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# Full-scale Measurement of Sail Shapes and Pressures

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## Abstract

This paper describes a method of deducing aerodynamic force components produced by individual sails. This is achieved by measuring the pressure distribution at a number of discrete locations over the sail and extrapolating these measurements into a distribution across the entire sail surface. The sail shape is measured using the camera-based VSPARS system and the force distribution over the sail surface is then determined. Full-scale testing has been undertaken to investigate how aerodynamic effects of trimming sails affects yacht performance.

## Introduction

Accurate prediction of a yacht's aerodynamic performance is a difficult but important task for the designer. Whether being used to design the best sails for the yacht or to trim the sails to their optimum shape, the more accurate these predictions are the better the yacht will perform.

Aerodynamic performance can be simulated in a number of ways, including wind tunnel testing (Le Pelley and Richards 2011), empirical analysis, potential flow calculations and though CFD analysis. However, all of these simulations have various drawbacks and inaccuracies (Wright et al. 2010) and often on-the-water testing at full-scale is required to fine-tune the models and corroborate the results.

Full-scale testing is usually carried out using a single yacht due to cost constraints. Many variables are measured (e.g. speed, heel angle, wind speed, etc.) and then interrogated in order to determine the change in the yacht's performance for different sailing configurations.

Where time and money have allowed, full-scale sailing dynamometers have been built (see for example Hochkirch 2000). These yachts have an internal force balance in order to measure forces produced independently by the appendages, hull, rig and sails. These have provided valuable insight into the various components of the yacht's equilibrium, and have contributed to the improvement in performance prediction over the years.

From a more practical viewpoint, many racing teams routinely record sheets tensions and rigging loads through miniature load cells or optical fibre load measurement systems. However, without measuring directional forces at all areas of restraint for each sail, little can be deduced about the aerodynamic forces and moments produced and such measurements are limited to use for structural analysis.

Pressure measurements on thick objects (wings, buildings, etc.) are usually carried out by measuring the local static pressures in relation to the free-stream static pressure, on all sides of the object. Forces and moments are then calculated for the body as a whole by summing all of the individual pressure components, each one acting over a prescribed area. The advantage with a thin sail is that the differential pressure across the sail can be easily measured at any location. This saves the difficult task of measuring a free-stream static pressure and also directly produces the pressure acting on the sail at that location.

Pressure measurements on sails have been made many times both in the wind tunnel and at full-scale (see for example Puddu et al. 2006). Most of these measurements have been for research purposes, and so have used relatively large numbers of pressure tappings in either differential or single-sided modes. Problems with pressure measurement include the expense and the fragility of the systems and the need to run intrusive tubes or cables over the sails.

Capturing sail shape in real time is now standard on many racing yachts. The VSPARS RealTime sail and rig deflection system (Le Pelley and Modral 2008) uses cameras mounted in the deck to track stripes on the sail, and is able to determine the accurate location and shape of these stripes in global coordinates. The system is used both in wind tunnel sail development (Le Pelley and Richards 2011) and by racing teams in order to trim sails to real time target shapes.

In order to achieve an accurate result when testing at full-scale, it is important for only one configuration change to be investigated at once. However, due to time and logistic constraints, often setups will vary between testing sessions. These may include deliberate changes (e.g. appendage variations) and incidental changes (e.g. extra crew, inconsistent rig tune, hull fouling).

This paper describes a system for determining the sails' aerodynamic performance by direct measurement rather than inferring the performance through a change in boat speed. A system named Force Evaluation via Pressures and VSPARS (FEPV) has been developed (Morris 2011) which combines pressure and shape measurement of sails, from which the aerodynamic forces and moments produced by each sail can be deduced. This produces a more accurate assessment of the performance changes brought about by the sails, and also provides a more accurate aerodynamic dataset for designers for subsequent Velocity Prediction Program (VPP) analysis. In order to make the system cost-effective, the number of pressure sensors used in the present study has been kept at the minimum required to maintain sufficient accuracy.

The FEPV system also significantly reduces the influence of other setup changes described above and could potentially allow a number of changes to be investigated in one sailing session.

