ADVANCES IN THE WIND TUNNEL ANALYSIS OF YACHT SAILS

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26th Symposium on Yacht Design and Construction
Hamburg, 4-5 November 2005

hanseboot
46th International Boat Show Hamburg

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Abstract

Wind tunnel testing of sailing yachts is a valuable research and effective design tool for competitive yacht development. This paper is designed to introduce the concepts of wind tunnel testing and show recent advances in the associated technologies and techniques.

The reasons for conducting wind tunnel tests for research and commercial design purposes are discussed and the differences to theoretical, numerical and other experimental methods explained. The concepts associated with wind tunnel testing and the phenomenon of speed gardient and twisted flow, which led to the development of the Twisted Flow Wind Tunnel (TFWT) at The University of Auckland, are reviewed. Challenges associated with modelling the flow structure and the physical properties of sails in the wind tunnel are discussed and related work on comparing wind tunnel data to full-scale measurements is referenced.

An overview of testing techniques used at The University of Auckland is given. The techniques range form qualitative methods of observing the flying shape, flow visualisation with smoke, bubbles or tufts to quantitative methods for measuring the forces acting on the model or parts of the model, investigating the flow field or measuring the surface pressures on the model. The use of laser scanning to determine the flying shape of a sail in the wind tunnel is also introduced.

The recently developed technique of obtaining real-time velocity predictions for the yacht in the wind tunnel while the sails are trimmed is also introduced. The concept and implementation of the Real-Time Velocity Prediction Program (RT-VPP) for wind tunnel testing are described. It is explained how this approach makes the process of trimming sails in the wind tunnel more like the real life situation and current limitations of the new system are discussed. Finally the context of how the Real-Time VPP can be used to assess the accuracy of aerodynamic force models is discussed and an example shown.

Nomenclature

β_A , β_{eff} , β_T	Apparent, effective and true wind angle [°]
ϕ	Heel angle [°]
$\mathbf{C}_F$, $\mathbf{C}_M$	Force and moment coefficient vector, $\mathbf{C}_F=(C_{FX}\ C_{FY}\ C_{FZ})^T$ [-], $\mathbf{C}_M=(C_{MX}\ C_{MY}\ C_{MZ})^T$ [-]
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]
C_D , C_L	Drag and lift coefficient [-]
q	Dynamic pressure [Pa]
V, V_{ref} , V_S	Wind, reference wind and boat speed [m/s]
V_A , V_{eff} , V_T	Apparent, effective and true wind speed [m/s]
z , z_{ref} , z_0	Height, reference height and roughness length [m]
CFD	Computational Fluid Dynamics
Dyna	Name of the Berlin Sail-Force-Dynamometer, a 10m IMS racer/cruiser yacht
RT-VPP	Real-Time Velocity Prediction Program
TFWT	Twisted Flow Wind Tunnel
VPP	Velocity Prediction Program

1 Introduction

During the design process of a sail, rig or indeed any part of a competitive sailing yacht it is of interest to the designer to know how well each component will perform. Clearly the earlier in the design process this can be established the better, since time and money can be saved. There are principally three ways to determine the performance of a yacht component: by full-scale or large-scale tests, by model-scale tests, and by computational fluid dynamics (CFD) or theoretical calculations. Which method or combination of methods is used depends on the particular case and the resources available. This paper sets out to describe one commonly used method to assess the performance of sails: wind tunnel testing.

It is not crucial to design the sails early in the design process so that full-scale testing of different sail shapes on the water is a feasible and commonly practiced option. Building a full-scale sail is however much more expensive than building a model sail for the wind tunnel. An International America’s Cup Class (IACC) spinnaker costs in the order of €20,000, where the wind tunnel version is about €100. In addition, testing a sail on the water is very time consuming since the natural test environment is not controllable and many test runs are required to gain confidence in the results and it is often difficult to pick up small differences in sail performance. Although the performance of different sails can be compared on the basis of the archived boat speed is it extremely difficult to separate the individual force components acting on a real yacht, i.e. how much force is produced by the sails, how much side force by the keel and how much resistance by the hull? The individual force components are however required by Velocity Prediction Programs (VPPs) and only a few purpose built sailing dynamometers have been used to achieve this. Apart from these few exceptions testing of sails on the water may reveal the fastest sail but the information has only limited use for future VPP analysis.

The other alternative to wind tunnel testing is to conduct CFD simulations or theoretical calculations. Theoretical calculations are a good basic tool but due to the complex three-dimensional flow structure around sails, their application to real problems of interest is very limited. In CFD calculations, the governing equations of fluid flow are used and rather than solving them analytically, they are solved numerically with the aid of computers. For upwind sails, where the flow is largely attached to the sails, accurate solutions can be achieved by using potential flow CFD simulations. For down wind sails the flow is however separated over large parts of the sails and since flow separation is a viscous effect, viscous flow equations need to be solved to model this. The lift and drag forces on a sail depend strongly on the separation and reattachment points of the flow. Predicting these points correctly is still a complicated challenge in viscous flow CFD simulations and accurate simulations are computationally very expensive.

In addition to being more cost effective than full-scale or large-scale testing wind tunnel testing provides a steady and controllable test environment where the individual forces acting on the sails can be measured. Wind tunnel testing is much less time consuming than testing on the water and can be conducted much earlier in the design process to evaluate not only sail shapes but also rig options. Since soft sails with similar properties to full-scale sails are used in the wind tunnel the trimming process is similar in the wind tunnel and on the water. Modelling a soft sail in viscous flow CFD simulations increases the computational time immensely since an iterative process is required to bring the calculated sail forces and the corresponding new sail shape into equilibrium. Trimming the sail by looking at the shape and the resulting performance, as one does on the water and in the wind tunnel, is not possible with viscous flow CFD simulations at present.

2 Wind Tunnel Testing of Yacht Sails

Wind tunnel testing is an effective and commonly used tool for research, development and design of rigs and sails. It is used for research purposes to study different aspects of yacht aerodynamics. Sail and yacht designers conduct wind tunnel testing to investigate different sail shapes and rig configurations.

For most applications a model of the hull, rig and sails is tested as shown in Figure 1. Due to the strong interaction between the sails, measurements are usually obtained for the whole sail plan together. 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. The wind tunnel models are hence equipped with remote control winches as shown in Figure 2 so that the primary sail controls can be adjusted easily while the wind tunnel is running. Good trimming of the sails is crucial for obtaining meaningful results in the wind tunnel. This is a task similarly complex to trimming sails on the water and many designers bring experienced sailors to the tunnel to trim the sails. Although wind tunnel testing is a scientific research tool, the testing process is strongly interlinked with practical sailing experience.

A typical design test session of one week might look at two or three different rig configurations and around 15 sails. Different rig configurations for an Open 60 class yacht might for example be a fixed mast versus a rotating wing mast. The emphasis on testing the sails is usually on reaching and downwind sails and a number of Code 0 type sails, reachers and spinnakers are tested. There are a number of different techniques for conducing tests like these and other types of investigations, which will be discussed in more detail in section 3. But firstly it is important to look closer at the flow characteristics to be modelled in the wind tunnel.

2.1 Vertical Speed Gradient and Twist

In real life the onset flow onto a sail of a yacht is not uniform. The flow has a vertical speed gradient and twist since the speed and direction of the flow change with height.

At sufficiently great heights above the surface of the earth the influence of friction along the ground becomes negligible. This region is called the free atmosphere. Within the boundary layer of the atmosphere the wind speed is slowed down by the friction along the ground as shown in Figure 3. The atmospheric boundary layer depth is typically between several hundred metres and 3000m depending on the wind intensity, roughness of the terrain and angle of latitude as described by Simiu and Scanlan [1]. The unaccelerated free atmosphere flow is parallel to the isobars but due to the reduced wind speed in the boundary layer the wind velocity crosses the isobars and is increasingly directed towards the low-pressure region as the height above the surface reduces. When considering yacht sails only the lower portion of the boundary layer up to about 100m above the ground is of interest and the change in direction in this region is minimal and can be ignored.

Figure 1: Scale model of a 10m IMS cruiser/racer yacht in the twisted flow wind tunnel

Figure 2: Inside of a wind tunnel model showing remote control winches and load carrying internal frame structure

The reduction of wind speed with height is however most significant in the lowest portion of the boundary layer and needs to be considered. A number of experiments and real life observations, summarised by Simiu and Scanlan [1], have shown that for horizontally homogeneous terrain the lower atmospheric boundary layer fraction of approximately 10% can be described by a logarithmic velocity profile very accurately. For yacht sails generally only heights up to 100m are relevant so that the logarithmic description can be used.

