A COMPARISON OF DOWNWIND SAIL COEFFICIENTS FROM TESTS IN DIFFERENT WIND TUNNELS

I.M.C Campbell, Wolfson Unit MTIA, University of Southampton, UK, imc@soton.ac.uk

Summary: 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 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 this 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 sail coefficients from the different tests showed broad similarity within a tolerance band, which helps validate the technique of wind tunnel testing of sailing yacht rigs. Conclusions have 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.

2. WIND TUNNELS

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

1994, Volvo automotive tunnel, Gothenburg, Sweden [1]
1991, former Marchwood Engineering Laboratory (**MEL**) wind engineering tunnel, Southampton, UK [2]
1996 and 2003, University of Southampton (**Soton**) aeronautical tunnel, UK
2006, Politecnico di **Milano** wind engineering tunnel, Bovisa, Italy

Table 1 Dimensions of the tunnel test sections

Tunnel	Volvo	MEL	Soton	Milano
Width m	6.6	9	4.57	14
Height m	4.1	2.7	3.65	4
Length m	15.8	20	3.7	35
Model scale				
ACC		20	18	12.5
W60	15		15	

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.

Table 2 Summary of sails tested

Tunnel name	Yacht class	Main Area	Gennaker	
			Code	Area
		m^2		m^2
Volvo	W60	117	G5	195
			G-MH-1B	243
MEL	IACCv1	197	CC1	423
Soton	IACCv2	215	A1	453
Soton	W60	117	ASY73B	300
			FASY	215
Milano	ACCv5	212	A2	531

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.

For windward/leeward courses, such as the America's Cup races in the IACC and ACC Classes the optimum true wind angles were βtw =150+/-10 degrees, with an associated mean gybe angle of 60 degrees. 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 Figure 1.

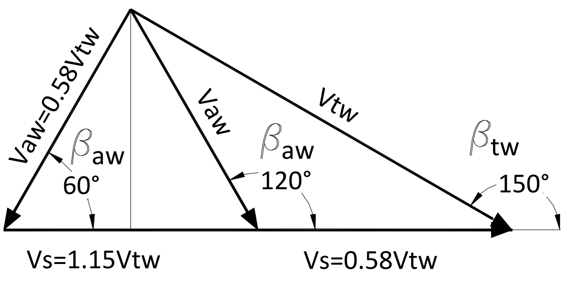


Figure 1 Wind triangle for downwind sailing

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 degrees 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 may be 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 degrees and lower. Downwind sailing is, however, characterized by low heel angles, typically less than 5 degrees 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 to 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 degrees is an interesting condition, which for Americas Cup Class yachts sailing arose in a true wind speed of 12 knots - the mid wind range for good sea breezes in Valencia. 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.

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 degrees, 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.

$$Cd = D \Big/ \tfrac{1}{2}\rho Vaw^2 A \cdots (1)$$

$$Cdi = ACl^2 \Big/ \pi He^2 \cdots (2)$$

$$Di = L^2 \Big/ \tfrac{1}{2}\rho Vaw^2 He^2 \cdots (3)$$

The reduction of measured forces to aerodynamic coefficients depends on apparent wind speed (Vaw) or the associated dynamic pressure and sail area (A). Measurement accuracy of these 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 equation 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. The effective rig height is a useful parameter to derive because, as shown in equation 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 that are sometimes used in the definition of lift and drag coefficients of other bodies in different applications.

7. WIND SPEED MEASUREMENTS

The four tunnels had different wind circuits that affected the wind speed profiles and their measurements. Sail tests require relatively large working sections and low wind speeds compared to convention aeronautical testing. The working test section in conventional aeronautical wind tunnels is downstream of a larger section of the tunnel with a contraction, which improves the flow uniformity and reduces the turbulence intensity. But there were no contractions immediately upstream of any of the sections used for these tests because of the requirement for a large working section.

The model in the Volvo wind tunnel [2] was approximately 25m downstream from the last corner and approximately 10m from the start of the slotted wall test section. The flow uniformity was very good with variations in pitot pressure of +/- 0.2%. The boundary layer δ thickness was approximately 80mm.

The model in the low speed section of the University of Southampton wind tunnel was only approximately 2m from the last corner and its associated smoothing screens. An additional screen was fitted prior to the W60 tests with the aim of improving the flow uniformity. This had a static pressure drop of twice the dynamic pressure, which was suitable for use in wind tunnels. The flow, however, was not as uniform as the in the Volvo tunnel and there were consistent variations of dynamic pressure across the model's location with an rms value of 5%. The flow in the high speed section, which was downstream following a contraction with a 5:1 area ratio, was much more uniform and the reference speed for the tests was taken from this section. The boundary layer was within 150mm from the tunnel floor.

The tunnels at the Marchwood Engineering Laboratory and the Politecnico di Milano were designed for wind engineering work so had long sections used to grow a stable boundary layer flow to model that of the atmosphere, albeit at a scales at least an order of magnitude smaller than those of sail test models.

The MEL wind tunnel [1] was open circuit with a bell mouth intake that drew air from the outside environment into the enclosed working section. The inlet was fitted with screens to help isolate the flow in the test section from the external wind environment but some sensitivity remained. The air was drawn down the working section by a single 1MegaWatt centrifugal fan and exhausted back outside. The tunnel was reported to have suffered from a slow oscillation in its wind speed, likened to an organ pipe effect, but sail force measurements were averaged over a period of approximately 1 minute such that any oscillations did not affect the results, evidenced by good repeatability. The tunnel floor was covered with toy lego brick blocks to increase its roughness and create a boundary layer, which extended to a height of approximately 500mm. The flow speed remained consistent within the boundary layer and was measured from a pitot tube within the working section.

The Politecnico di Milano wind tunnel had a closed circuit, with a bank of fourteen fans driving the air through the final bend into the low speed section. The tunnel floor was smooth and the boundary layer was approximately 300mm thick but there were consistent lateral and vertical variations in flow speed and across the location of the model. These were associated with the flow pattern from the individual fans and amounted to an rms variation in pitot pressure of approximately 5%. The tunnel had a high speed section on the return circuit below the low speed section with a contraction ratio of approximately 3:1so, to avoid the problems with the flow variations, the mean flow speed was taken from measurements in this section.

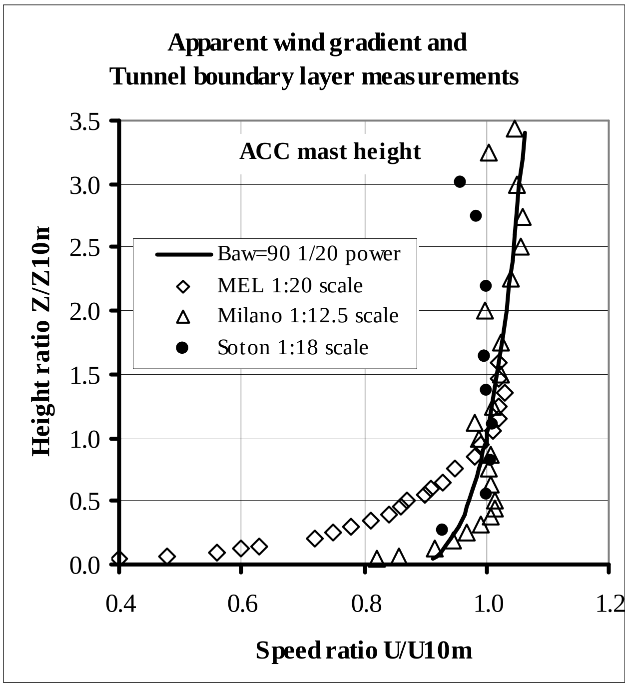


Figure 2 Wind tunnel gradients at the time of the tests

Examples of the flow measurements taken at the time of the wind tunnels test in way of the model are shown in Figure 2 together with the apparent wind gradient for the 1:12.5 scale ACC yacht model tested in the Politecnico di Milano tunnel. Unevenness in the wind profile can be seen in data from this and the Southampton tunnel but it should be noted that the mean test speed was derived from a grid of measurements taken across the test area not just those shown in Figure 2.

