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A comparison of downwind sail coefficients from tests in different wind tunnels

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ABSTRACT

This paper contains results from five different tests on model sailing yacht rigs and sails. The tests were conducted by the author in four different wind tunnels over a fifteen year period between 1991 and 2007. The tests were conducted as part of development programmes for Whitbread 60 and America's Cup Class yachts and for particular racing teams. They were originally subject to commercial confidentiality so have not been published previously.

Although the aim of the original tests was to compare sail designs and develop the performance of the individual yachts the aim of this study is somewhat different and uses the data to compare wind tunnels. The paper describes features of the wind tunnels that affect the results together with the test requirements for investigation of downwind sailing performance. A large number of individual results are presented from tests over a range of apparent wind angles and curves of maximum lift and drag coefficients from each tunnel are then compared.

Although the original tests were not designed for benchmarking wind tunnels the lift coefficients from the different tests showed broad similarity within a 10% tolerance band and the drag coefficients within 20%. The difference between the tolerance bands being partly attributed to the dependence of induced drag on the square of lift. These together with similarities in the trends of the coefficients with apparent wind angle help validate the technique of wind tunnel testing of sailing yacht rigs. Conclusions have also been drawn from the results about the effect of lift on the drag of downwind sails and the overall accuracy of wind tunnel tests on rigs.

1. Introduction

The Wolfson Unit MTIA's archives contain a large body of commercially confidential data from wind tunnel and other tests. The results presented in this paper have been abstracted from five different wind tunnel sail test projects, selected to enable results from different wind tunnels to be compared. Permission to publish the results was kindly given by the clients.

Even though only one or two comparable sail configurations were selected from each of the five test programmes there remained a large amount of data to condense into this paper, which provides the basis for a reasonably rigorous evaluation of downwind sail wind tunnel testing.

The tests were originally conducted to aid the development of the individual yachts and their sails and relative results between sails were consistent within each test. The aim of this paper was to examine consistency between different wind tunnel tests.

The sail coefficients presented in this paper are the original values obtained at the time of each test, they have not been re-analysed or corrected to improve correlation as a result of the analysis performed for this paper. Comments are given in this paper where corrections may be applicable and future collaborations between wind tunnel organisations may help identify corrections for sail testing (e.g. Viola and Flay, 2011; Tahara et al., 2012).

2. Wind tunnels

The four wind tunnels used together with the year of the test were:

1994, Volvo automotive tunnel, Gothenburg, Sweden. Nilsson and Berndtsson, 1987.

1991, former Marchwood Engineering Laboratory (**MEL**) wind engineering tunnel, Southampton, UK. Robins, 1978.

1996 and 2003, University of Southampton (**Soton**) aeronautical tunnel, UK.

2006, Politecnico di **Milano** wind engineering tunnel, Bovisa, Italy.

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The principle features of the tunnels that could affect the sail tests are given in Section 6.

3. Tests

Two of the five tests from which results have been abstracted were of Whitbread 60 yachts (W60), developed for Round the World races. The other three tests were of America's Cup Class yachts of different versions; both IACC and ACC.

The W60, IACC and ACC yachts were similar, being single masted sloop rigs with asymmetric gennakers set from spinnaker poles. There were differences: fractional and masthead sails were tested on the W60s and mainsails were developed during the period of the tests with increasing leech roach leading to squared headed sails. Results are presented from both W60 and IACC yachts tested in the Soton tunnel so the effect of these differences on the sail coefficients can be seen.

4. Downwind sailing angles

The apparent wind angles for downwind sailing vary depending on the course, the size and performance of the yacht, its boat speed and the true wind speed (Wright et al., 2010).

For windward/leeward courses, such as the America's Cup races in the IACC and ACC Classes the optimum true wind angles were $\beta tw = 150 \pm 10^{\circ}$, with an associated mean gybe angle of 60°. VPP calculations provide the optimum true wind angle (βtw) and associated apparent wind angles (βaw), however these are obtained from the simple solution of the wind triangle, as illustrated in Fig. 1.

It can be seen that the apparent wind angle is dependent on the ratio of boat speed to true wind speed (Vs/Vtw) and varies between 60° and 120° for ratios between 1.15 and 0.58. The boat speed tends to be higher than true wind speed in light winds and lower in stronger wind speeds because of the non-linear relationship between hydrodynamic resistance and aerodynamic thrust.

