An Experimental Investigation of Asymmetric Spinnaker Aerodynamics Using Pressure and Sail Shape Measurements

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A method for determining the aerodynamic forces and moments produced by sails at full-scale is investigated in this work. It combines simultaneous on-water pressure and sail shape measurements. The system has been given the acronym FEPV (Force Evaluation via Pressures and VSPARS). The experimental pressure and sail shape data were obtained from on-water tests conducted on a Stewart 34 Class yacht equipped with an asymmetric spinnaker. Data were recorded for a range of apparent wind angles in light winds, in order to check the reliability, accuracy and repeatability of the system. The flow around the sails is studied qualitatively by analysing the pressure distributions and sail shape. It was found that the results showed similar trends to the published literature, in spite of the low wind speeds during the tests. The accuracy of the system was investigated by wind tunnel tests, with particular reference to the determination of the entire sail shape from the stripe images and the VSPARS outputs, and was found to be relatively good, even for the foot shape which is outside the camera viewing region.

NOMENCLATURE

FEPV	Force Evaluation via Pressures and VSPARS
AWA	Apparent wind angle (deg)
CFx	Driving Force Coefficient ( )
CMx	Heeling Moment Coefficient ( )
Fx	Driving Force (N)
Mx	Heeling Moment (N.m)
TWS	True Wind Speed (m/s)
AWS	Apparent Wind Speed (m/s)
Vs	Boat Speed (m/s)

1 INTRODUCTION

Sail aerodynamics is commonly investigated by using wind tunnel testing [1, 2] and numerical methods [3 - 5]. However, both methods have various drawbacks [6]. Full-scale testing is usually required to validate results from these methods. Moreover, full-scale testing allows the investigation of yacht performance in real sailing conditions, quantification of the actual forces at work [7 - 9] and, for example, studies of the effects of the rigging on yacht performance [9, 10].

Several full-scale sail pressure measurements have been carried out in recent years [8, 11 - 14]. Difficulties in carrying out pressure measurements include the interference of the taps on the sails, the effects of long tubing to connect the taps to the transducers, the recording of an undisturbed static reference pressure, and zeroing of the pressure transducers [14, 15].

Capturing sail shape at full scale is now commonplace on many racing yachts. Many investigators have developed their own systems for determining sail shape [8, 9, 16]. Various full-scale techniques for the assessment of aerodynamic loads have been developed to date for sailing applications. The use of sail boat dynamometers [17 - 19] has been significant in improving performance prediction. Strain gauging the rigging and sails [9] has provided useful information on wind/rig/sail interaction. However, the determination of aerodynamic forces by combining pressure and sail shape measurements at full-scale enables useful insights into steady and unsteady sail aerodynamics to be obtained [7, 8, 10] by providing considerable detail on how and where the forces are developed.

This paper reports on research on sail aerodynamics which is a continuation of previous work at the University of Auckland aimed at developing reliable and accurate methods for carrying out full-scale experiments on sailing yachts [7, 10, 20]. The system has been named FEPV (Force Evaluation via Pressures and VSPARS, where VSPARS stands for “Visual Sail Position and Rig Shape”). The recording method combines pressure and sail shape measurements to obtain the aerodynamic forces and moments produced by sails at full scale.

Le Pelley et al. [7] presented the results of the first full-scale test carried out using the FEPV system and a validation of the full system through wind tunnel testing for upwind sailing. Bergsma et al. [10, 20] describe an application of the FEPV system to upwind sailing, where the effects of shroud tension on upwind sailing performance were investigated.

The present study extends the previous research from upwind to downwind sailing. The results from full scale testing in very light winds are presented, and an assessment of the accuracy of the sail shape interpolation procedure was carried out in the wind tunnel. On the day of the scheduled testing the wind strength was lower than ideal, but testing could not be changed to another day due to the considerable setup and people commitments. The accuracy of the sail shape interpolation procedure was determined by comparing sail shape predictions from VSPARS data, with physical measurements.

2 COMPONENTS OF FEPV SYSTEM

2.1 VSPARS AND SAIL SHAPE MEASUREMENT

The VSPARS system was developed in the Yacht Research Unit (YRU) at the University of Auckland by Le Pelley and Modral [16]. It is designed to capture sail shape both in the wind tunnel and whilst sailing. It uses deck-mounted cameras that look up at several coloured stripes on the sails. The camera lens distortion and the perspective effects are taken into account by the software, which then produces the global coordinates of each stripe relative to a fixed datum position on the yacht, as illustrated in figure 1.