Reduced wind speeds over the lower part of the model sails were most significant in the MEL tunnel.

The wind speeds us for the downwind sail tests were approximately 5 m/s. This was within both the structural strength of the model and the power of the remotely operated sheet winches. It also matched the scale relationship between the wind pressure and sail cloth weight, ensuring reasonable modelling of the flown sail shapes. The test Reynolds numbers were consequentially less than full scale by the order of the model scale, i.e. a factor for at least 12.5 to 20 lower than full scale. This is an unavoidable feature of model testing.

8. WIND GRADIENT AND TWIST

The apparent wind speed gradient and twist that is experienced by the yacht when sailing depends on the true wind gradient and the yacht's speed and heading. This involves solution of the wind triangle shown in Figure 1 with height.

Tests with a twisted flow device [8] were conducted in the Milano tunnel for the America's Cup using a true wind gradient measured in Valencia for the prevailing sea breezes. The gradient was curve fitted by a power law of between 1/20 and 1/30, which was considerably lower than the conventional 1/7 or 1/10 curves. The associated apparent wind gradients and twist for a 1/20 true gradient are shown in Table 3 for different ratios of boat speed (Vs) to true wind speed (Vtw), which correspond to racing conditions for downwind sailing at a true wind angle of βtw = 150 degrees.

Table 3 Calculated values for the apparent wind gradient

Vs/ Vtw	Vaw/ Vtw	Baw	Twist		Vaw/Vaw10m	
		10m	Boom	Mast	Boom	Mast
ratio	ratio	deg	deg	deg	ratio	ratio
0.6	0.57	118.0	-4.9	3.1	0.88	1.10
0.7	0.53	108.4	-6.5	4.2	0.89	1.09
0.8	0.50	97.5	-8.0	5.3	0.91	1.08
0.9	0.50	86.1	-8.8	6.1	0.94	1.06
1.0	0.52	75.0	-8.9	6.5	0.97	1.04
1.1	0.55	64.9	-8.3	6.4	1.00	1.02
1.2	0.60	56.3	-7.5	6.0	1.02	1.00

Considerable twist occurs below boom level, where it has little influence on the sails and its effect on modelling in the wind tunnel is on hull windage. It can be seen that the twist at the boom was only slightly greater than at the masthead. After some adjustments of the vanes in the wind tunnel, similar twist was achieved at the boom and mast of +/- 5 degrees.

It can be seen from Table 3 that the actual apparent wind gradient at sea is relatively small at high boat speed ratios, which are associated with light winds. So these conditions are reasonably represented by the uniform wind speeds in the Soton and Volvo tunnels. The wind gradient in the Milano tunnel, shown in Figure 2, was representative of medium wind sailing conditions with apparent wind angles of 75 to 108 degrees. The deep boundary layer in the MEL tunnel was less representative of the downwind sailing conditions, which is not surprising as the tunnel was designed to model the true atmospheric wind gradient for building work not the apparent wind gradient produced by a moving yacht.

9. BLOCKAGE CORRECTIONS

The most significant correction for downwind sail measurements made in closed jet test sections is the wake blockage correction. This corrects for the reduced pressure, i.e. higher suction, in the wake resulting from the tunnel wall constraints on the streamlines downstream of the model. The so called Maskell correction was applied to some of the tests using the method given in ESDU data sheet 80024. The correction is based on the drag due to separated flow, obtained by subtracting of the induced drag due to the measured lift.

Although the wake blockage is calculated from the measured drag the correction is of the base pressure acting on the sails so is applied to both lift and drag forces.

Wake blockage corrections were studied by the automotive industry in the 1980s, when manufacturers were vying to produce low drag coefficients for their cars and the Volvo tunnel was designed with slotted walls in an attempt to overcome the problem. The test section has similarities with an open jet tunnel, where blockage corrections are applied in the opposite sense due to less suction of the wake, but at the time of the tests blockage corrections were not applied to the sail test results from this tunnel.

The MEL tunnel was relatively large compared to the Southampton tunnel so at the time an average estimate of the wake blockage correction was applied to all results. The analysis process was refined for subsequent tests such that corrections were calculated for individual test points. The maximum correction factors used for the tests in this paper are shown in Figure 3.

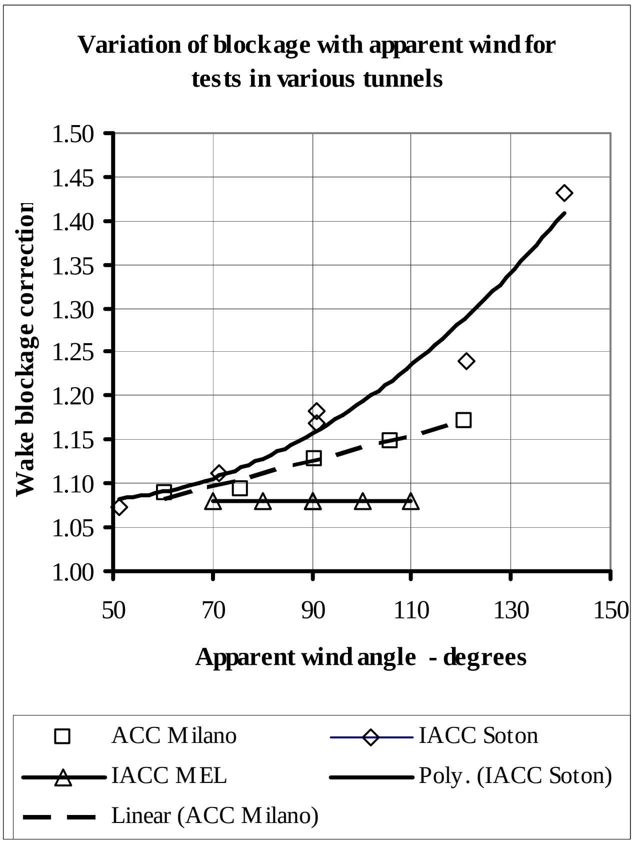


Figure 3 Wake blockage corrections for different tunnels

It can be seen that the wake blockage corrections in the Southampton tunnel were approximately twice those in the Milano tunnel, particularly at the wider apparent wind angles where the lift was lower and the drag due to separation was higher. In retrospect the wake blockage corrections applied to the MEL data are low compared to those applied to the Milano tunnel data. Some wake blockage could also be retrospectively applied to the Volvo tests.

10. MEASUREMENT METHODS

The results given in this paper were obtained using test methods that were evolved by the Wolfson Unit MTIA over a prolonged period and numerous projects. They were derived from the methods used by the Yacht Research Group at the University of Southampton in the 1960s, described by A J Marchaj in his classic book Sailing Theory and Practice, but differ considerably due to improved dynamometry, data acquisition, model sail construction, remote winch operation and test procedures [7].

Different dynamometers were used in the different tunnels but all were calibrated and corrected for interactions with an overall accuracy and repeatability of the order of +/- 1%. The models were isolated from the wind tunnel turntables to avoid problems with tare corrections on roll moments due to wake interactions. The measurements included the forces due to the hull, deck, mast, rigging and sails.