It is therefore necessary to test downwind sails through a wide range of apparent wind angles, although there may be different sails designed for different ranges of angles. Similar apparent wind angles can occur at lower true wind angles associated with reaching, although they tend towards 60° and lower. Downwind sailing is, however, characterised by low heel angles, typically less than 5° for the ACC yachts, whereas reaching performance can cause significant heeling. The maximum driving force is of primary interest for downwind sail testing, with the heeling moment having little effect on sailing performance. This is different from upwind and reaching where depowered sail settings are of importance for sailing in moderate and strong wind conditions.

Downwind sailing at an apparent wind angle of 90° is an interesting condition, which for America's Cup Class yachts sailing arose in a true wind speed of 12 knots – the mid wind range for good sea breezes in Valencia Spain, the location for AC32 and AC33 America's Cup races. At this angle all the driving force was derived from aerodynamic lift and all the heeling force from drag so maximum driving force equated to maximum lift.

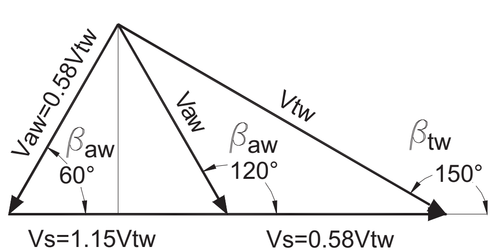

Fig. 1. Wind triangle for downwind sailing.

At deeper apparent wind angles the lift force contributed to the righting moment as opposed to contributing to the heeling moment at closer or smaller apparent wind angles. The heeling moment tended to zero at an apparent wind angle of 135°, where the righting moment from the lift force balanced the heeling moment from the drag force or in other terms where the resultant aerodynamic force was aligned with the boat axis.

5. Data reduction

The measured forces can be expressed in various ways and although a yacht's performance depends principally on driving force and heeling moment in the body axis it is better to compare sail aerodynamics in conventional lift and drag coefficients in the wind axis. These are used in VPP calculations and show less variation with apparent wind angle than forces in the body axis.

$$\text{Drag coefficient } \mathrm{Cd} = D/1/2\rho \mathrm{Vaw}^2 A \quad (1)$$

$$\text{Induced Drag coefficient } \mathrm{Cdi} = A\mathrm{Cl}^2/\pi \mathrm{He}^2 \quad (2)$$

$$\text{Induced drag } \mathrm{Di} = L^2/1/2\rho \mathrm{Vaw}^2 \mathrm{He}^2 \quad (3)$$

The reduction of measured forces to aerodynamic coefficients depends on apparent wind speed (Vaw) or the associated dynamic pressure and sail area (*A*). The Induced drag due to lift is dependant on the Effective Rig Height (He) and measurement accuracy of these parameters is discussed in separate sections of this paper but the influence of any differences between the tunnels is discussed here.

Relative results between sails tested in one tunnel remain unaffected by errors in the wind speed measurement, provided it is taken in a consistent manner. Scaling to the yacht's performance depends on the wind speed measurement for the yacht as well as that in the tunnel, which is also problematic since measurements for the yacht are generally obtained from a masthead anemometer that is particularly affected by masthead downwind sails and by the prevailing wind gradient.

Both the lift and drag coefficients would appear to be affected similarly by differences in wind speed but this does not apply to the induced drag due to lift. It can be seen from Eq. 2 that the induced drag coefficient depends on the square of the lift coefficient and the aspect ratio, which has been expressed as He^2/A where He is the effective rig height – a distance related to the geometric rig height (Teeters et al., 2003). The effective rig height is a useful parameter to derive because, as shown in Eq. 3, it is independent of sail area but its correct determination relies on the correct measurement of dynamic pressure. This can cause differences when comparing effective rig heights from tests in different wind tunnels.

6. Sail areas

Both the America's Cup Class Rule and the Whitbread 60 Class Rule had sail measurements designed to produce the surface area of the sails. There were differences in the details of the measurements but the differences between the actual and measured surface areas of the sails will have been relatively small, within a few per cent. Details of the measurements are given in the published class rules.

The sail coefficients given in this paper are based on the Rule measurements of sail area and not the planform or projected areas