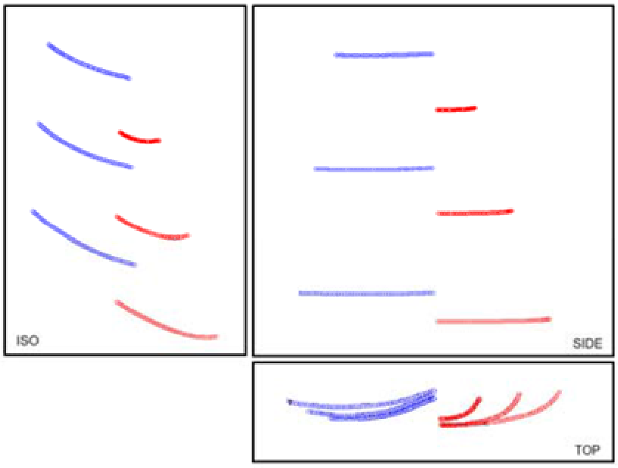


Figure 1: Global coordinates of VSPARS stripes for a mainsail and jib.

2.2 PRESSURE MEASUREMENT SYSTEM

In order to avoid the issues associated with the use of long tubing and the recording of a reliable static reference pressure [15], in the present measurements the differential pressures across the sails were measured directly by using double-sided pressure sensors with transducers placed at the measuring locations as shown in figures 2a and 2b. The transducers were connected directly across the suction and pressure sides of the sail. In order to reduce the interference with the flow, sensors on the mainsail were covered with sail-cloth patches, and sensors on the gennaker were placed into pockets created by the overlap of adjacent sail panels.

Although the use of a very large number of pressure sensors can lead to a highly accurate interpolated pressure distribution, the FEPV system is intended to be a cost- and time-effective system that could be used by yacht racing syndicates to improve their knowledge of sail design. Therefore a self-imposed limit of 24 sensors for the mainsail and 44 for the gennaker was used. The mainsail is equipped with 3 rows of 8 sensors placed at ¼, ½ and ¾ sail heights, while the gennaker is equipped with 3 stripes of 12 sensors plus a 4th stripe of 8 sensors placed at 7/8 of the height. The additional stripe at 7/8 height was used because previous studies in the wind tunnel have shown that the chord-wise pressure distribution on a gennaker can change dramatically between ¾ and 7/8 heights. Therefore it was felt that a simple interpolation up to the head using the ¾ stipe data would not be sufficiently accurate. The sampling frequency for the pressures was 60 Hz, but they were averaged over 30 measurements to filter out higher frequency fluctuations and resulted in an effective sampling rate of 2 Hz. Further details describing the pressure system can be found in Morris [21].

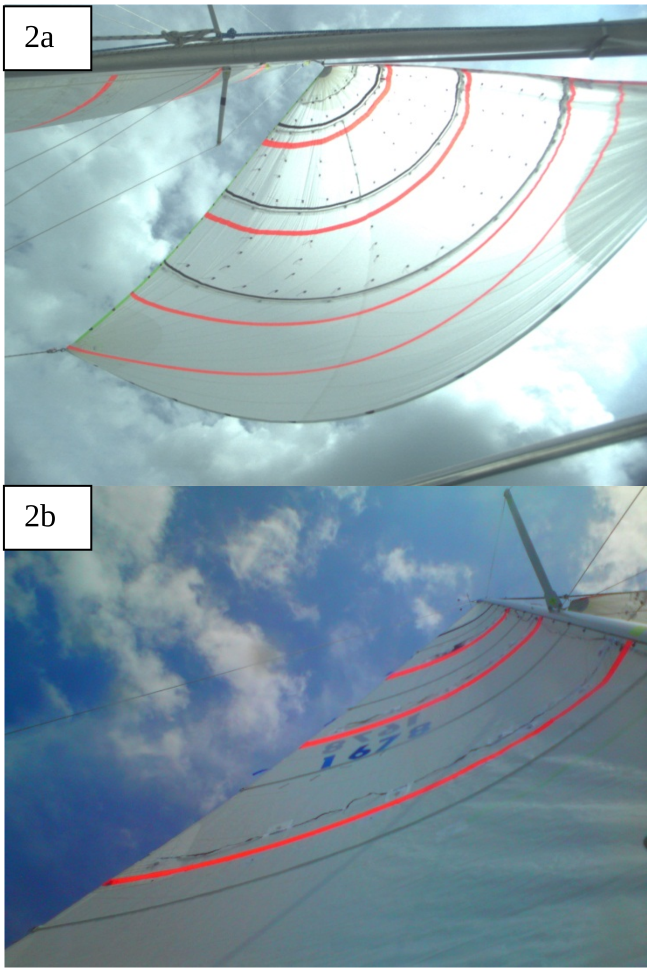


Figure 2: VSPARS images of a) gennaker and b) mainsail, during full scale testing.