The data acquisition system used for these tests displayed in real time the sail forces, measured on body axes. The sail sheeting and spinnaker pole adjustment were made remotely with the wind on, which enabled the sail settings to be optimised and the maximum forces to be sought. Individual test points were obtained by averaging force measurements over a period of time, of the order of 30 seconds, and each point represents the result of several minutes of sail adjustments using the real time display.

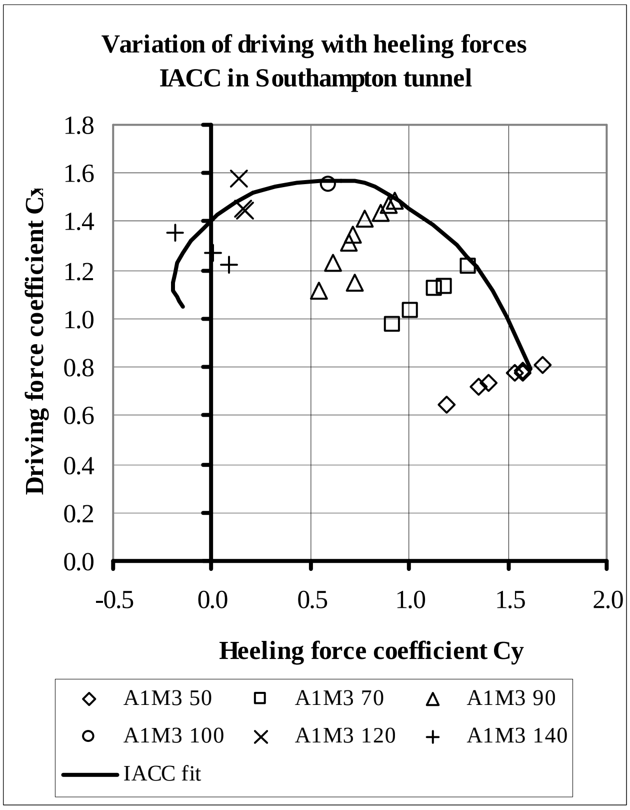


Figure 4 Driving and heeling force coefficients

Procedures for downwind sail testing, where heel angles are small, were developed to obtain the maximum driving force that the rig could produce, since this would cause the yacht to sail at its fastest speed downwind therefore real time VPP techniques are not required during downwind wind tunnel tests. Once the sail coefficients were derived the VPP was used to predict apparent wind angles for different true wind speeds, using the wind triangle shown in Figure 1.

Typical results are shown in Figure 4 from measurements were made with a number of different sail settings at different apparent wind angles. The force data was plotted at the time of the tests and although tests were made at discrete apparent wind angles the forces were presumed to vary smoothly with apparent wind angle so low values could be identified and sails readjusted in the search for the maxima. It can be seen that the driving force coefficients are greatest at apparent wind angles between 90 and 120 degrees. The same force data can be transformed from body to wind axes to produce the lift and drag coefficients shown in Figures 8 and 9. In addition the centre of effort height can be obtained from the heeling moment measurements, as shown in Figure 13.

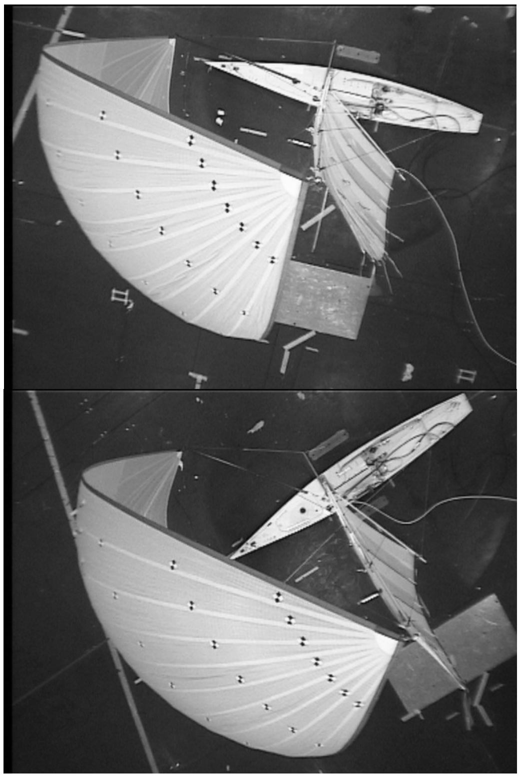


Figure 5 Sails set at two apparent wind angles

The sails are readjusted at each apparent wind angle and, as can be seen in Figure 5, the use of the spinnaker pole results in similar sail geometry relative to the apparent wind direction with quite different sheeting relative to the yacht.

Although the maximum forces are of primary interest for downwind sailing, other useful information on the rig performance can be extracted from the lower force measurements by plotting the variation of drag coefficients with the square of lift, as shown in Figure 12. Linear trends in the data can be seen, particularly at the lower wind angles of 50 to 70 degrees and these are attributable to the variation of induced drag due to lift. The reduced lift conditions are achieved mainly by adjustment of the mainsail sheeting angle, with this sail acting like a flap to the highly cambered asymmetric sail and there is a range of settings where this flap causes relatively small changes to any flow separation so of the variations in drag are associated with invicid flow. The slope of the induced drag line can be used to derive and effective aspect ratio and height or span for the rig that can provide a useful comparison between the tests.

11. DISCUSSION OF RESULTS

The curves summarising the maximum lift coefficients from all the tests are shown in Figure 6 and the associated drag coefficient curves in Figure 7.

Given there were differences between the tunnels, wind, yacht design, models and sails over the 16 year test period, as discussed previously, it is remarkable that the maximum lift coefficient curves are all similar within a 10% band. All the tests showed the maximum lift coefficient to occur at apparent wind angles between 50 to 70 degrees and to be slightly lower at 90 degrees.

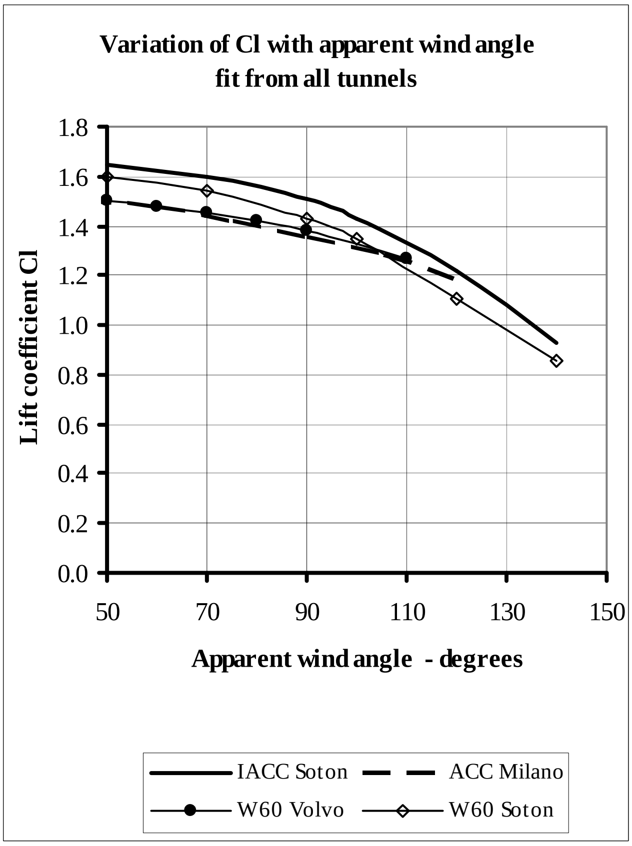


Figure 6 Summary of maximum lift coefficients

Maximum lift was sought at 90 degrees since this will have produced maximum driving force so there is probably something associated with the sail geometry and sail interaction that enabled higher lift to be achieved at the closer angles and also for the lift to reduce at wider angles. The side shrouds limit the boom sheeting angle to less than 90 degrees to the yacht's centreline, which may have restricted the lift at deeper apparent wind angles.