The atmospheric wind in relation to a stationary object is called the true wind. The true wind direction and speed (V_T) are usually defined at a reference height (z_{ref}) of 10m above the water. Providing that z_{ref} and the height z are not larger than 100m, V_T at a height z can be calculated from the logarithmic expression

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

where z_0 is the terrain roughness length. The roughness length for open water is a function of the wave height, which again is a function of the wind speed. Cook [2] hence gives the roughness length as

$$z_0 \approx 5 \cdot 10^{-5} \frac{V_T(z_{ref})^2}{g} , \tag{2}$$

where z_{ref} is 10m above the water and g is gravity. For typical true wind speeds between 5m/s and 15m/s this gives roughness lengths from 0.1mm to 1mm. If a constant value is assumed Kerwin [3] suggests using 1mm. Clearly ocean waves are much larger then these roughness lengths, but

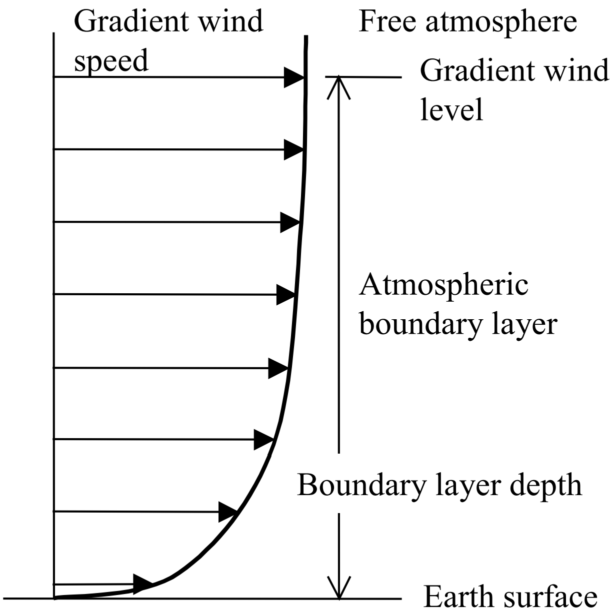


Figure 3: Atmospheric boundary layer

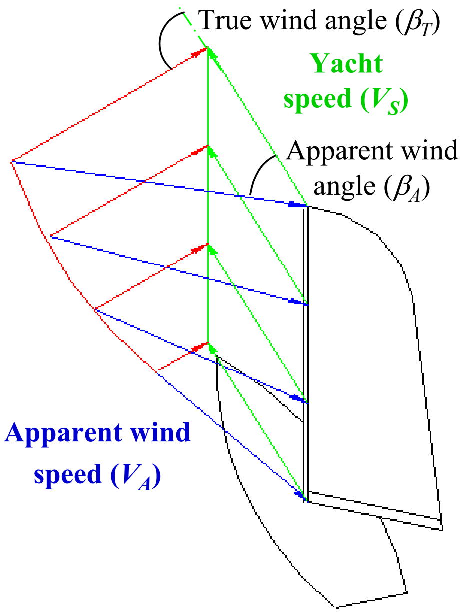


Figure 4: Onset-flow with speed gradient and twist onto a sail of a yacht on port tack ignoring the leeway angle

their crests are rounded enough for the flow to follow the curvature without separating, which reduces the friction and in turn the roughness length. In general ocean waves travel in the direction of the wind, which reduces the speed differential, friction and roughness length. This expression for z_0 is very generalised and more research is required for the roughness length of waves which are not fully developed. Similarly the logarithmic law only applies for homogeneous terrain and gradient wind but not for localised wind close to shore.

The apparent wind is the flow 'seen' by the yacht and the sails. It is the combination of the true wind and the wind due to the speed of the yacht (V_S). If the yacht moves at a fixed orientation (i.e. any pitching or rolling motion is ignored) its speed does not change with height. The apparent wind angle and speed for different heights resulting form the constant yacht speed and logarithmically increasing true wind speed is shown in Figure 4. It can be seen that the apparent wind speed and also the apparent wind angle increase with height above the water. The flow has a speed gradient since it increases with height and twist because its angle changes with height. The apparent wind angle (β_A) and speed (V_A) can be calculated from the geometric relationship at any height z with

$$\beta_A(z) = \tan^{-1}\frac{V_T(z)\sin(\beta_T+\lambda)}{V_T(z)\cos(\beta_T+\lambda)+V_S} - \lambda\,, \qquad \beta_A \in \left[0{,}180^\circ\right], \tag{3}$$

and

$$V_A(z) = \sqrt{V_S^2 + V_T(z)^2 + 2V_S V_T(z)\cos(\beta_T+\lambda)}\ , \tag{4}$$

where λ is the leeway angle (which is usually ignored in the wind tunnel) and V_T varies logarithmically with z as shown in equation (1).

The apparent wind speed and angle generally increase with height above the water. The change in apparent angle and speed does not only depend on the true wind speed, angle and profile but also on the speed and size of the yacht. Figure 5 shows the change in apparent wind speed (V_A) with height up the mast in non-dimensional form. The change in V_A/V_{Aref} is shown for two types of yachts, a 10m IMS cruiser/racer and a Volvo Ocean 60 (VO60), sailing in a V_T of 8m/s for two sailing conditions, sailing upwind at a β_T of 40° and sailing downwind at a β_T of 160°. The reference apparent wind speed (V_{Aref}) is calculated for each β_T at a height 40% up the mast. The profiles for both yacht types are similar in each sailing condition. The change of V_A/V_{Aref} is significantly larger when sailing downwind for both yacht types. From the geometric relationship presented in Figure 4 it can be deduced that V_A decreases as β_T increases. As a result a change in V_T with height has a stronger effect on V_A/V_{Aref} as β_T increases. For the VO60 sailing downwind the V_A has a minimum and increases rapidly close to the water surface. Compared to the 10m IMS cruiser/racer, the VO60 is able to achieve a higher V_S/V_T ratio because it is a larger yacht and a more high performance orientated design. As a result the V_S is much larger than the V_T close to surface and hence dictates the wind direction and velocity in this region. When sailing deep downwind this can lead to an increase in V_A close to the water surface. The sail performance is however not significantly affected since this increase in V_A usually occurs below the foot of the sails. The change in V_A/V_{Aref} is slightly larger for the 10m IMS cruiser/racer in both conditions. Since its mast height is smaller than the VO60's and the true wind speed gradient is larger close to the surface, the resulting change in V_A/V_{Aref} over the height of the mast is more pronounced for the smaller yacht.

Figure 6 shows the change in apparent wind angle (β_A) with height up the mast for the same two yacht types and sailing conditions as before. The reference height for β_A is again taken as 40% of the mast height. For sailing upwind it can be seen that the change in β_A over the span of the sails is only 2-3° and the difference between the twist profiles of the two yacht types is not noticeable in Figure 6. For the downwind condition presented in Figure 6 the twist is much more significant. For the 10m IMS cruiser/racer the change in β_A over the span of the sails is about 10° and for the VO60 approximately 35°. The change in β_A is much larger for the VO60 since it is able to achieve a higher V_S/V_T ratio, which, as described before, results in V_S being the main contributor to the apparent wind speed and direction close to the water surface.

2.2 The Twisted Flow Wind Tunnel

There are many wind tunnel types for different applications. Aeronautical wind tunnels produce uniform flow and are mainly used for testing planes, wing sections, other flying objects and so on. In combination with a rolling road they can be used for the testing of automotive vehicles. Planetary boundary layer tunnels simulate the vertical speed gradient over the earth's surface by producing an onset flow that changes with height and are mainly used for building tests and environmental studies. Since the twist angles for upwind sailing conditions are usually small as described in section 2.1 they can be ignored and planetary boundary layer tunnels can be used for testing upwind sails. For downwind and reaching conditions however the twist angles are more

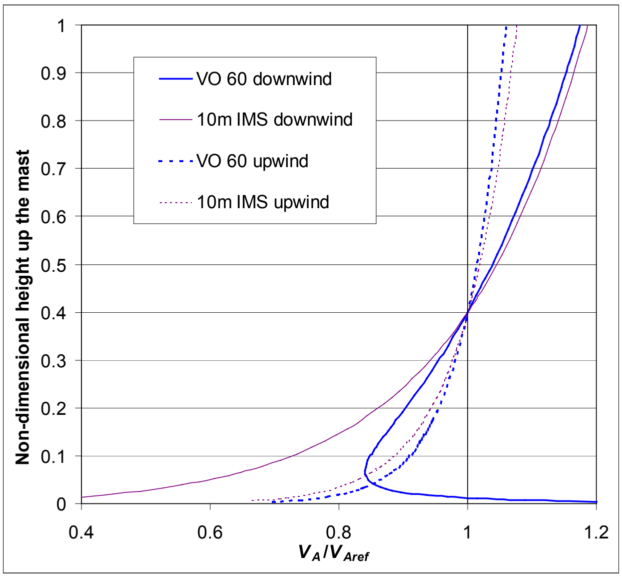


Figure 5: Wind speed profiles for a 10m IMS cruiser/racer and a Volvo Ocean 60 for true wind angles of 40° and 160°

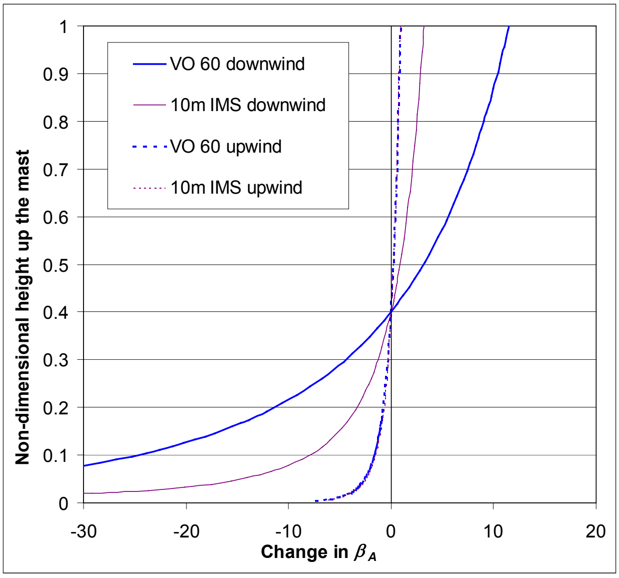


Figure 6: Twist profiles for a 10m IMS cruiser/racer and a Volvo Ocean 60 for true wind angles of 40° and 160°

significant and should be modelled in the wind tunnel.