2.3 FEPV DATA ANALYSIS

The FEPV analysis was coded in Matlab, and uses the output files from VSPARS and the pressure system to obtain the aerodynamic forces.

The whole sail surface is created from the known stripe shapes and the known tack position. The position of the head is estimated by extrapolating a spline curve passing through the known tack point and each stripe luff point. The head is assumed to be flat with no camber and to have a small finite length. Similarly, a spline curve joining the leech points of the known stripes is extrapolated upwards to the known head height position and also downwards by the known leech length of the sail, to give the head and foot twists respectively, together with the first estimate of the clew position.

Unfortunately the foot shape cannot be captured by the camera as it is out of the viewing area. Therefore an initial foot shape is estimated by fitting a spline curve through the known tack and clew positions together with a 3rd point given by an estimated foot depth and draft position, obtained by extrapolating the depth and draft position of the known stripes. This foot shape is then scaled in both the longitudinal and transverse directions to match the known foot length.

Starting from the "low resolution" sail shape defined by the VSPARS stripes and the foot and head positions, a fine quadrilateral mesh is then interpolated over the sail surface.

The sail pressure distributions are obtained from the discrete pressure values recorded by the pressure system which are interpolated linearly, firstly in the chord-wise direction, and then secondly in the span-wise direction towards the head and the foot. The pressures are interpolated to the centre of each geometrical cell in order to obtain a pressure map distribution over both entire sails, as shown in figure 3. The VSPARS stripes and pressure tap locations are also shown in the figure.

The choice of linear interpolation in the chord-wise direction allows the leading edge suction peaks and separation bubbles to be captured [7]. Forces in specified directions are computed by integrating the known pressures acting over the cell areas taking into account their surface normal directions. Moment contributions from each cell are calculated about the specified yacht moment reference centre.

3 FEPV SYSTEM VALIDATION

In an earlier study [7] the FEPV system was validated for upwind sailing through wind tunnel testing. Results from the FEPV system were compared in terms of forces and moments to measurements from the wind tunnel force balance, and good agreement was found.

The tests for the upwind validation were conducted at an apparent wind angle (AWA) of 25° and a heel of 20°. Three types of trim change were investigated. Firstly, the main was swept through 8 trim settings from hard sheeted to fully eased using a combination of both mainsheet and traveller, whilst the jib was left in a standard trim position. Secondly, the jib was swept from hard sheeted to fully eased using the jib sheet, whilst the main remained at a standard trim. Finally, both sails were eased together over 8 settings. The trends shown by the FEPV calculations compared well with the force balance results. The driving force and rolling moment predicted by the FEPV method were respectively 10% and 5% less than measured by the force balance. This underestimation is thought to be due to the additional windage from the mast, rigging etc., which is not measured by sail pressure integrations.

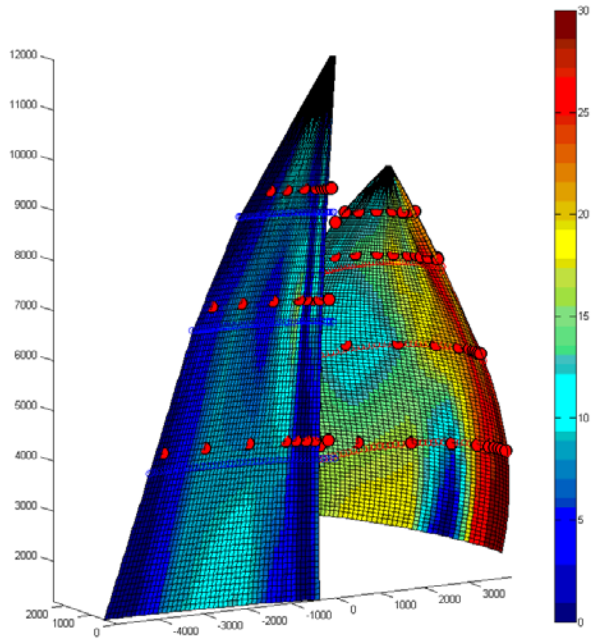


Figure 3: Pressure map distribution over the entire surfaces of the two sails.