The drag coefficient curves show greater variation than the lift curves of approximately 20% and with the opposite trend of drag increasing with apparent wind angle. The factors influencing these differences are considered further.

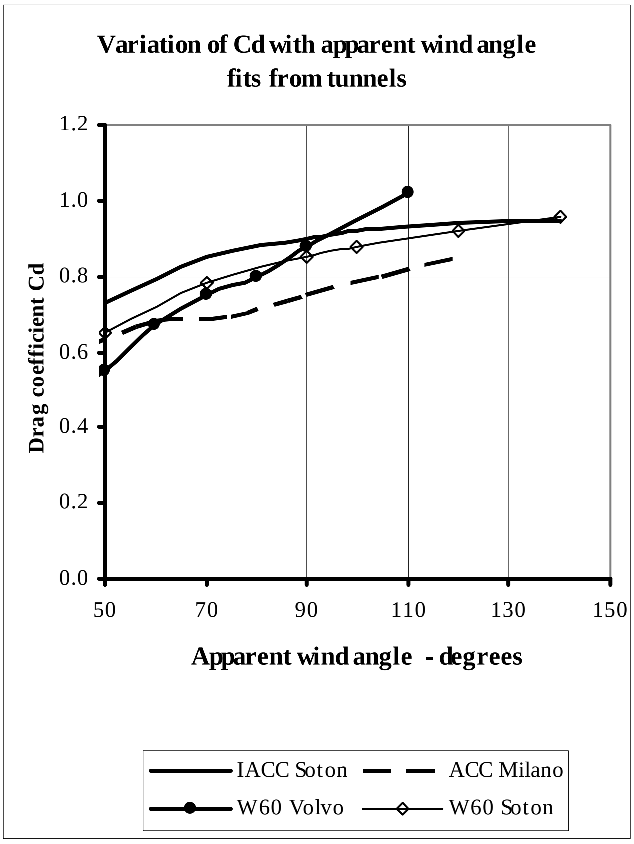


Figure 7 Summary of maximum drag coefficients

Comparison of lift and drag from the two different tests in the Soton tunnel on the W60 and IACC models produced similar maximum lift and drag curves with slightly lower values from the W60. Both these tests included reduced lift settings, although conducted at slightly different apparent wind angles, and the variation of drag coefficient with the square of lift is shown in Figures 12 and 20. The effective rig heights from the slope of the induced drag lines were very similar, being 89% of the mast height above the water-line for the IACC rig and 90% for the W60 rig. These are lower than the effective rig heights used for upwind rigs, although these have some form of deck sealing.

The intercept of the induced drag line at zero lift can be considered to be the base drag, including viscous drag, windage from the hull and rigging and any drag due to separation that does not vary due to lift. There was an apparent increase in base drag to increase with apparent wind angle, as can be seen from Figure 12 by the difference in the parallel lines from the IACC tests at apparent wind angles of 50 and 70 degrees. This may be caused by increased separated flow off the gennaker at higher apparent wind angles.

The drag due to windage of the hull and rig was measured with the sails removed and is shown in Figures 9 and 12 and it can be seen that it is relatively small compared to both the total sail drag and the residual base drag after subtraction of the induced drag.

The W60 fractional and masthead gennakers produced similar lift and drag coefficients but it can be seen from Figure 21 that their centre of effort heights were distinctly different. The centre of effort only varied with apparent wind angle by a few percent but it can be seen by comparing Figures 13 and 21 that the IACC tests produced slightly higher centres of effort.

The IACC tests in the MEL tunnel produced only a few maximum lift points compared to the complete IACC tests conducted in the Soton tunnel so the results are shown plotted together in Figures 8,9,12 and 13. It can be seen that the lift was similar except at the apparent wind angle of 110 degrees and the drag approximately 10% lower. It is possible that the wake blockage was underestimated at the apparent wind angle of 110 degrees, as discussed previously, however whilst increasing the correction could improve correlation in lift it would reduce the drag. The centre was higher from the MEL tests, particularly at the problematic apparent wind angle of 110 degrees, and this may be attributed to the boundary layer shown in Figure 2.

Data from the W60 tests in the Soton and Volvo tunnels are shown in adjacent Figures 16 to 23 for ease of comparison. Lift and drag coefficients were similar at an apparent wind angle of 90 degrees but were lower from the Volvo tunnel at lower apparent wind angles and higher at higher angles except for a single test point at an angle of 50 degrees. This point has both higher lift and drag than the curve fit though the data set but it can be seen from Figure 22 that the drag is consistent with the increase in induced drag due to lift. It is therefore possible that the sails were not set in the Volvo tests to produce the maximum lift, except at this single point. It can be seen from Figures 20 and 22 that the induced drag from the effective rig height obtained from the Soton tests at an apparent wind angle of 60 degrees also matched the Volvo test results at 40 and 50 degrees, albeit with lower base drag. It is possible that the absence of any blockage correction to the Volvo tunnel data influenced the higher lift and drag data at the apparent wind angle of 90 degrees.

Two different sized gennakers were tested in the Volvo tunnel and slightly higher drag coefficients were measured from the smaller G5B. There centre of effort heights were similar, although the G5B was recorded to be a fractional gennaker, but the height tended to decrease with apparent wind angle, not remain constant as from the other tunnel tests. It is possible that there was a roll moment measurement problem.

Data from the IACC tests in the Soton tunnel and the ACC tests in the Milano tunnel are shown in adjacent Figures 16 to 23 for ease of comparison. The Milano tests were the most recent and used the largest model in the biggest tunnel and were undertaken with great care as part of a comprehensive 14 week test programme.

It can be seen that both the lift and drag were lower from the Milano tests and the centre of effort was slightly higher. It is possible that either the wind gradient or twist reduced the maximum lift coefficient from the Milano tunnel with, as discussed previously, an associated reduction in induced drag. Although different apparent wind angles were used in the Soton and Milano tests it can be seen from inspection of lift and drag data in Figures 12 and 14 that the Milano data matched the Soton data at comparable values of lift.

The Milano tests were focused on achieving the maximum sail force in order to compare different gennaker shapes, so there were not many reduced lift points to use to compare induced drag and effective rig heights with those from the Soton tests. It is, however, notable from Figure 14 the concentration of lift and drag coefficients from tests over a wide range of apparent wind angles compared to the spread of driving and heeling forces shown in Figure 4. There is a similar concentration of data from the W60 Volvo tests shown in Figure 22, particularly at reduced values of lift. The effect of the apparent wind angle on the aerodynamic coefficients is secondary to its effect on the transformation of the aerodynamic force vector from wind axes to body axes.

Finally, it is possible that higher lift coefficients were obtained from the Soton tunnel because of the fine scale turbulence induced into the flow by the smoothing screens immediately upstream of the model, which was a unique feature of this tunnel. It is also possible that full scale maximum lift coefficients could be higher than those measured in any of the wind tunnels but they should not be lower.

12. CONCLUSIONS

Consistency has been found in the maximum lift coefficient obtained from the different wind tunnel tests on downwind sails within a band of 10% across the range of apparent wind angles associated with downwind sailing.

Induced drag is associated with the lift produced by the downwind sails with an associated effective rig height of approximately 90% of the mast height above the water-line, which is lower than associated with upwind sails. This induced drag accounts for some of the 20% variation in the maximum drag coefficients obtained from the different wind tunnel tests.