Since twisted flow is a phenomenon almost exclusively encountered in sailing, a Twisted Flow Wind Tunnel (TFWT) has been developed at The University of Auckland especially for testing yacht sails. The concept of the TFWT was originally developed by Flay et al. [4] for the New Zealand America's Cup Challenge in 1995. Flow with a speed gradient and twist is simulated in the TFWT by generating flow with a planetary boundary layer speed profile that is twisted by vertical vanes situated upstream of the test section (Figure 7), which is 7 meters wide and 3.5 meters high. The air is sucked into the open circuit tunnel at one end by two 3-metre diameter 4-bladed fans, each driven by a 45 kW electric motor. Behind the fans the flow is straightened and conditioned by a honeycomb grid and two screens as illustrated in Figure 8. In the enclosed section of the tunnel the planetary boundary layer profile is developed. A trip board, planks or blocks are placed in the wind tunnel to assist in the development of the vertical speed profile. The vertical vanes which twist the flow with height are placed at the end of the enclosed section in front of the open test section.

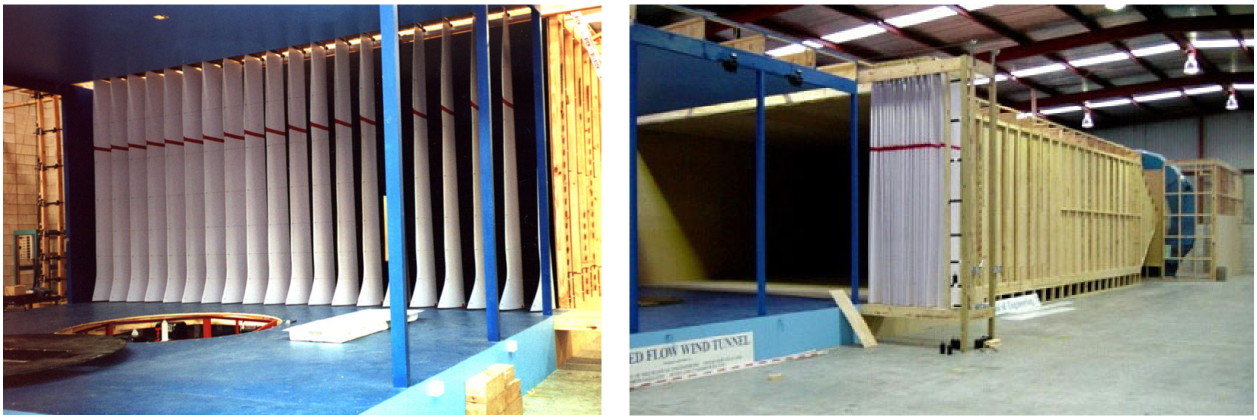


Figure 7: Twisted Flow Wind Tunnel (TFWT) with and without flow twisting vanes installed

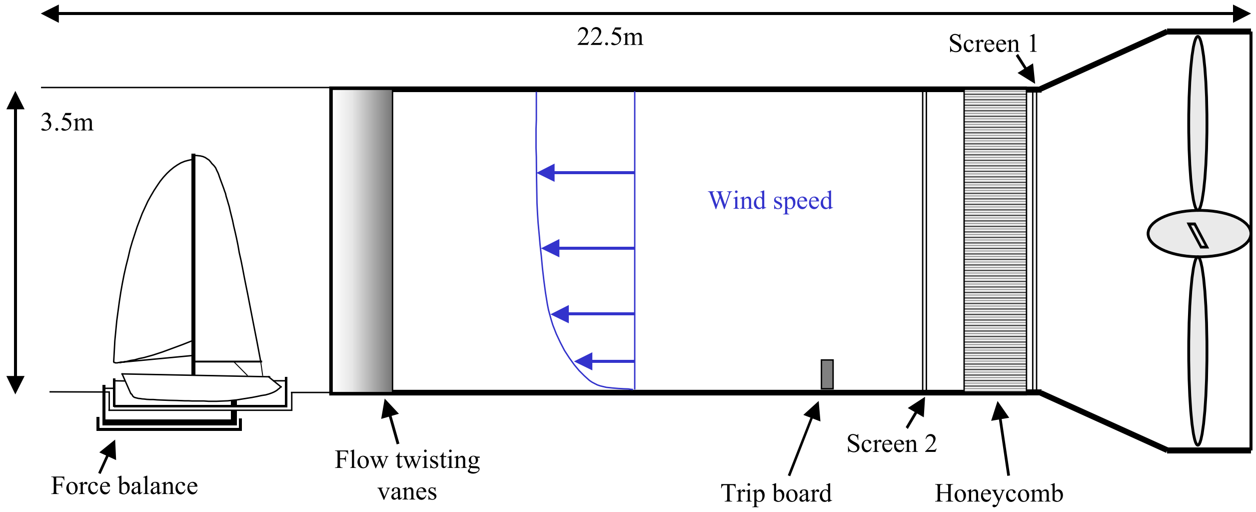


Figure 8: Schematic diagram of the Twisted Flow Wind Tunnel (TFWT)

2.2.1 Flow Structure

Since the concept of the TFWT was first developed in 1995 research has constantly been conducted to advance the wind tunnel set-up, especially with regards to improvements in the flow structure. The TFWT is an open circuit tunnel and the size and shape of the building hence influence the flow in the test section. This was very evident when the tunnel was moved from its original location to the current building. To improve the flow the tunnel has been moved within the current building and shortened with great success. The vane design has been improved recently, which reduced the wake from the vanes significantly. Interest is also on modelling the turbulence intensity and length scales more accurately in the wind tunnel. More full-scale work is however required in investigating the wind structure at low heights over the water as encountered by yachts.

2.3 Physical Similarity

In addition to modelling a geometrically similar sail shape it is important to correctly model the physical behaviour of the sails and the flow at model-scale. A number of non-dimensional ratios need to be considered. Ideally the Reynolds Number (*Re*) in full-scale and model-scale should be the same in order to ensure the same viscous flow behaviour. *Re* is defined as

$$\mathrm{Re} = \frac{Vl}{\nu} \ , \tag{5}$$

where V is the speed of the flow, l is the reference length and ν the kinematic viscosity. The reference length reduces with the factor of the model-scale. If the *Re* is to be kept constant the speed in the tunnel must be increased or the kinematic viscosity reduced. Changing the kinematic viscosity in the wind tunnel significantly is not practical. The ability to increase the flow speed in the wind tunnel is also limited due to the material strength of the soft sails so that the full-scale Reynolds Number cannot be matched in the wind tunnel. Research has been conducted by Hawkins [5] to investigate the significance of not matching the Reynolds Number and it has been shown that the effect is not of first order significance.

A number of non-dimensional ratios are concerned with the physical properties of the sails. The membrane mass ratio is only important when inertial forces are significant. Wind tunnel tests are usually only concerned with static loading and no dynamic effects are considered so that the membrane mass ratio does not need to be matched. The membrane elasticity ratio allows for aero-elastic effects of the sailcloth. But since the stretch in modern sailcloth is minimal and model sails are fabricated from real sailcloth, the membrane elasticity ratio will be matched if the dynamic pressure is matched. The dynamic pressure in the wind tunnel is similar to the dynamic pressure on the water so that the membrane elasticity ratios are comparable. The membrane fold height ratio is a measure of the sailcloth stiffness. The sailcloth needs a sufficient amount of flexibility to allow the sail to adopt the flying shape prescribed by the pressure distribution. The fold height ratio hence does not need to be matched exactly to the full-scale sail as long as the model sail is flexible enough to maintain its natural shape.

The weight/pressure ratio is the ratio of the gravitational downward force due to the sail weight and the pressure force of the wind. It is easy to imagine that a heavy spinnaker in a light breeze will sag or collapse giving a very different flying shape to a fully inflated sail. The research by Hawkins [5] showed that the weight/pressure ratio should be within certain limits but does not need to be matched exactly. It needs to be ensured that the spinnaker inflates properly but also that it does not over inflate. It is therefore important to have experienced trimmers present during testing to ensure that the flying shape in the wind tunnel resembles the flying shape on the water.

Wind tunnel testing is often used for comparative analysis so that the accurate scaling of the results to full-scale is not strictly necessary. This makes the discussed approximations less significant. One can be confident that a sail that performs better than another sail in the wind tunnel will also perform better on the water. It is however more difficult to predict accurately how much better it will perform in full-scale.

2.4 Full-Scale and Model Data Comparison

Because of the uncertainties discussed in sections 2.2.1 and 2.3 it is of interest to gain a better understanding of how well wind tunnel measurements relate quantitatively to full-scale measurements. Obtaining the aerodynamic forces on the water while sailing requires a specially constructed sail force dynamometer where the rig is isolated from the hull and connected only through a six-component force balance. Due to the complexity and resourcing only three sail force dynamometers have been constructed. The most recent being Dyna, the Berlin Sail-Force-Dynamometer, a 10m IMS cruiser/racer yacht developed at the Technical University Berlin by Hochkirch [6]. The full-scale data of Dyna is made available and compared to wind tunnel measurements by Hansen et al. [7]. The 15% scale model of Dyna is shown in Figure 1.