The pressure system used for the present full scale downwind testing is the same as that used for the upwind sailing tests, and so it was felt that no further pressure system validation was required. However, a validation of the sail shape generation for downwind sail shapes was necessary because of the much more highly curved shape of gennakers compared with upwind sails. Indeed, particular attention was needed to assess the accuracy of the foot shape and the determination of the clew position, as these positions are obtained from extrapolations rather than from direct VSPARS measurements. Wind tunnel tests were carried out on a model scale VO70 yacht to obtain data for this assessment, as shown in figure 4. Two different gennakers were tested at AWAs varying from 60° to 120° in order to cover the full range of AWAs of interest at full scale.

The clew, foot depth, and draft positions were measured physically during each test, and the sail stripe positions were also recorded by VSPARS, and used by the FEPV software to determine the sail shape. The results of this comparision are shown in Table 1. The moment reference centre is located at the base of the mast, with *x* positive forward, *y* positive towards port and *z* positive upwards. Differences in clew positions in the *x, y* and *z* directions are given in Table 1. Foot depth and draft position are expressed as a percentage of the chord length. Average chord lengths of 1400 mm and 1100 mm for sails 1 and 2 respectively can be used for reference.

Figure 4: VO70 model scale yacht used for FEPV wind tunnel validation – comparison of calculated sail postions with physical measurements.

Table 1: Comparison of clew coordinates and foot shape between FEPV and physical measurements.

	Sail 1		Sail 2	
	60 AWA	80 AWA	100 AWA	120 AWA
Coordinate	difference [mm] between FEPV and Exp measure			
x_clew	27	41	-10	-3
y_clew	4	-63	-27	-34
z_clew	50	16	-36	-46
Sail 1				
	60 AWA		80 AWA	
[%chord]	Experimental	FEPV	Experimental	FEPV
foot depth	16.7	18.1	25	23
foot draft	34.1	39.4	39	41.2
Sail 2				
	100 AWA		120 AWA	
[%chord]	Experimental	FEPV	Experimental	FEPV
foot depth	30.9	27.8	36.6	30
foot draft	44.9	50.5	44.7	50.7

The results show that the FEPV system can predict the clew position with an accuracy of better than ±70 mm (but usually much less). Fairly good agreement in foot shape is obtained as well, with errors within 5% of the chord length. As a general pattern, the present FEPV analysis software overestimates the foot depth and underestimates the draft position.

It was observed during these FEPV validation tests that the foot of the sail was constantly moving, probably due to shedding of the foot vortex, which is a common characteristic of downwind sailing. Therefore the physical location of the sail could not be determined to better than a few cm (3-5 cm) during the tests, and so this is the validation accuracy.

4 DOWNWIND FULL-SCALE TESTING

4.1 TEST SETUP

A Stewart 34 Class yacht was used for the full-scale testing. It was decided to equip the yacht with an available gennaker, which unfortunately was sized to fit a smaller boat, namely an International Platu25, which is about 7.5 m long. The gennaker was hoisted from a pole held against the forestay. Although this setup was not ideal, the gennaker flew in a reasonable manner, as can be seen in figure 2a.

Both the mainsail and gennaker were equipped with VSPARS stripes and differential pressure transducers (figure 2a and 2b). A GPS unit, sampling at a rate of 2.5 Hz, was used to record the speed over ground and boat location, while the boat instruments logged boat speed, wind speed and direction at 1 Hz. An Inertial Measurement Unit (IMU) was placed in the yacht cabin and logged the boat motion at 10 Hz. The VSPARS stripe recording system uses a sampling frequency of about 0.3 Hz which enabled several images to be averaged to obtain the shapes of the stripes for the FEPV calculations.

A custom-made data acquisition unit recorded all these data, each one at its own sampling rate, and so the data were all time stamped to enable subsequent synchronous processing of the data streams.

The measurements were performed in the Hauraki Gulf, Auckland, NZ, in a fairly constant but very light breeze between 6 and 8 knots with almost flat water, in an area with insignificant tidal flow.