There were similar trends in the variation of lift and drag with apparent wind angle from each of the wind tunnels, indicating the validity of these trends. These trends showed a reduction in the maximum lift coefficient with apparent wind angle and an increase in the drag coefficient, with part of this increase associated with the base drag.

There were variations in the centre of effort height that could be attributed to the different wind gradients in the tunnels.

Lower maximum lift coefficients were obtained from the Milano tunnel, which may be attributed to the wind gradient and twist simulated in this tunnel or it is possible that fine scale turbulence in the Soton tunnel allowed higher maximum lift to be achieved.

The applied wake blockage corrections appear to have aided the correlation of sail coefficients obtained from different wind tunnels.

The effects of apparent wind angle on aerodynamic coefficients, defined in the wind axes, are smaller than those on the driving and heeling force coefficients, defined on the body axes.

The general similarity in the sail coefficients obtained from the different tests in different wind tunnels helps validate the technique of wind tunnel testing of sailing yacht rigs.

13. WIND TUNNEL RESULTS

The following figures contain results from each of the five different tests of lift and drag coefficients and centre of effort height.

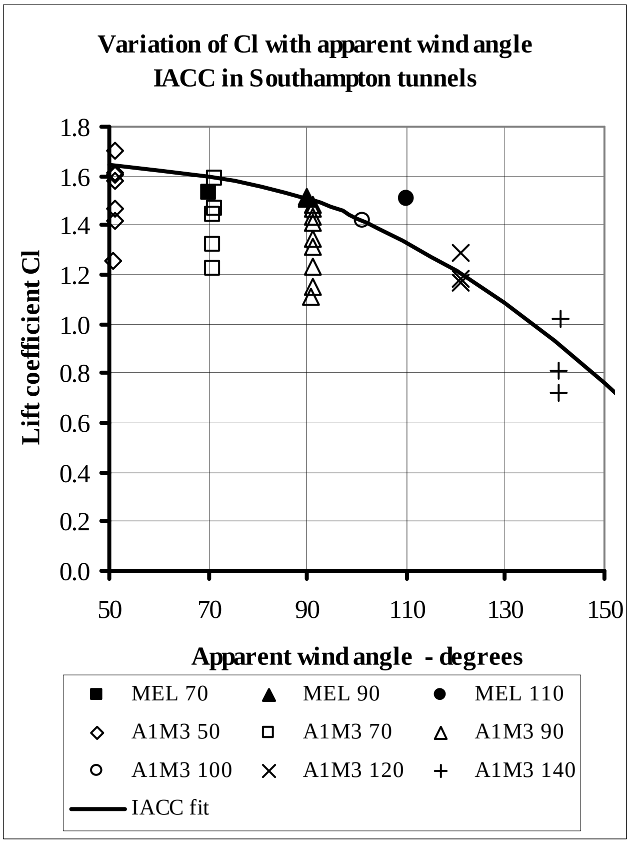


Figure 8

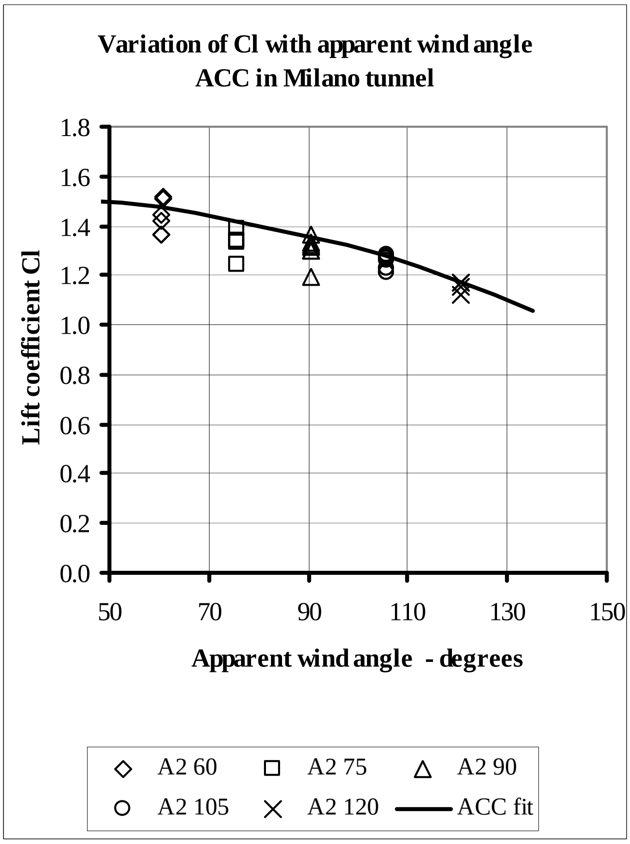


Figure 10

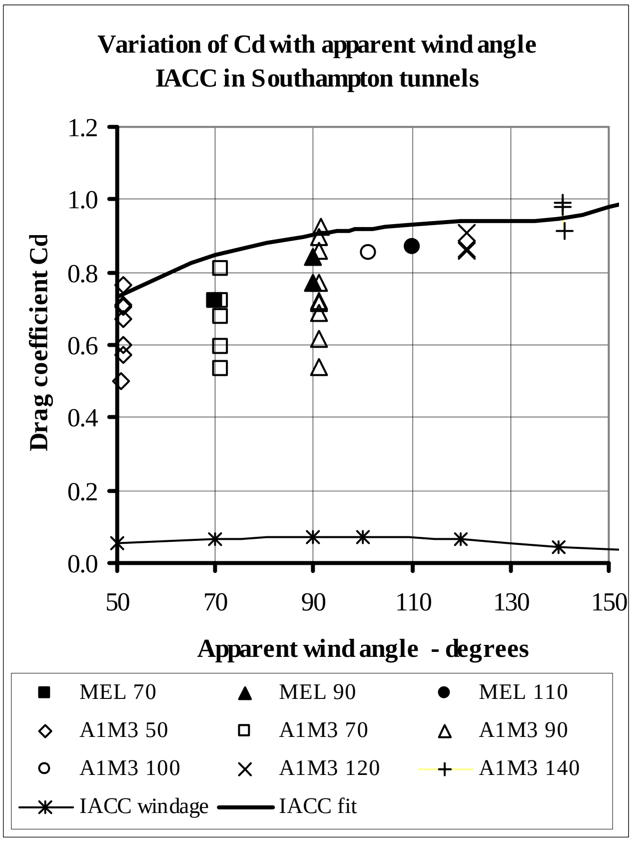


Figure 9

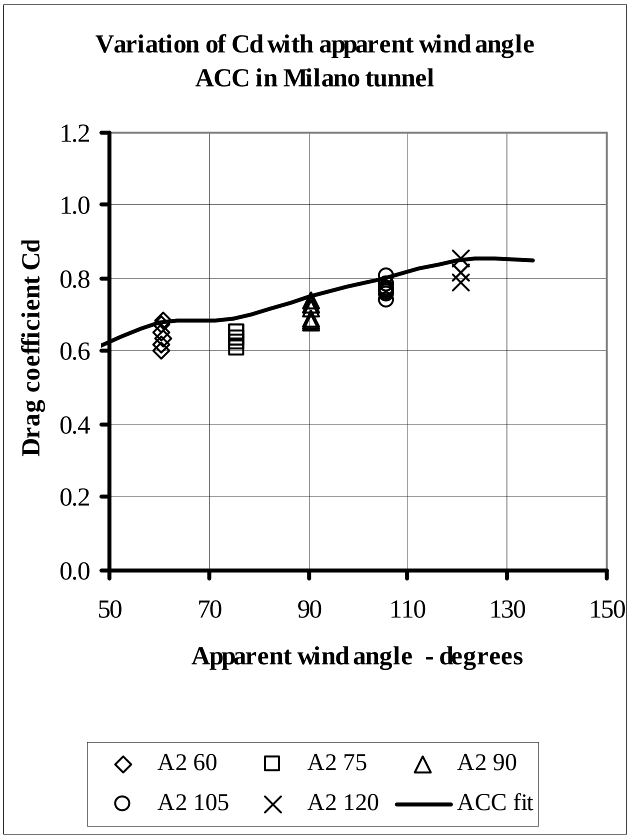


Figure 11

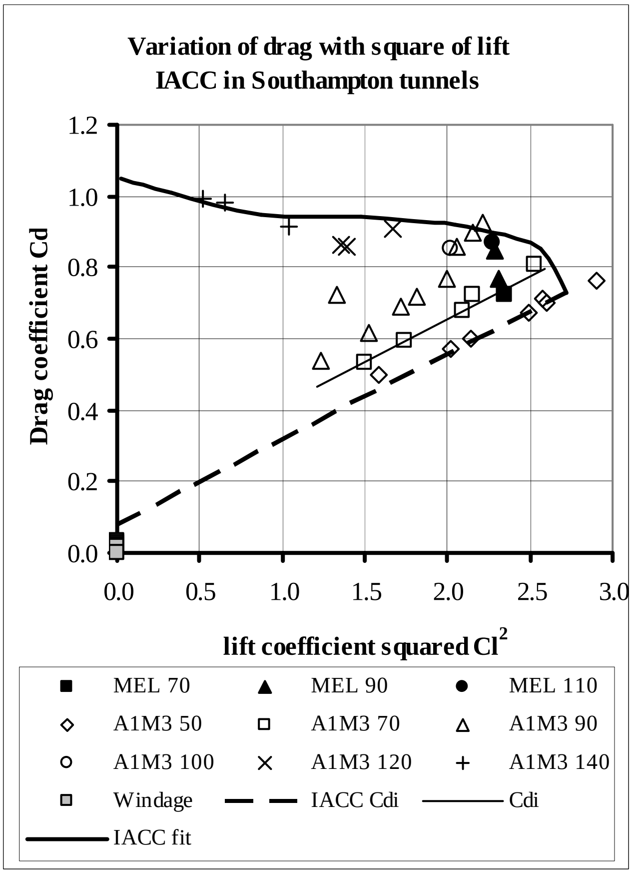


Figure12

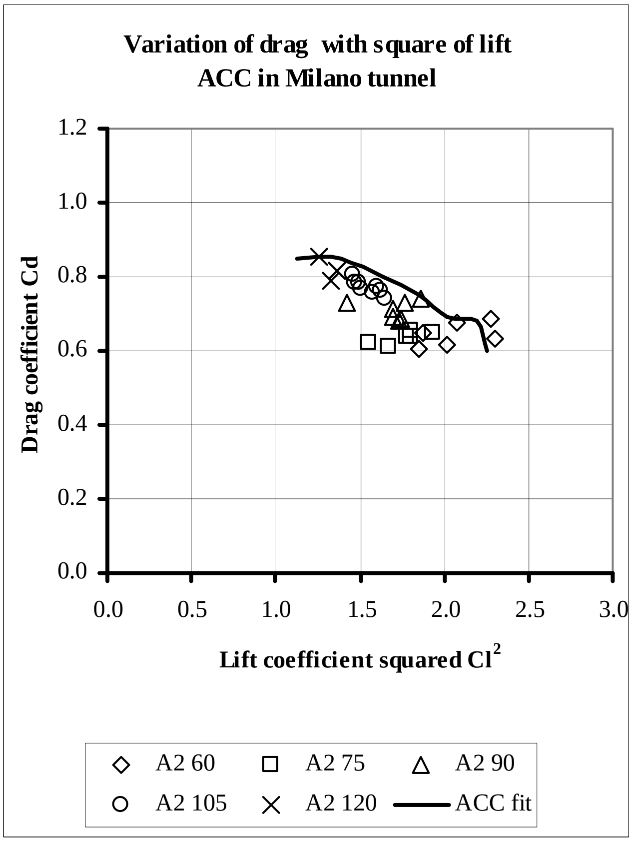


Figure 14

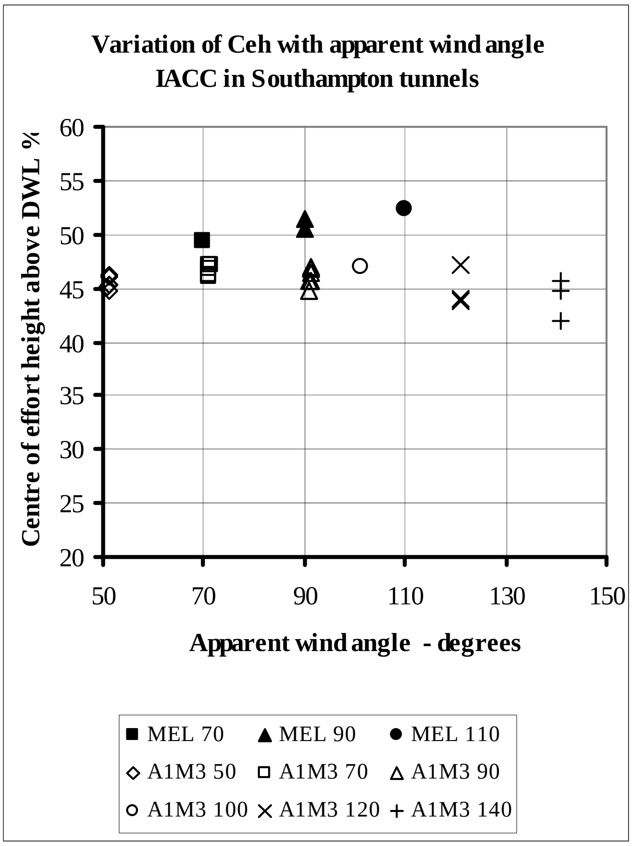


Figure 13

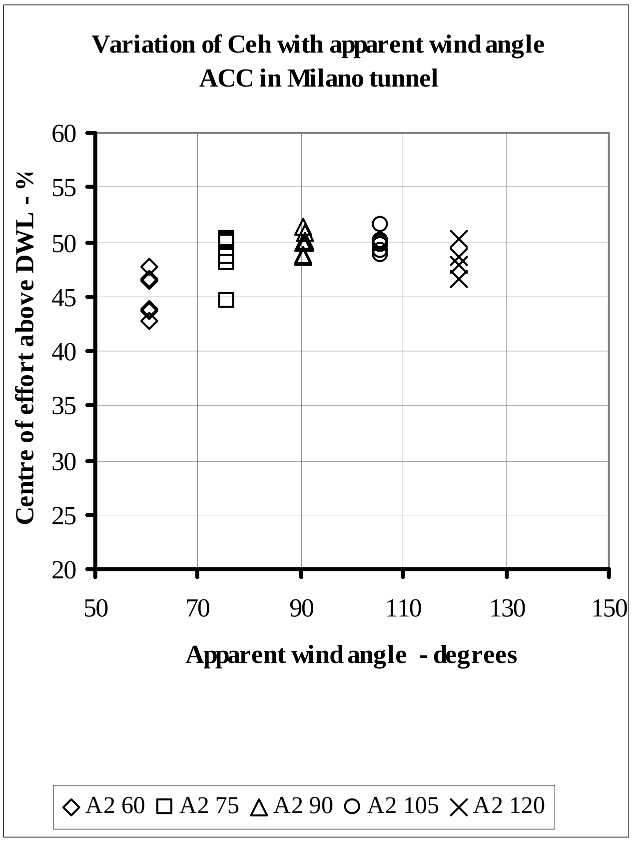


Figure 15

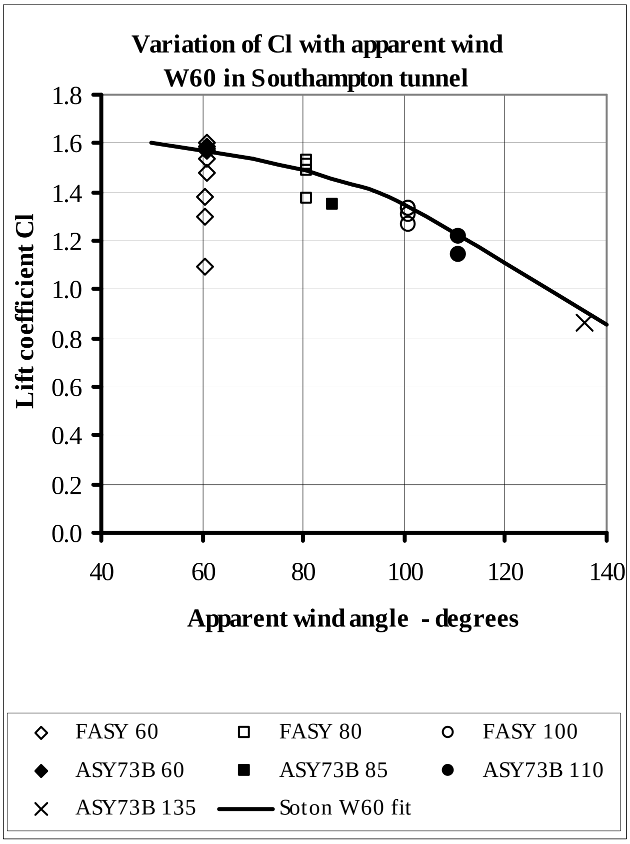
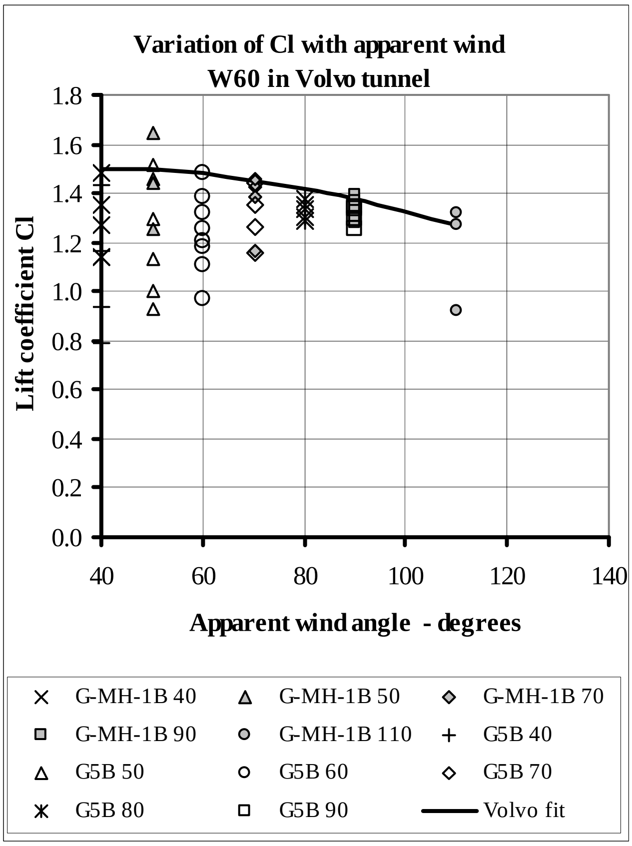


Figure 16



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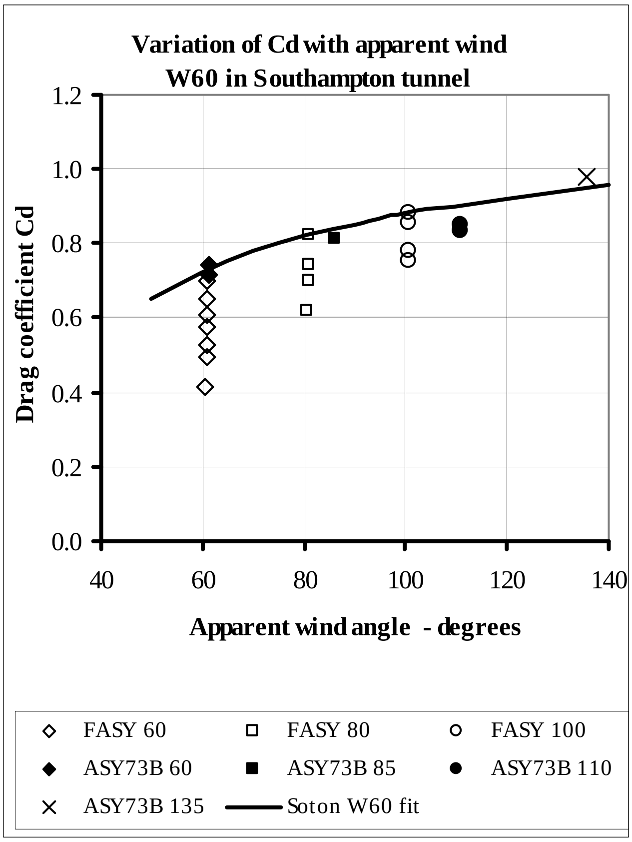


Figure 17

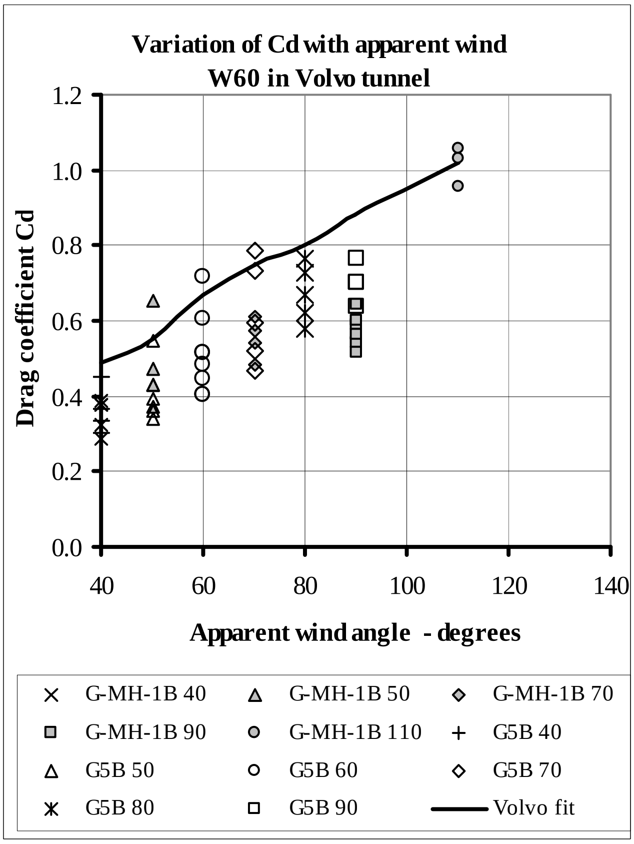
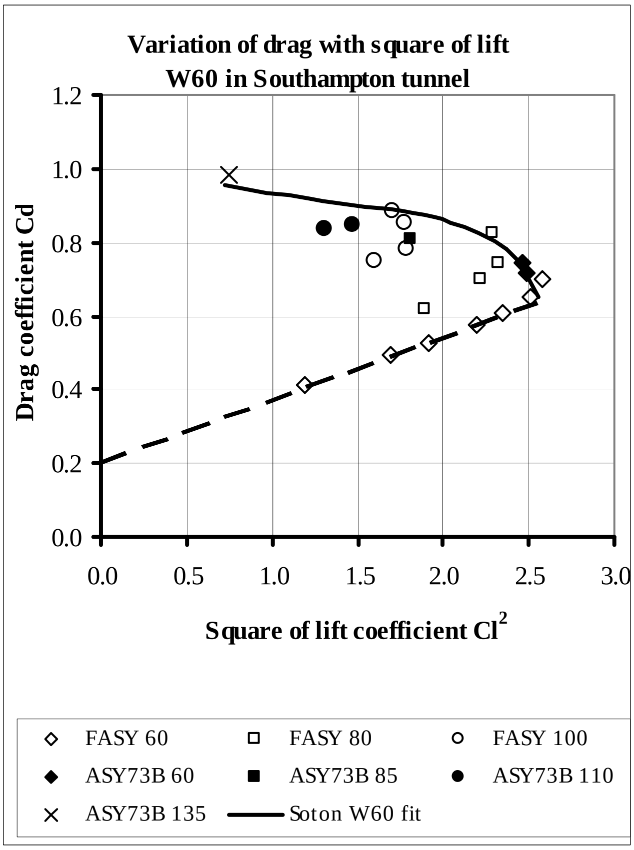