## Components of the FEPV System

### VSPARS Sail Shape Measurement

The VSPARS RealTime system has been used to capture the shape of the sails in the wind tunnel and whilst sailing. This system uses cameras on the deck of the yacht to automatically track 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 shown in Figure 1. The rig deflection and forestay sag are also reflected in the output.

The whole sail surface then needs to be created from these known stripes and the known tack and head points. This is carried out in the FEPV code.

The position of the head of the sail can be estimated even if there is no stripe there, by simply extrapolating a line passing through the known tack point and each stripe luff. The head is assumed to have no camber and have at least a small finite length (i.e. not a true pinhead sail). As there is no theoretical limit to the number of stripes which can be applied per sail, stripes can be applied quite near to the head to make this extrapolation as short and therefore as accurate as possible. At the foot however, the accuracy from the camera system decreases because of the increasing perspective effects induced by having long stripes close to the camera, so the bottom stripe height is limited to about 1/6 of the luff length.

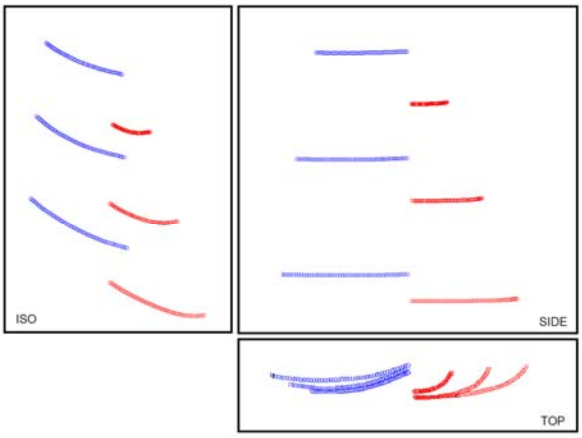


Figure 1. Stripe coordinates from VSPARS

A spline curve joining the leech points of the three known stripes is then extrapolated upwards to the known head height and then downwards by the known leech length of the sail, giving the head and foot twists respectively.

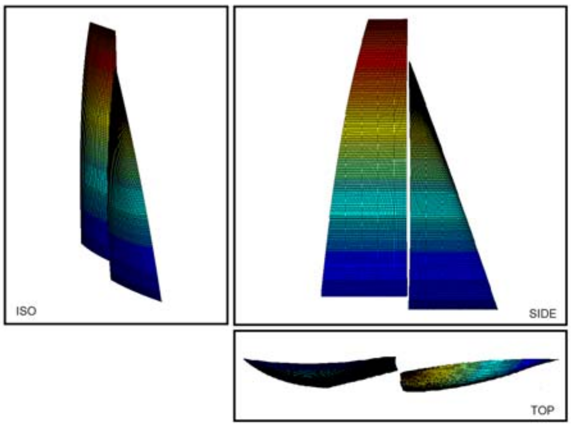


Figure 2. Sail geometry recreated from VSPARS stripes.

To create the foot, an estimated foot depth and draught position is used to create a 3rd point (which can be easily measured at run time) through which a spline can be fitted. The length of this initial estimate will not necessarily match the known sail foot length, so the curve is scaled in longitudinal and transverse directions to match the known foot length.

With the sails now defined by spline curves at the edges and at the measurement stripes, a fine quadrilateral cell mesh is interpolated over the sail surface. For each cell, the area, distance of cell centre from datum and the unit normal vector are calculated. The final sail geometry is shown in Figure 2.

### Pressure Measurement

Whilst it would be possible to measure pressures at a large number of locations across the sail and hence obtain a highly accurate interpolated pressure distribution, the aim of this study was to produce a cost- and time-effective system that could be used by yacht racing syndicates to improve their knowledge of sail design. For this reason, a self-imposed limit of 24 pressure sensors per sail was used. These were arranged in 3 horizontal rows of 8 sensors per row. The rows were placed adjacent to the coloured stripes used by the VSPARS system for shape measurement.