The work highlighted that both full-scale and wind tunnel testing have difficulties associated with them. In the wind tunnel care must be taken to model the flow correctly and good trimming of the sails is crucial. Full-scale measurements on the other hand are conducted in an unsteady environment and it is difficult to measure all relevant data accurately. As a result the scatter in the full-scale data is significant. Nevertheless the wind tunnel and full-scale measurements relate to each other well. In general the downwind results tend to agree better than the upwind results.

A repeat of the comparison with the wind tunnel in its new configuration as described in 2.2.1 showed that the results are fairly sensitive to the tunnel set-up and further work is required to explain this.

3 Wind Tunnel Techniques

3.1 Visual Observations

One of the most useful techniques, especially for downwind sails, is simply to observe the flying shape of the sail. Even with modern sail design software it is difficult to predict the way the sail will fly. The ability to walk around the sail and examine the flying shape of different sails, and the effect trim changes have on the shape, from various viewpoints is extremely useful. Many of these viewpoints can only be achieved from a helicopter in full-scale. This makes the wind tunnel a convenient tool for sail trimmers to practice trimming different types of sails and their feedback is vital. Often a bad sail can already be distinguished from a potentially good sail just by visual observations without conducting any measurements.

3.2 Flow Visualisation

In order to understand the physics behind flow around a sail, flow visualisation techniques are useful qualitative tools to employ. Cotton tufts can be used to show the flow close to the surface. Smoke or neutrally buoyant helium based bubbles can be inserted into the flow to visualise the flow path of the wind. Particles like bubbles can potentially be used to perform Particle Image Velocimetry (PIV) or Laser Doppler Velocimetry (LDV) to obtain quantitative information of the flow field, but such systems have so far not been implemented at The University of Auckland and flow visualisation is only used as a qualitative technique.

An example for using cotton tufts to visualise the flow is shown in Figure 9 by McLean [8]. Cotton tufts are attached to the leeward side of a solid spinnaker and under UV light the region on the low-pressure side of the sail where the flow is separated can clearly be seen as dictated by the flapping cotton tufts. Determining the separation point of the flow is important since the forces generated by a lifting surface with partially separated flow largely depend on it. The position of the separation point influences the amount of lift and drag produced by the sail. A region where the flow is attached produces mainly lift whereas a region of separated flow produces much more drag. Hence the lift to drag ratio of a sail changes significantly depending on the size of the separated flow region.

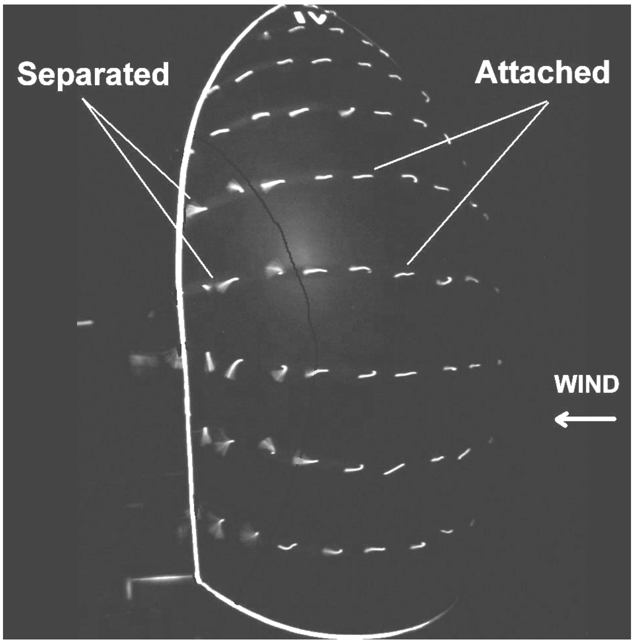


Figure 9: Cotton tufts on a solid spinnaker under UV light showing regions of attached and separated flow

3.3 Force Measurements

Quantitative information on the sail performance is obtained by measuring the forces acting on the model sails and hull. A six-component force balance is located under the wind tunnel floor in the test section and three brackets of the balance protrude through the tunnel floor to hold the model. The force balance can be turned together with the floor above (turntable) to change the apparent wind angle. The turntable has a recess to allow the waterline of the hull to coincide with the wind tunnel floor. The recess can be filled with water to prevent any airflow under the hull.

The force balance consists of six Linear Voltage Displacement Transducers (LVDTs). Each LVDT measures the voltage due to its displacement in one direction. A calibration matrix as described by Bonniot [9] relates the six voltages to the forces $\mathbf{F}=(F_X\ F_Y\ F_Z)^T$ and the moments $\mathbf{M}=(M_X\ M_Y\ M_Z)^T$. The force in the x-direction (F_X) is called the driving force since it acts along the centreline of the boat and propels the boat forward. Similarly F_Y is the horizontal side force, as it acts perpendicular to the centreline of the yachts. The moment about the x-axis (M_X) is the heeling moment since it tries to rotate the yacht around its centreline.

With the sails set in the desired position the forces and moments are typically acquired over a period of 1-3 minutes and averaged. The measured forces are of the order of 10-30 Newton and the LVDTs of the force balance have an accuracy of ± 0.05 Newton. The forces and moments are then best expressed as force and moment coefficient vectors ($\mathbf{C}_F$ and $\mathbf{C}_M$) with equations

$$\mathbf{C}_F = \frac{1}{qA_S}\mathbf{F}\ , \tag{6}$$

$$\mathbf{C}_M = \frac{1}{qA_S^{1.5}}\mathbf{M}\ , \tag{7}$$

where A_S is the reference sail area of the model and q is the dynamic pressure in the wind tunnel, which is related to the reference wind speed (V_{ref}) in the tunnel through

$$q = \frac{\rho}{2}V_{ref}^2\ , \tag{8}$$

where ρ is the density of air.

In aerodynamics the forces are usually expressed in terms of lift and drag, where lift is defined as the force perpendicular to the onset flow and drag as the force in line with the onset flow. Hence the force coefficients $\mathbf{C}_F$ need to be rotated by the apparent wind angle (β_A) to obtain the coefficient of lift (C_L) and drag (C_D) with

$$\begin{pmatrix} C_D \\ C_L \end{pmatrix} = \begin{bmatrix} \cos\beta_A & -\sin\beta_A \\ \sin\beta_A & \cos\beta_A \end{bmatrix} \begin{pmatrix} C_{FX} \\ C_{FY} \end{pmatrix}\ , \tag{9}$$

providing that the input data is expressed following the right hand coordinate system convention.

From the results for different apparent wind angles, lift and drag coefficient curves can be obtained. These curves are used to compare different sail designs or to predict the performance of the yacht using a Velocity Prediction Program (VPP). In addition to the C_L and C_D curves it is also necessary to consider the centre of effort position, which can be obtained from the measurements by considering the moment coefficients. If the model in the wind tunnel is tested at a heel angle this needs to be taken into account as well when the measurements are examined. Hansen et al. [10] for example cover the analysis of wind tunnel measurements in more detail.

It is also feasible to set up the model in the wind tunnel in such a way that the wind tunnel force balance is only attached to part of the model so that only the forces on parts of the yacht are measured. The model with the mainsail can for example be attached to the force balance whereas the genoa is held in place by other supports. This way sail interaction can be studied. The forces on the hull/deck have recently been measured by installing a second six-component force inside the hull/deck shell of a wind tunnel model. The wind tunnel model of Dyna is designed with an internal frame structure that carries the rig loads and a hull/deck shell as shown in Figure 2. The model can be set up so that the hull/deck shell is connected to the frame only through the second force balance. The hull/deck forces are measured to investigate the influence the flow around the sails has on the windage of the hull and if the hull windage forces are adequately modelled in VPPs.

3.4 Flow Measurements and Wake Surveys

There are a number of probe types to measure the flow at discrete points in the flow field. They are however intrusive techniques since the presence of a probe influences the flow field. A pitot tube with a pressure transducer or a hot wire anemometer can be used to measure the dynamic pressure or the wind speed respectively. A hot wire measures the wind speed through the change in electrical resistance of a thin heated wire, which changes depending on the flow speed. A hot wire has a much higher frequency response but is more fragile than a pitot tube. If the direction of the flow is also to be determined a multi-hole pitot tube or a cross wire are commonly used devices. The holes of the multi-hole pitot tube are arranged at known angles to each other and by measuring the pressure at each hole the direction of the flow can be calculated. Similarly a cross wire consists of two hot wires arranged at known angles to each other so that the flow direction can be determined.

One application of flow measurements is a wake survey. A systematic series of flow measurements are take downstream of the sails so that the measurement points form a grid. Through the measurements the flow pattern downstream of the sails can be investigated. Figure 10 by Locke [11] for example shows the vorticity and stream function of the wake downstream of an International America's Cup Class (IACC) yacht, which is sailing upwind at a heel angle. From the measurements it is also possible to evaluate the lift and drag forces acting on the sails and the load distribution. Wake surveys provide insight into flow patterns for research purposes but are not often used in the design process due to the time intensive testing procedure.

3.4.1 Flow Measurements Above the Mast

In recent times Cobra probes have been used for most flow measurements at the TFWT. A Cobra probe is basically a four-hole pitot tube with the pressure transducers located in the body of the probe so that the tube length between the holes and the pressure transducers is kept as short as possible. This reduces the response time and frequencies of up to 1000Hz can be measured, which is sufficient for almost all applications at the TFWT.