In this light breeze the sails were just able to fly. Such low wind speeds made it difficult to accurately measure the pressures across the sails, which varied from 0 to 30 Pa for the gennaker and from 0 to 15 Pa for the mainsail, due to the sensitivity of the pressure transducers. . More wind would have been preferred, but the tests were planned for a certain day and could not be rescheduled, and the wind was light on the day.

Nevertheless, the system proved to be effective and provided repeatable results, as discussed in section 4.2

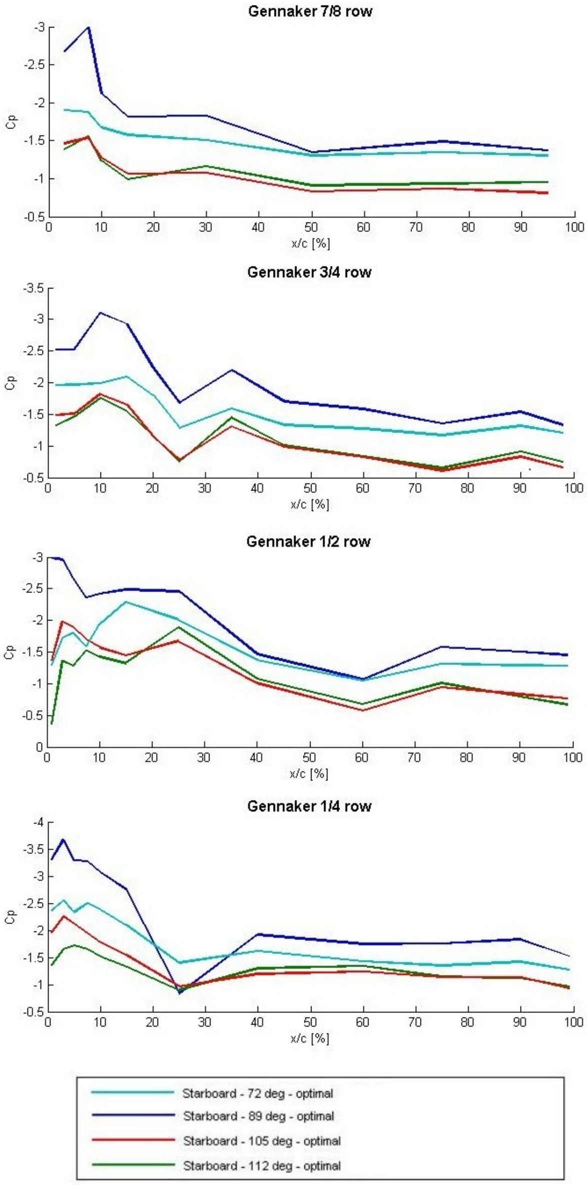
The aim of the tests was to check the reliability and accuracy of the FEPV system, the repeatability of the tests, and to qualitatively study the flow around the sails by analysing the pressure distributions and the sail shape. The yacht was sailed at its optimum trim on starboard tack for AWAs varying from 65° to 115°. A total of 24 runs were carried out, each about 60 s long. Sail trim (optimal sail trim with gennaker on the verge of luffing) was kept constant for each run and the boat heading was kept as straight as possible to enable the results to be averaged over the run time (45 – 60 s). Measurements from the instruments on board (including the pressures and sail shapes) were averaged over the run time, and the FEPV code used the average values for the computations.

5 RESULTS

In 2009, Viola and Flay [2] carried out wind tunnel tests on asymmetric spinnakers. Their results show that on the leeward side of the spinnaker the pressure has a negative peak at the leading edge, followed by a slow pressure recovery up to the trailing edge in stalled flow. In attached flow the suction peak at the leading edge is followed by a quick pressure recovery at around 10% of the curve length followed by a second suction peak due to the section curvature. Downstream of the second suction peak, that occurs between 10% and 40% of the curve length, the pressure becomes less negative, and then constant due to the trailing edge separation.

Figures 5 and 6 show typical full-scale pressure distributions for the gennaker and mainsail respectively at different AWAs plotted against the sail chord percentage. The suctions are generally higher over the entire surface for lower AWAs. This trend is confirmed in terms of driving force determined by integration, which is higher for the lower AWAs. In all the figures showing pressure and force coefficients, the dynamic pressure was calculated based on the apparent wind speed (AWS), and the pressure differences are leeward-windward, thus giving negative values. The pressure coefficient plots have the negative direction upwards, as is common in showing pressure distributions on wings.

