architecture, software design and consultancy with focus on parametric modelling, fluiddynamic analysis and formal optimisation. He studied mechanical engineering and naval architecture at the Technical University of Berlin from which he received his doctoral degree in 2000. He realised and applied the complex measurement system DYNA -- the TU Berlin's sailing yacht dynamometer. At TU Berlin he lectures aero- and hydrodynamics of sailing as well as hydrostatics and stability of ships.