Correct simulation of the profiles of apparent wind speed and twist for testing yacht sails

by

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Introduction to the Twisted Flow Wind Tunnel

The Twisted Flow Wind Tunnel (TFWT) at the University of Auckland is unique in that it is the only tunnel in the world (known to the authors) to allow an accurate simulation of the wind around the sails of a moving yacht. The wind tunnel is an open jet configuration inside a large warehouse, and has recently been upgraded and enlarged. Two 3 m diameter fans blow air down a 25 m long rectangular section, through retractable twisting vanes, to a 3.5 m high by 7 m wide working section. Models are mounted on struts connected to a six-component balance (which uses LVDTs as the sensing elements) positioned below a 2.4 m diameter turntable.

How twisted flow develops for sailing yachts

A yacht is essentially a body moving with forward speed through water. As a yacht moves through the water, the wind it sees is not the true wind speed and direction, but the apparent or relative wind. The motion of the yacht has the effect of reducing the wind angle and either increasing or decreasing the wind speed, depending on the yacht's heading. Thus when a boat accelerates from rest in a constant direction the wind angle changes. This effect explains why light racing dinghies and windsurfers start off sailing higher than their desired course and then bear away when they have sufficient speed, often with their sails tightly trimmed, to account for the close apparent wind angle.

When there is a sufficiently strong wind there will be an atmospheric boundary layer above the surface of the water. Expressions have been developed which approximate the vertical profile of the boundary layer over open sea as a function of wind speed [1] assuming a steady-state fully developed sea. However, if a yacht were moving in true wind without an atmospheric boundary layer, the apparent wind direction would be the same at all heights. In normal conditions, however, the relatively low wind speed near the sea surface is combined with the boat speed to produce a very small apparent wind angle. At the masthead, the true wind speed is greater and therefore the apparent wind angle is also greater. The apparent wind angle and speed at a particular height are derived simply from the resultant of the true wind speed at that height and the boat speed, as shown in Figure 1.

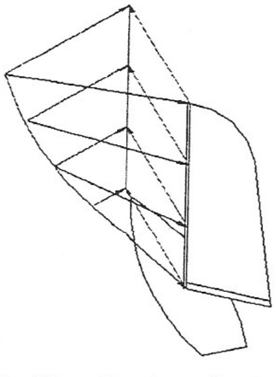

Figure 1 – Visualisation of twist profile

The wind profile seen by a yacht, therefore, is not the true wind profile but an apparent wind profile. When a yacht is sailing close to the wind, the upwind component of boat speed is effectively added to the true wind speed at all heights. Therefore the relative difference between wind speeds low down and high up the mast is less than for the true wind profile. Conversely, when sailing downwind the boat speed is subtracted from the true wind profile, resulting in larger relative differences in wind speed and hence a more "severe" velocity profile. With modern performance yachts this effect can be rather extreme, and when sailing off-wind the profile can reverse low down because of high boat speed, and the wind speed may be faster at deck level than slightly higher up the mast.

Importance of using twisted flow

In the TFWT, the velocity and twist profiles are usually non-dimensionalised at a height of 10 m. This is done as 10 m is both a common reference height and is also near the horizontal centre of effort of a Volvo Open 60 yacht sail. This means that there will be no twist at 10 m, positive twist below 10 m and negative twist above 10 m. For a yacht sailing downwind the twist at deck height may approach 30°. The masthead twist may then be around 15° in the other direction.

Wind tunnel results can be used to determine accurate predictions of sail force coefficients for input into velocity prediction programs (VPP). However, most commercial wind tunnel sail testing is aimed at comparing between different sails of a similar general form. The wind tunnel is used to determine the best cut of sail of a particular type, and also the conditions in which one type of sail becomes more efficient than another. A typical set of variations of one base sail may examine factors such as girth at different heights, clew height and luff length. If there were no velocity and twist profiles at full scale a conventional wind tunnel could be used to carry out comparative tests between sails. However, the twist and velocity profiles allow simulation of the correct airflow around the sails and hence calculation of the correct sail forces. Even comparative testing is not possible without correct profile simulation because of the variations of sail shape with height; sails do not set properly unless the wind twist is modelled. A difference is seen in the flying shape when a twist profile is used and there is also a significant difference in the overall sail forces.

To assist with Volvo Open 60 testing, two target profiles were determined, representative of upwind and downwind sailing conditions, and then simulated in the wind tunnel.

Setting up the twist profile

A set of adjustable turning vanes is used to twist the flow in the TFWT. These consist of streamlined flexible sheets of material that can be positioned upstream of the working section. The leading edges are fixed, whilst the trailing edges are linked by wires at various heights to electric winches with digital potentiometer displays. By weighting the ends of the wires opposite to the winches the vanes can be twisted to any desired angle within approximately a ±40° range.

To set up the desired Volvo profiles, a direction vane mounted on a vertical traversing arm was used to measure the direction of the resulting wind at the model location. These measurements confirmed that the direction of the wind at the model location was approximately the same as the tangent to the vane curve at the downstream edge. The direction vane was also used to provide a correlation between the winch readout and the wind angle. Comparisons between the ideal and measured upwind and downwind twist profiles are shown in Figure 2.

When the vanes are twisted, the outlet area at their downstream edge is reduced. Continuity states that the flow through the vanes will therefore be accelerated. However, as the amount of twist changes with height, the wind speed will be accelerated more at regions of high twist. It is therefore necessary firstly to set the correct twist profile and then to install and measure the velocity profile, as there is a significant difference in velocity with and without vane twist.