The flow around the gennaker top stripe is stalled for all AWAs, as can be seen from the lack of pressure recovery after the leading edge peak, which occurs at around 5% of the chord length. The rows at ¾ and ½ of the height show similar behaviour; the leading edge suction peak, occurring at 5 to 10% of the chord length is followed by a pressure recovery (perhaps due to an intermittent leading edge separation bubble reattachment), a suction increase due to the sail curvature, and then a reduction in suction as the trailing edge is approached. However the sail is not able to generate much suction, probably due to the very light winds, and therefore the suction due to curvature is very small. This can be confirmed by the small values of pressure differences, which range between 10 and 30 Pa. The bottom row (1/4) has similar chord-wise distributions, with even smaller suctions generated by sail curvature, and only for the lowest AWAs. There is something interesting happening at 25% of the chord, where the suctions are lowest, but the reason for this is unknown – possibly a transducer issue. Increased AWAs over 100° drastically flatten the pressure distributions in the proximity of the leading edge.


Gennaker 7/8 row

Gennaker 3/4 row

Gennaker 1/2 row

Gennaker 1/4 row

Figure 5: Gennaker pressure distributions for AWAs of 72°, 89°, 105° and 112°

It is worth noting the consistency of the pressure distributions obtained in such light airs. When testing at full-scale, zeroing of the pressure sensors is not an easy task because the wind cannot be turned off, and because of the sensitivity of the transducers to their orientation if the sail and sensors are put into a bag to obtain a uniform pressure.

The pressure differences on the mainsail are even lower than on the gennaker, having maximum values of only 15 Pa.

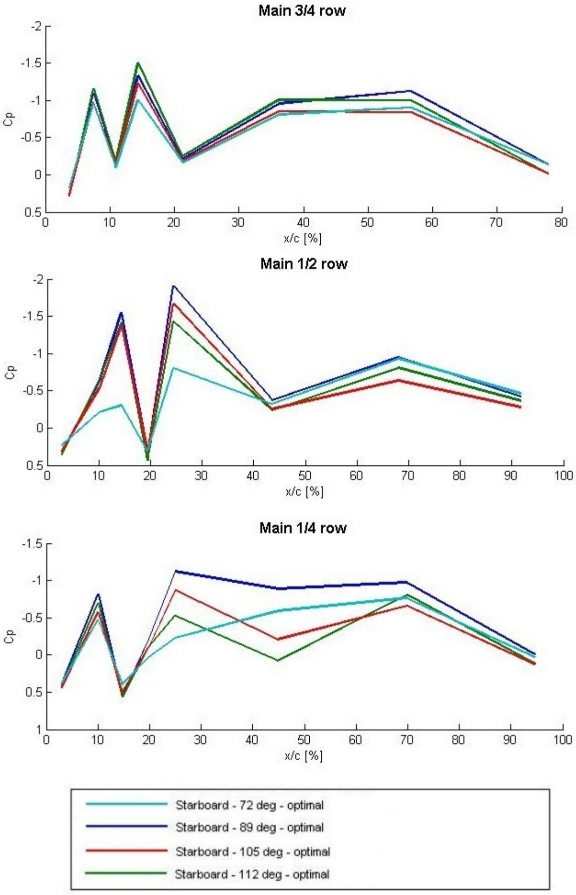


Figure 6: Mainsail pressure distributions for AWAs of 72, 89, 105 and 112°.

The flow on mainsails is affected by the presence of the mast [22] which usually produces a separation bubble behind it with a low recirculation flow velocity and a low pressure core on the front part of the mainsail. This helps explain the suction peak at 7 to 15% of the chord exhibited in figure 6, followed by pressure recovery where the flow reattaches. Figure 6 shows 2 further suction peaks at all heights and for all AWAs. The reasons for these are not clear, but might be due to the sail curvature not being very fair due to the lack of pressure, thus resulting in a wavy sail surface. This will be the object of future investigations by the YRU.

Another atypical behaviour is the presence of positive values of differential pressures before and after the leading edge suction peak. Again, this might be due to some reverse flow in the separated area. This behaviour is not likely to be caused by incorrect zeroing of the pressure transducers, as they were zeroed several times on shore (before and after the tests) and at sea during the measurements.