One example of conducting flow measurements with a Cobra probe is an investigation into the flow above the top of the mast. On a full-scale yacht the wind direction and speed are usually measured by a cup anemometer and direction vane on top of the mast. The flow above the top of the mast is however likely to be influenced by the presence of the sails and the measurements hence do not represent the free stream apparent wind. This introduces inaccuracies when comparing full-scale data to wind tunnel or CFD results where the free stream flow is treated as being equivalent to the apparent wind. It also means that the true wind speed and direction calculated form the apparent wind measured on top of the mast is not correct.

The influence of the flow above the mast due to the sails is investigated as part of the comparison to the full-scale measurements described in section 2.4. Cobra probe measurements are conducted 130mm above the mast of the wind tunnel model of Dyna. This is equivalent to the full-scale position of the cup anemometer and direction vane approximately 0.9m above the mast. Measurements are presented for the model at heel angles of 0°, 12.5° and 25° with mainsail and genoa at apparent wind angles between 20° and 90°, and the upright model with mainsail and spinnaker at apparent wind angles between 60 and 180°. The results shown are expressed as the differences to the free stream flow that is not affected by the sails. Figure 12 shows the change in effective wind angle (β_{eff}) for the different sailing conditions. The effective wind angle can be described as the apparent wind angle in the heeled plane of the yacht as shown in Figure 11

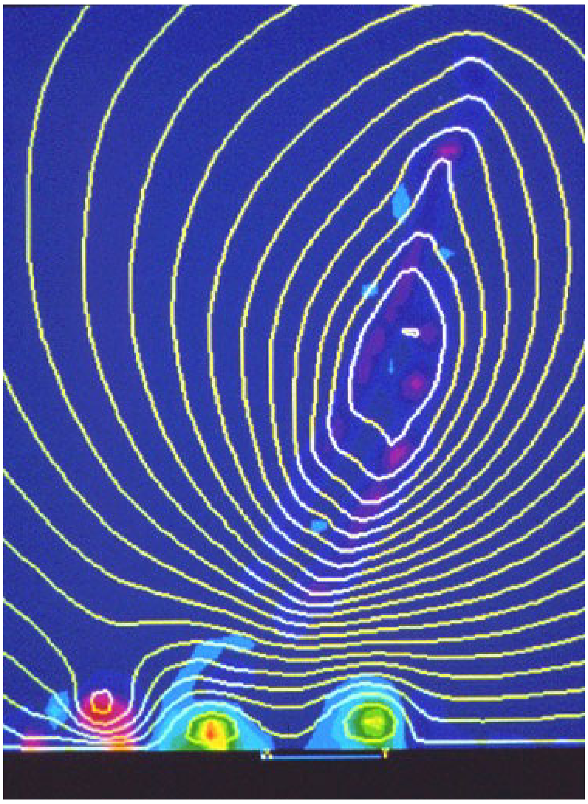


Figure 10: **Wake survey of IACC yacht sailing upwind with a heel angle showing vorticity (shaded contours) and stream function (line contours)**

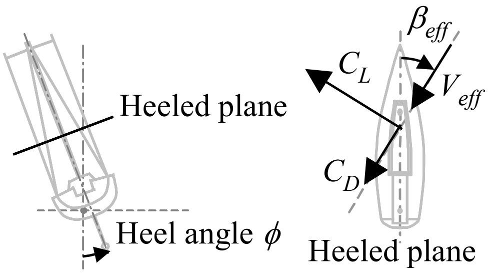


Figure 11: **Effective angle (β_{eff}) and effective wind speed (V_{eff}) in heeled plane of the yacht**

and is geometrically related to the apparent wind angle (β_A) and the heel angle (ϕ) by

$$\beta_{eff} = \tan^{-1}\left(\tan\beta_A \cos\phi\right), \qquad \beta_{eff} \in \left[0,180^\circ\right]. \tag{10}$$

For a heel angle of 0° the effective angle hence equals the apparent wind angle. The effective angle theory is an approach to remove the effect of heel from aerodynamic sail data. Although it does not succeed in making measurements independent of heel angle it certainly reduces the effect of heel when presenting the data. From Figure 12 it can be seen that the effective angle is larger above the mast than in the free stream flow for all sailing conditions considered. The increase is largest for small effective angles and reduces as the effective angle increases. The change in effective angle tends to increase with heel angle although the effective angle theory is used. The change in β_{eff} is caused by the tip vortex, which produces induced drag and is related to the amount of lift. This explains why the curve is not too dissimilar in shape to a C_L curve. A direct comparison to other work is difficult since many factors influence this effect. As described by Marchaj [12], wind tunnel tests of a 1/6 scale One Tonner model by Kamman show an increase in effective angle of about 5° in a similar position above the mast, for tests at an effective angle of 25° and heel angle of 20°. This is approximately 0.8° more than the results in Figure 12. It needs to be remembered however that the One Tonner tested by Kamman has a masthead genoa compared to the fractional rig of Dyna, which would increase the change in flow angle. Kamman estimates a maximum measurement error of less than ±2° whereas the Cobra probe measurement accuracy is estimated as typically better than ±0.2°.

Figure 13 shows the change in inclination angle (δ) of the flow for a series of effective wind angles. The inclination angle is the angle of the flow out of the heeled plane of the model. It can be seen that the change in flow is directed upwards for all effective wind angles and increases with β_{eff}. For the heeled cases it needs to be remembered that only the change in inclination angle is plotted and that the inclination angle of the free stream flow is not zero but already directed upwards. As the effective angle increases the sails are eased and present a greater obstruction to the flow so that the flow is progressively directed more upwards to get around the sails.

In addition to considering the flow angle changes, the changes in the flow speed also need to be considered. Similarly to β_{eff}, the effective wind speed (V_{eff}) is defined as the flow component of the apparent wind speed (V_A) in the heeled plane of the yacht. It is hence geometrically related to V_A by β_A and ϕ with

$$V_{eff} = V_A\sqrt{1-\sin^2\beta_A \sin^2\phi}\ . \tag{11}$$

If the yacht is not heeled the effective wind speed equals the apparent wind speed. Figure 14 shows the percentage change of the effective wind speed for different effective wind angles. Due to the low wind tunnel speed the accuracy of the changes in V_{eff} is limited to an estimated ±0.5% for most cases. A clear trend with effective wind angle and heel angle cannot be seen from the mainsail and genoa tests, which could in part be related to the limited accuracy of the system. It can however be said that the effective speed increases between 1 and 5%. For the mainsail and

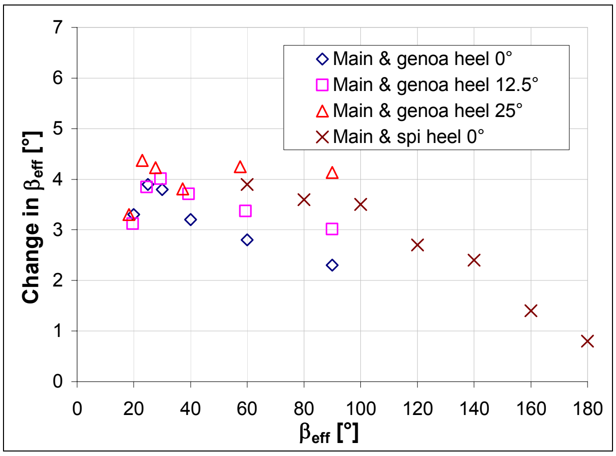


Figure 12: Change in effective angle (β_{eff}) of flow 130mm above mast due to presence of sails

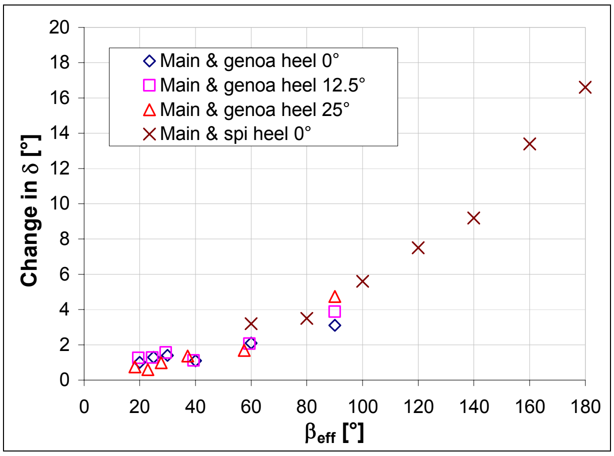


Figure 13: Change in inclination angle (δ) of flow 130mm above mast due to presence of sails