Setting up the velocity profile

The upwind profile was achieved by having a smooth wind tunnel floor upstream of the working section. The profile matched the target well above a height of about 0.4 m. Below this, the natural roughness of the tunnel floor slowed the flow more than was required. However, this is below the height of the boom of the model yacht so is of less importance.

The downwind velocity profile requires more roughness and turbulence than the upwind profile, and was simulated by placing various types of roughness and turbulence inducers on the floor of the wind tunnel upstream of the working section. Few attempts have been made to measure full-scale turbulence intensity on sailing yachts and, therefore, the main objective was to simulate the velocity profile. After trying several techniques, corrugated sheeting was laid on the tunnel floor to achieve the required roughness low down. This had a retarding effect up to about 0.5 m at the model location. A vertical wooden barrier with a ramp leading up to it was placed upstream of this. This has the effect of mixing the flow to a higher level, increasing turbulence and also slowing the flow down. It was found that altering the height of the fence slightly had a significant effect on the velocity profile. The upwind and downwind velocity profiles are shown in Figure 3.

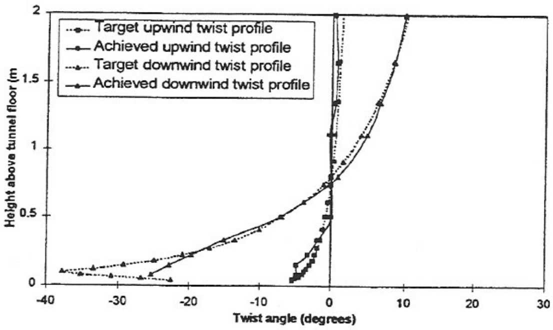

Figure 2 – Upwind and downwind twist profiles

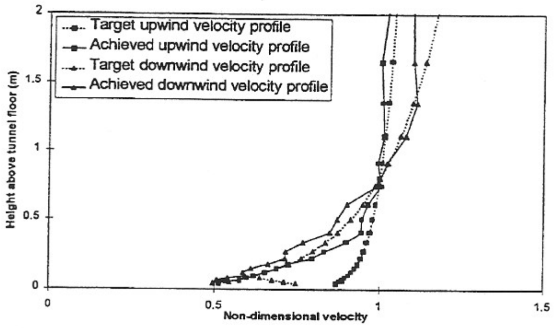

Figure 3 – Upwind and downwind velocity profiles

Application of techniques to a Volvo Open 60

A 1:12.5 scale model of a Volvo Open 60 was mounted on a force balance in the centre of an adjustable turntable. The model was tested in the upwind and downwind conditions with suitable sail configurations. At each angle, the sails were trimmed via remotely controlled winches mounted in the model. The balance is connected via an A/D card to a PC which shows real-time forces and moments on the model. The sails were trimmed by maximising the drive force indicated by the display. The balance outputs were then sampled over a period of 120 seconds and average loads calculated. The sails were then adjusted slightly and the reading repeated.

All of the tests were then repeated with the twist profile removed (i.e. straight flow). In one case it was also possible to observe the model in straight flow with the sails set up for the same apparent wind angle with twisted flow. There was a noticeable difference in the sail trim required to produce maximum drive force.

Figure 4 shows the drive force for the upwind sails with and without the vanes twisted. The results between the two cases are very similar, as the amount of twist in the upwind case is very small. Figure 5 shows the drive force for the downwind sails with and without the vanes twisted. It can be seen that the sails perform significantly better when flown in the correct flow; in particular at the tighter angles where they are acting to produce more lift than drag.

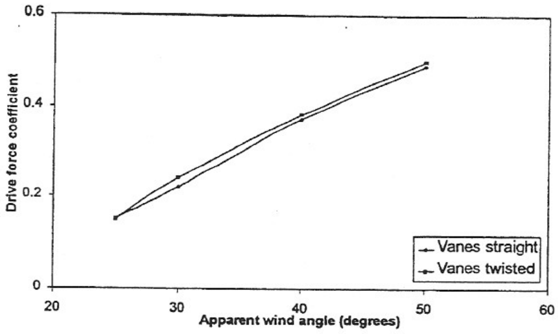

Figure 4 – Upwind sail drive force with and without vane twist

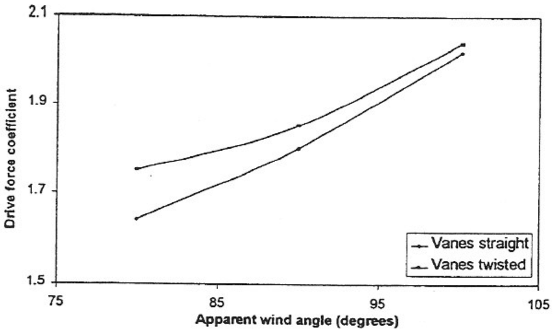

Figure 5 – Downwind sail drive force with and without vane twist

Conclusions

For the accurate simulation of the airflow around a yacht's sails, and for the measurement of resulting sail forces, it is necessary to model as closely as possible the conditions in which it is sailing. Even the comparison of similar model sails requires the twist and velocity profiles to be simulated correctly. The flying shape of the sails will be affected by these factors.

The velocity and twist profiles can be simulated using roughness element, flow barrier and twisting vane techniques.

It is essential also to be able to trim the model sails in response to the driving force in real time.

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