Taking into account the sensors drift with time and temperature, the sensitivity of the transducers to their orientation and the noise during the measurements, the estimated accuracy of the pressure measurements for the current test is of about ±2.5 Pa, and thus ±0.3 in terms of pressure coefficients for the actual wind conditions.

The variation of the driving force coefficient (*CFx*) with AWA is shown in figure 7. As discussed above, it was difficult to achieve significant suction over the sails due to the light winds. This has given values of *CFx* that are quite small (in the authors' experience) for the whole range of AWAs investigated.

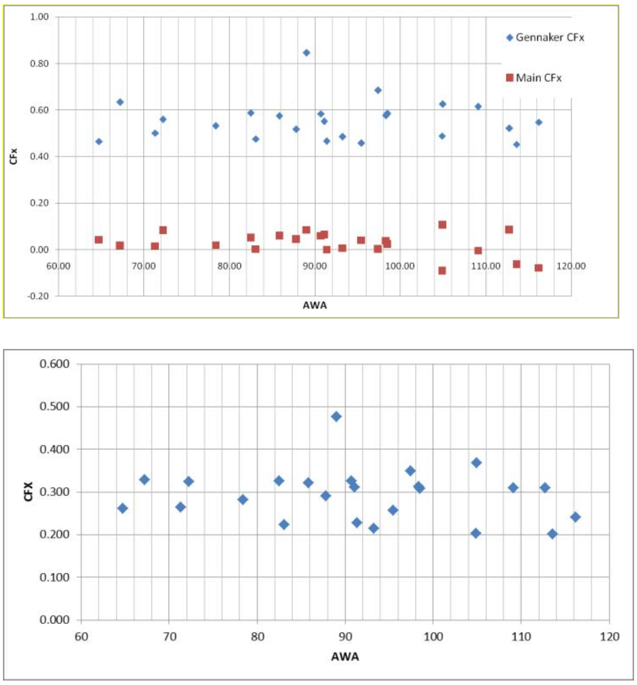


Figure 7: Drive force coefficient vs. apparent wind angle. Upper graph gennaker and mainsail coefficients, lower graph sum of gennaker and mainsail coefficients.

The results in figure 8 also show that the yacht performance varies quite significantly in the range of true wind speeds (TWS) encountered during the tests (3 to 5 m/s). Figure 8 shows CFx plotted against TWS for runs carried out at similar apparent wind angles. The results generally show that an increase in TWS results in an increase in CFx, whereas repeated runs carried out at a similar TWS result in similar values of CFx. Hence it appears that the sails become more efficient as the TWS increases; perhaps they are less prone to separation.

For all AWAs the mainsail contributes only a very small amount to the driving force compared to the gennaker (see the upper graph in figure 8). Indeed, the *CFx* values vary between 0.45 and 0.85 for the gennaker and between 0 and 0.11 for the mainsail. This is as-expected, but note that the presence of the mainsail increases the loading on the gennaker due to the upwash it generates.

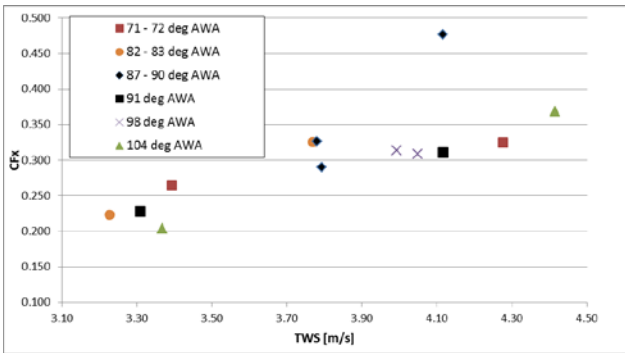


Figure 8: Drive force coefficient vs. true wind speed.

The heeling moment coefficient (*CMx*) generally decreases with increase in the AWA, as shown in figure 9 (note that the reference length for *CMx* is the mast length). The scatter in the results might be due to the different behaviour of the boat at lower and higher wind speeds. The values of heel angle are generally low (figure 10) and increase in an approximately linear manner with increase in the heeling moment (and thus decrease with increase in AWA).