Figure 19



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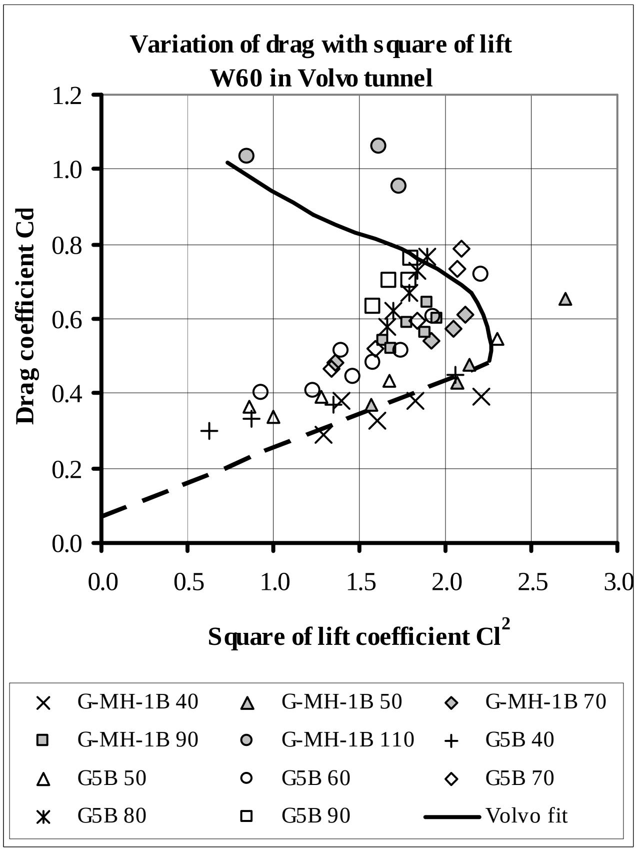

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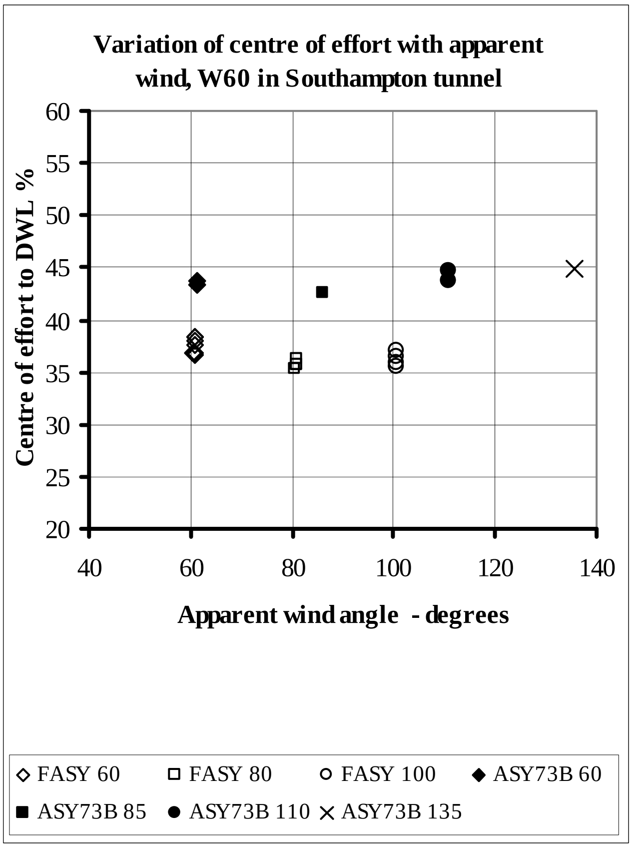

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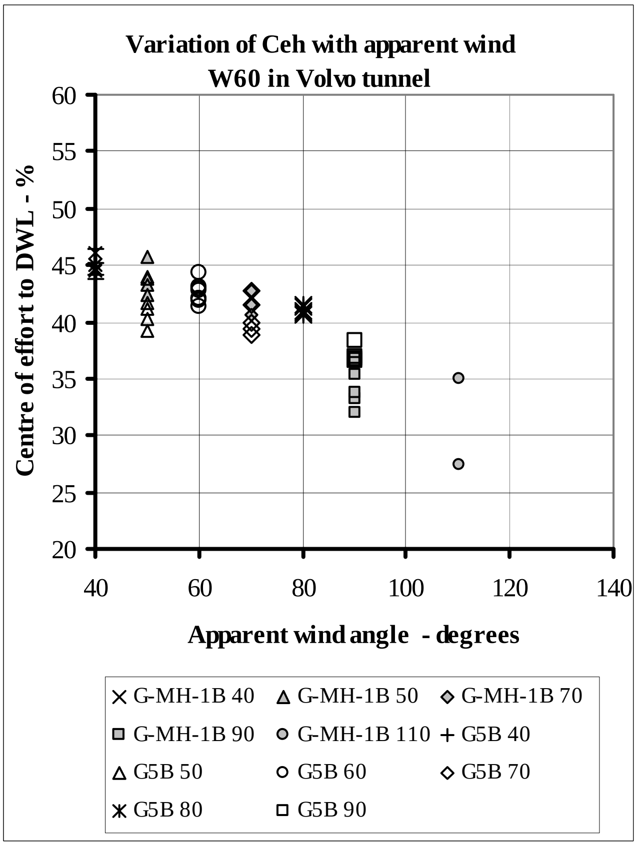

Figure 23

14. ACKNOWLEDGEMENTS

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16. AUTHOR'S BIOGRAPHY

Ian Campbell is an Emeritus Fellow at the University of Southampton, having previously worked at the Wolfson Unit MTIA for 38 years. He has conducted numerous experiments and trials for the development of sailing yachts and power craft and was Senior Scientist for the Luna Rossa challenge for the America's Cup in 2007. The Wolfson Unit was awarded, as a group, the RINA Small Craft medal in 2013 in recognition of its services over many years to the small craft industry. Ian continues to cruise in his own yacht and race his dinghy.