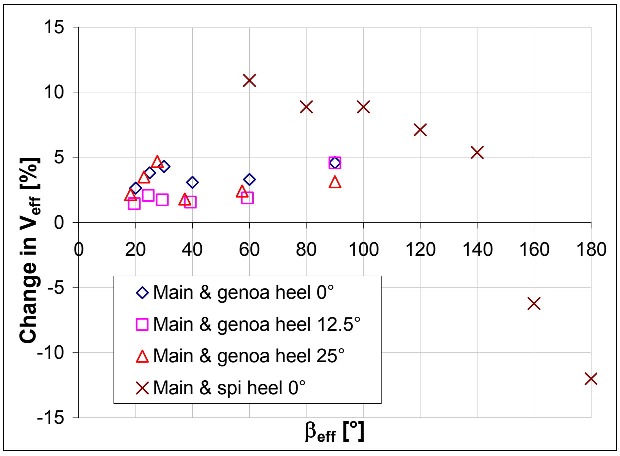


Figure 14: Change in V_{eff} of flow 130mm above mast due to presence of sails

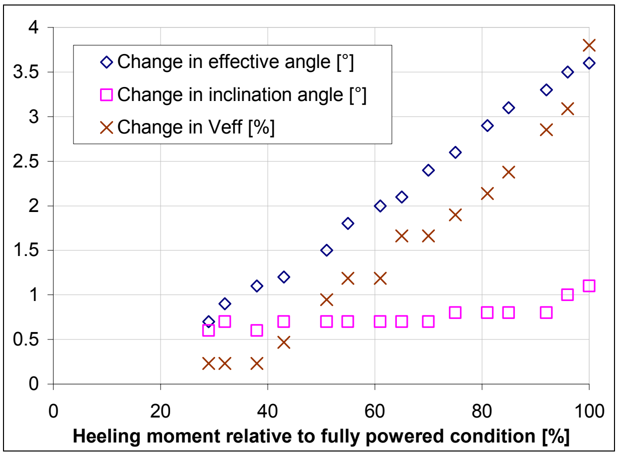


Figure 15: Change in inclination angle, effective angle and V_{eff} vs. heeling moment for flow 130mm above mast with main and genoa at 25° apparent wind angle and 0° heel

spinnaker tests a clear trend with effective wind angle can however be seen (Figure 14). The flow is accelerated by up to 11% for small β_{eff}. The amount of acceleration becomes less as β_{eff} increase and at approximately 150° the flow speed is equal to the free stream flow. For angles larger than 150° the speed is less than the free stream flow by as much as 12% at β_{eff} of 180°.

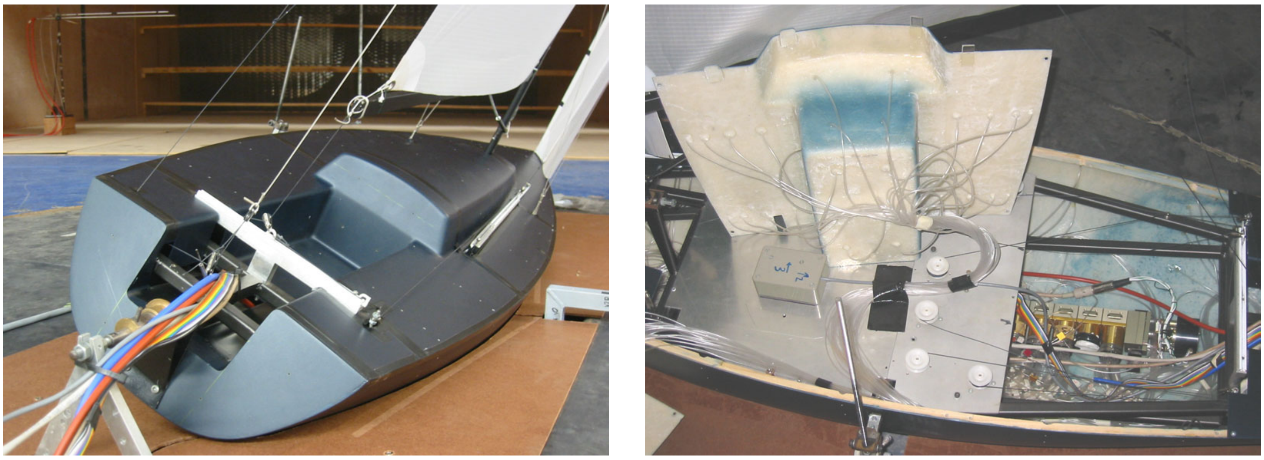
The flow measurements are used to correct the full-scale data mentioned in section 2.4, but it needs to be remembered that these measurements depend on the sail trim. They were obtained for properly trimmed fully powered-up sails. To illustrate this Figure 15 shows how the changes in effective angle, inclination angle and V_{eff} are affected by depowering the sails at an effective wind angle of 25° and a heel angle of 0°. The sails are progressively depowered by easing the main sheet, lowering the traveller and easing the genoa. The reduction in heeling moment is used as a measure of how much the sails are depowered. In Figure 15 the heeling moment is shown as a percentage of the fully powered-up case (100%). It can be seen that the influence of the sails on the flow above the mast is almost linearly related to the heeling moment for all three flow components.

3.5 Pressure Measurements

Measuring surface pressures is a commonly used technique in wind tunnel testing of buildings and airplanes for example. It has recently also been used in relation to sail aerodynamics at The University of Auckland. The surface of the model is tapped with small holes. Inside the model tubes connect the taps to pressure transducers. Due to the large number of pressure taps required to cover all important areas of the model in enough detail it is common to use a Scanni-valve system, which enables one pressure transducer to sequentially measure a number of different taps. Fewer pressure transducers are required but the measurement process takes longer. When looking at dynamic flow behaviour the pressures need to be sampled simultaneously at high frequencies and a digital pressure scanning system for up to 512 taps has been developed by Li et al. [13] primarily for building tests.

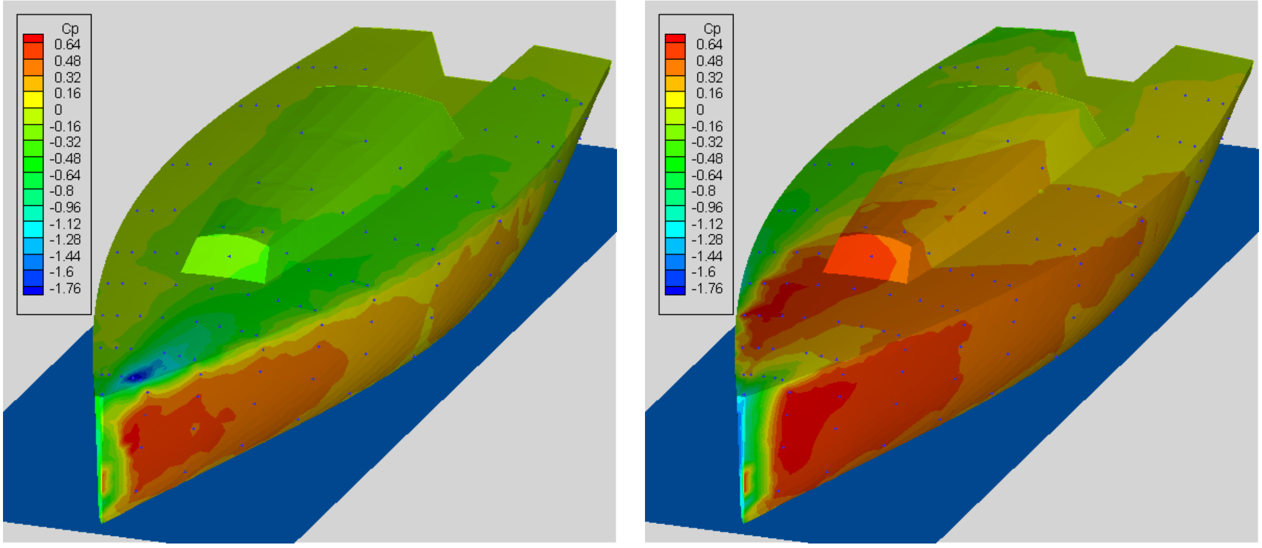
Pressure tapping of sails is however challenging as most sails in real-life are single surface foils. The surface pressures on a solid mainsail and spinnaker combination have been measured for research purposes and some conceptual work has also been conducted on measuring surface pressures on soft upwind sails in the wind tunnel. Recently a series of surface pressure measurements on the hull and deck of a sailing yacht have been carried out to investigate the influence the sails have on the flow around the hull and to verify the hull/deck force measurements described in section 3.3. Pressure tapping the hull and deck of the Dyna model is similar to tapping building models since there is sufficient internal space for the tubing and the pressure transducers due to its internal frame structure and the surrounding hull/deck shell as shown in Figure 16b. For these tests a Scanni-valve system is used since the pressures are too low to be measured accurately with the digital pressure scanning system, which is designed for testing at higher wind speeds. The hull and deck of the model are fitted with the maximum of 188 pressure taps this system supports with four pressure transducers.

The measured pressures are non-dimensionalised and interpolated over the surface using the universal kriging algorithm as described by Davis [14]. Figure 17 shows two plots of interpolated pressure measurements for the model upright in the wind tunnel at an apparent wind angle of 25°. The markers on hull and deck indicate the positions of the pressure taps. Figure 17a shows the pressure plot for the yacht without sails and Figure 17b for the yacht with mainsail and genoa. It can clearly be seen that the sails cause positive downward pressure on the deck, especially on the windward side of the genoa. The positive pressure on the windward side of the hull is also increased indicating that the hull acts as an extension of the sails, especially forward of the mast where the gap between the deck and the genoa is small.



a: Outside view of pressure tapped hull and deck **b:** Inside view of pressure tapped hull and deck

Figure 16: Wind tunnel model for surface pressure measurements on hull and deck



a: Yacht without sails **b:** Yacht with main sail and genoa

Figure 17: Surface pressure plot on hull and deck for yacht on port tack at apparent wind angle of 25° (looking from windward)

3.6 Flying Shape Analysis by Laser Scanning

In addition to measuring the forces acting on sails and investigating the flow field around sails it can also be of interest to determine the flying shape of the sails in the wind tunnel. This is particularly important when wind tunnel tests of downwind sails are to be compared to CFD simulations. In most Reynolds Averaged Navier-Stokes Equations (RANSE) CFD simulations the flying shape of the sail is specified unlike in the wind tunnel and full-scale where the sail takes up its natural flying shape based on the pressure distribution.