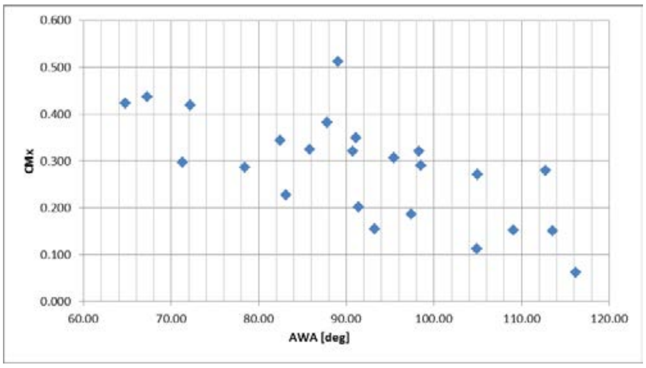


Figure 9: Heeling moment coefficient vs. AWA.

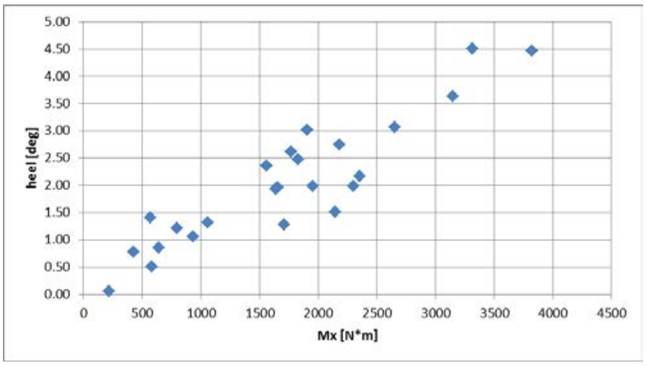


Figure 10: Heel angle vs. heeling moment.

Figures 11 and 12 show the overall drive force (*Fx*) and boat speed (*Vs*) plotted against the AWA. In this case a clear trend of increasing *Fx* for low AWA can be identified, as well as the expected increase in *Fx* for the runs performed in slightly stronger winds (red symbols in figure 11). The boat speed is generally higher for low AWAs (giving a higher AWS), and this is associated with a small increment in heel angle. This is as-expected since the lower AWAs gave the higher thrust.

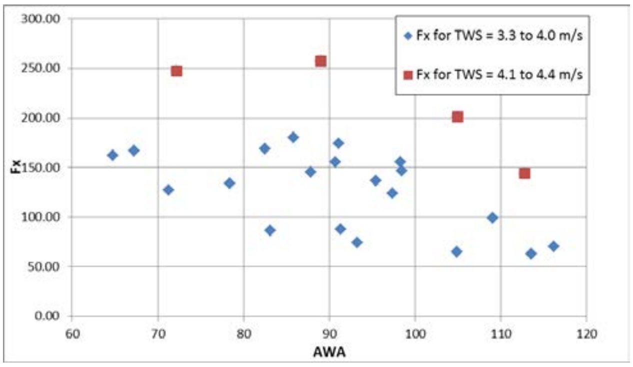


Figure 11: Drive force vs. apparent wind angle.

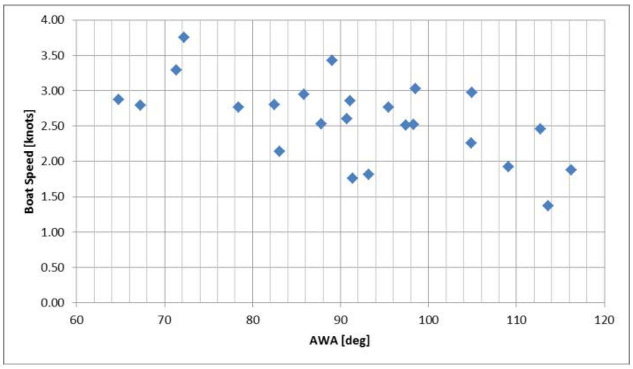


Figure 12: Boat speed vs. apparent wind angle.

6 CONCLUSIONS

A method for determining the aerodynamic forces and moments produced by a yacht's sails at full scale is investigated in this work. It combines simultaneous on-water pressure and sail shape measurements.

The sail shape measurement component of the system has been investigated through wind tunnel testing, and shown to be accurate.

The system has been used for downwind sailing in low wind speeds at full scale and proved to work well, and provided reasonably accurate and repeatable aerodynamic performance measurements.

The next steps in this project are to use the FEPV system to investigate unsteady sail aerodynamics at full scale for both upwind and downwind sailing.

The pressure distributions showed similar behaviour to other published results.

The mainsail contributed only a small amount to the driving force compared to the gennaker.

The thrust, Fx and the boat speed, Vs, both decreased as the AWA increased.

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