One commonly used method of determining the flying shape of upwind sails in full-scale is photo-imagery where the flying shape is computed based on pictures of the sails. For downwind sails this is however more difficult and at the TFWT a three-dimensional laser scanner is used. A sail scan with a grid spacing of 10mm takes about 30 seconds and returns the coordinates of the point measurements as shown in Figure 18. The accuracy of each point measurement is 2mm. Some post-processing is then required to identify the points belonging to the individual sails and to fit a surface through the points for each sail. Once a sail surface has been created it can be used for CFD simulations and so on.

3.7 Performance Prediction using Real-Time Measurement Data

Another tool recently developed at The University of Auckland is the Real-Time Velocity Prediction Program (RT-VPP), which predicts the boat speed from the wind tunnel measurements in real-time and enables the sails to be trimmed to maximise boat speed rather than drive force. This makes the process of trimming sails in the wind tunnel much more similar to the real life situation.

3.7.1 Assessing Sail Performance

Wind tunnels are often used as a sail design tool for comparative testing of different sails. A number of different sails are tested with the goal of determining which sail performs best in a certain sailing condition. With the most basic approach the sails are judged by simply comparing the maximised drive force coefficients measured in the wind tunnel. 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. The heeling moment generated by the sails can lead to an excessive heel angle of the yacht,

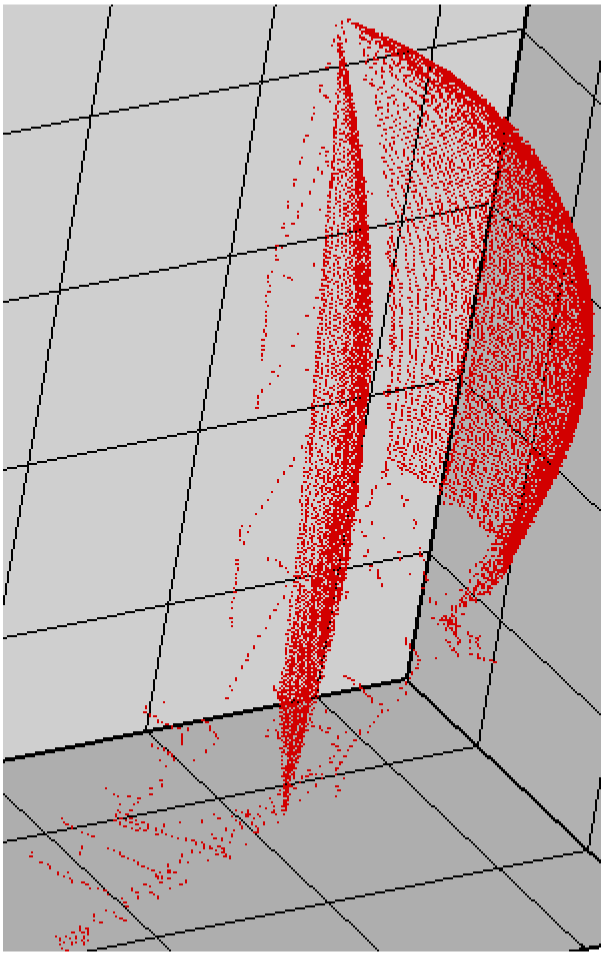


Figure 18: Laser scan data points of wind tunnel model with mainsail and spinnaker

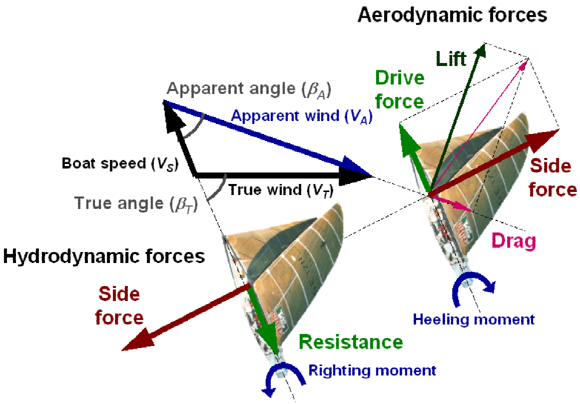


Figure 19: Forces and moments acting on a sailing yacht that are modelled by a three equation VPP

which increases the hydrodynamic resistance and reduces the appendage and aerodynamic efficiency. This could result in a slower boat speed although the drive force generated by the sail is larger than for a different sail that produces less heeling moment. M_X can be considered by trying to maximise the drive force and at the same time keep M_X below 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. This argument is not confined to M_X, similarly choosing a sail that reduces the aerodynamic side force and consequently the leeway angle or a sail that reduces the yaw moment (M_Z) and hence rudder angle could result in a better boat speed although it produces less drive force. 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.

3.7.2 Velocity Prediction Programs (VPPs)

VPPs are popular tools which predict the speed of a yacht at the design stage based on semi-empirical mathematical models of the forces acting on the yacht. In most cases a steady state analysis approach is taken. The yacht is assumed to operate in a constant wind environment. The 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 often 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 and rudder must balance the side force of the sails. A third equation is taken from the heeling moment and righting moment equilibrium. Figure 19 shows the forces and moments considered by a three-equation VPP.

In addition to balancing the forces a VPP also needs to account for changes in the trim of the sails. Depending on the wind strength the optimal sail 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 for the same reasons as discussed in relation to comparing different sails in section 3.7. The sails hence need to be trimmed differently in stronger winds. Departing from the optimal sail shape is approximated in most VPPs by using optimal aerodynamic force coefficients in conjunction with trim parameters: reef, flat and more recently twist. The trim parameters mathematically describe the effect depowering has on the forces and moments produced by the sails. VPPs optimise the boat speed by adjusting the trim parameters until the maximum boat speed is obtained.

3.7.3 Real-Time VPP

Instead of developing a completely new VPP for the wind tunnel, the Real-Time VPP (RT-VPP) is designed as an additional module for FRIENDSHIP-Equilibrium, a semi-empirical VPP developed by FRIENDSHIP SYSTEMS and based on research conducted at the Technical University Berlin by Hochkirch [6]. FRIENDSHIP-Equilibrium was originally intended as a research tool and is designed in a modular way so that incorporating the RT-VPP is feasible. For this application it solves for the steady state equilibrium for up to six degrees of freedom using a Newton-Raphson solver and optimises the yacht speed in an outer loop by varying the trim parameters using the Hooke-Jeeves-Algorithm as shown in Figure 20. Within FRIENDSHIP-Equilibrium the forces acting on the yacht are abstracted by so called 'force modules' which can easily be added or removed and combined in any number of ways so that the user has a lot of flexibility when modelling a sailing yacht. Figure 20 shows how FRIENDSHIP-Equilibrium can be used with either a semi-empirical rig force module ‘Rig (r,f,t)’ that uses trim parameters as described in section 3.7.2 or with the wind tunnel force module ‘Rig (WT)’ of the RT-VPP. One of the big advantages of using the RT-VPP is that the trim parameters are no longer required since the sails are adjusted by the trimmer in the wind tunnel. The outer optimisation loop shown in Figure 20 is hence disabled when the RT-VPP is used.

The forces and moments acting on the wind tunnel model are measured with the six-component force balance of the TFWT by the RT-VPP application written in the data acquisition software LabVIEW. The measurements are non-dimensionalised and the force and moment coefficients passed to the wind tunnel force module of FRIENDSHIP-Equilibrium. FRIENDSHIP-Equilibrium uses the coefficients to calculate the full-scale aerodynamic forces, solves for the equilibrium sailing condition of the yacht and returns the results to the RT-VPP where they are displayed and saved. This implementation of the two applications running simultaneously and communicating via shared memory is schematically shown in Figure 21.

As part of the equilibrium condition FRIENDSHIP-Equilibrium calculates the heel angle of the yacht. It is hence possible to dynamically heel the model in the wind tunnel to the calculated angle and a system controlled by the RT-VPP has been developed where an electric motor heels

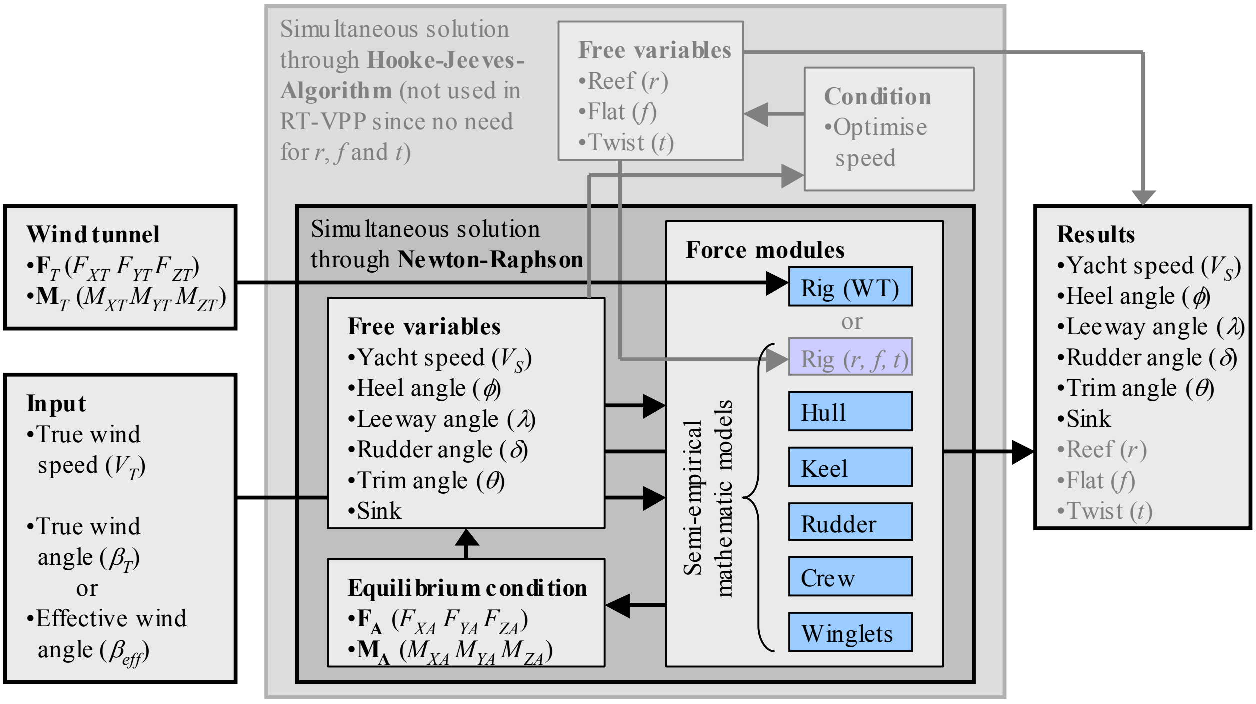


Figure 20: Schematic description of FRIENDSHIP-Equilibrium and the RT-VPP force module for wind tunnel testing

the model and accelerometers measure the heel angle as indicated in Figure 21. For wind tunnel measurements without the RT-VPP this is not possible because the resulting heel angle of the yacht is not known. It has to be approximated and the measurements corrected using the effective angle theory mentioned in section 3.4.1.

One of the constraints of the RT-VPP is that the turntable in the wind tunnel defines the apparent wind angle the sails 'see' as constant during a wind tunnel run. In real life the performance of a sailing yacht is however usually defined with respect to the true wind angle since it is an important real life parameter when sailing. A yacht is to sail from one point to another as fast as possible. For a constant true wind angle the apparent wind angle varies as the boat speed changes (see section 2.1). When the sails are trimmed in the wind tunnel the boat speed changes and the apparent wind angle needs to be adjusted. Ideally the turntable angle should be changed dynamically similar to the heel angle. This has however not been implemented yet due to challenges in tare force corrections and possible numerical instability of the system. From a sail design point of view it can be argued that sails are designed for specific apparent wind angles since they relate best to the aerodynamic behaviour. Hence optimising the yacht speed with respect to the true wind speed and the apparent angle might be possible for the RT-VPP. Work presented by Hansen et al. [10] has shown that this method should only be used with care in certain sailing conditions. For sailing conditions where it is better to optimise the yacht speed with respect to the true wind angle an apparent wind angle correction has been implemented in the RT-VPP to adjust the measured C_L and C_D for changes in the apparent wind angle.

3.7.4 Real-Time VPP Applications

There are mainly two applications for the RT-VPP. It is an effective tool for the comparative testing of sails since it makes the process of trimming the sails in the wind tunnel much more similar to the real life situation, especially when the model is dynamically heeled. The sails can be tested at the correct heel angle and the sails can be compared straight away without any post processing of the data. On the other hand much more effort is required before the wind tunnel testing to set up the VPP modelling of the yacht. In an investigation into the heel effects on downwind sails by Le Pelley and Hansen [15] the RT-VPP has 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.

Secondly the RT-VPP can be used as a research tool to investigate the ways aerodynamic forces are modelled in VPPs. Since the RT-VPP does not rely on trim parameters it can be used to examine their results. Initial wind tunnel tests using the RT-VPP have been carried out by Hansen et al. [10] with the wind tunnel model of Dyna to show how RT-VPP results compare to predictions using a semi-empirical VPP with the trim parameters reef and flat. Trim parameters are based on assumptions relating to upwind sailing conditions. Hence upwind tests are carried out to investigate three true wind angles (β_T) of 40°, 50° and 60° for different true wind speeds (V_T). The model in the tunnel is kept at 0° heel during the initial study since only the trim parameters are to be investigated and not changes due to dynamic heeling as well. Firstly the sails are trimmed to the optimal shape in the wind tunnel without the RT-VPP for a range of apparent

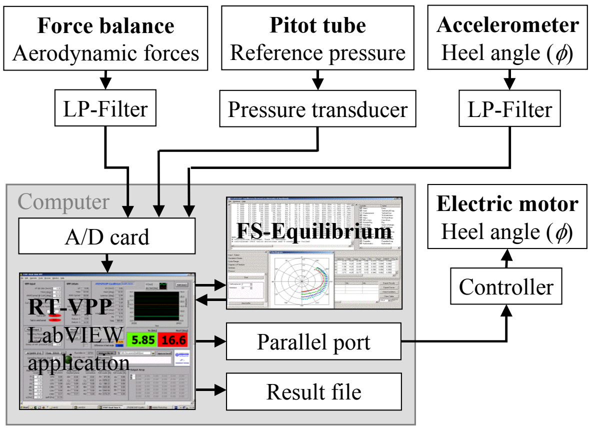


Figure 21: Schematic implementation diagram of the Real-Time VPP in the wind tunnel

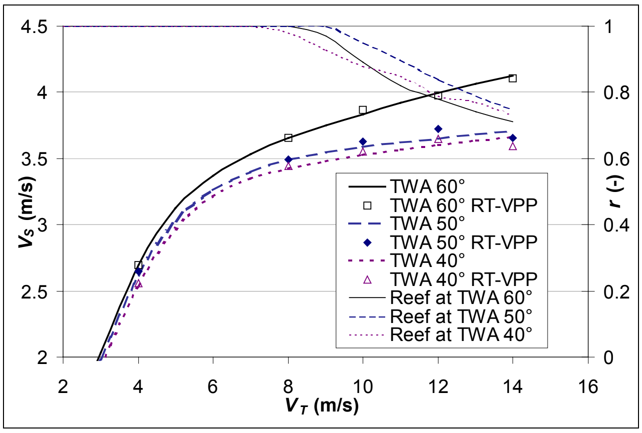


Figure 22: Yacht speed for different β_T calculated with a semi-empirical VPP and the RT-VPP

wind angles. Particular attention is paid to β_A of 25°, 30° and 40° since the β_T of interest result in similar β_A. From these measurements the C_L, C_D and centre of effort curves are developed as input for the semi-empirical VPP.

The RT-VPP with apparent angle correction (see section 3.7.3) is then used to obtain the best sail trim in the wind tunnel by optimising the boat speed for $\beta_T = 40°$, 50° and 60° for $V_T = 4$, 8, 10, 12, 14m/s. Figure 22 shows the boat speed (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 the trim parameter reef (r) used by the semi-empirical VPP, which can range from 1 (sail fully powered up) to 0. The trim parameter flat (f) remains at 1 for all cases. For $\beta_T = 50°$ and 60° no de-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 the C_L, C_D and centre of effort curves. 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 physically 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 is currently used to investigate aerodynamic force modelling in more detail.

In the future the RT-VPP might also be extended to simulate instationary effects and manoeuvring in the wind tunnel. While FRIENDSHIP-Equilibrium has already been used successfully for manoeuvring simulation in a time stepping mode, more research and development on measuring dynamic sail forces in the wind tunnel is necessary before such a system produces useful results. In addition extended input including gyradii and coefficients for added mass and damping of the hydrodynamic forces is also required.

Conclusions

Wind tunnel testing of yacht sails is a flexible research and design tool largely due to all the testing techniques available. A lot of time and effort is involved in developing and continually improving the testing procedures. The wind tunnel testing of yacht sails is only part of the research conducted at the TFWT. Another large proportion of the research is dedicated to improving the testing environment, by measures such as moving and shortening the tunnel and upgrading the vanes, and improving the testing techniques through for example the laser scanning system and the Real-Time VPP. Wind tunnel testing is already commonly used in conjunction with full-scale testing and the laser scanning system makes it now more feasible to also use wind tunnel testing in conjunction with CFD simulations. Through the Real-Time VPP the sail trimming in the wind tunnel is more similar to the real life situation and the performance of a sail is now apparent right away and not only after post processing of the data.

These recent developments show that advances have been made towards achieving the goal of having a “virtual yacht” and one can be confident that even more significant advances will be made in the wind tunnel towards this goal in the near future.

Acknowledgements

The authors sincerely thank all their colleagues at The University of Auckland and FRIENDSHIP SYSTEMS who contributed to this paper. Special thanks go to Professor Peter S. Jackson at the University of Canterbury for his continued input and support.

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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, fluid-dynamic analysis and formal optimisation. He studied mechanical engineering and naval architecture at the Technical University (TU) 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.

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