A differential pressure measurement system was developed specifically for this testing. The system consists of ultra-low range differential pressure sensors mounted in custom plastic housings. These housings, approximately 40mm diameter and 10mm thick, were stuck to the surface of the sail on one side and a small hole melted through the Dacron sail to a pressure port on the bottom. Then a light sail cloth patch approximately 150mm square was applied over the upper surface with another hole through to the upper pressure port (figure 3). In this manner, the differential pressure is measured directly by the sensor with no tubes present.

The design of the pressure transducer housing was the result of several wind tunnel tests comparing the pressure response from a range of wind directions to the response from a single flush tapping. The final housing with cloth patch had only a small effect on the measured pressure.

Figure 3. Differential pressure sensors on the sail

The signal from each sensor is amplified and connected to a ribbon cable running to the luff. At the luff, a 12-bit analog to digital converter digitises the signal and, again via a single flat ribbon cable, sends the signal to a small USB-driven microcontroller at the tack of the sail. By using clamp wiring fittings, transducers can be added anywhere along a chordwise stripe and stripes can be added anywhere up the luff, even after the system is present on the sail. The microcontroller combines the data from all of the taps on the sail and sends them in a single sentence back to the data acquisition PC. The system is capable of running over 150 pressure sensors at up to 20Hz, all powered and connected by a single USB cable.

The main limitation of this pressure measurement system is that it is not waterproof because of the openings to each pressure sensor, so the testing had to be carried out on a fine day and care taken not to get the sail wet. Also, the zero reading of the pressure transducers tends to drift significantly with time and temperature, so the system needs to be re-zeroed from time to time. Whilst easy in a wind tunnel, this is difficult to achieve on a moving yacht, with the sails needing to be covered in sail bags to ensure zero differential pressure.

The initial sensor placement was done with reference to typical upwind sail pressure distribution plots calculated by a Vortex Lattice Method. The sensors were distributed in order to capture the suction peak and overall distribution as well as possible.

Combining Shape and Pressure Measurements

The FEPV system has been coded in Matlab, and uses as inputs the real-time output files from VSPARS, the measured differential pressures on the sail surface, and a configuration file giving information about the sail dimensions and location of the pressure sensors on the surface.

As the pressure sensors were aligned in chordwise stripes, interpolation was initially carried out in a chordwise direction. Several methods of interpolation were investigated during a wind tunnel study but simple linear interpolation seemed to be most effective overall. This system reduces accuracy in some areas but allows the important leading edge peaks and separation bubbles to be captured. It also produces a sensible extrapolation towards the leech in most places.

The pressures were then interpolated linearly in a spanwise direction towards the head and foot of the sail. This model does not take account of the edge effects and the decrease in suction at the head and foot of the sail. The form of this falloff is not known and is assumed to happen fairly rapidly over a short distance.

## Full-scale Testing Setup

Following initial wind tunnel validation, a set of full-scale tests were undertaken. The aim of these tests was to determine the influence of changing trim on the aerodynamic forces and moments. Firstly, the main was swept over a number of 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 a number of settings. These sweeps are henceforth referred to as main sweep (MS), jib sweep (JS) and combined sweep (CS).

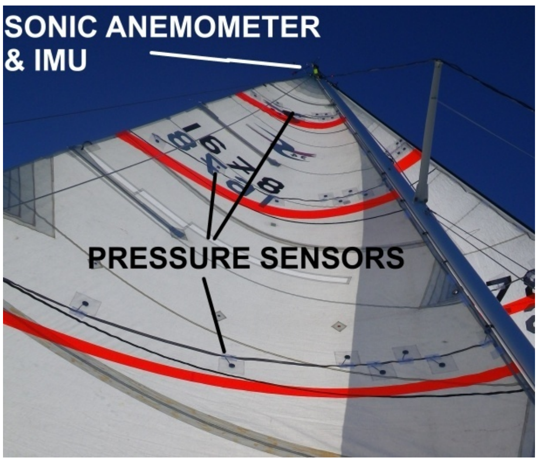


Figure 4. Stewart 34 sail layout

A Stewart 34 yacht with masthead rig and overlapping genoa was used. Three VSPARS stripes were placed on each sail. Differential pressure transducers were attached in chordwise rows on each sail. A sonic anemometer and intertial measurement unit (IMU) were used at the masthead to measure apparent wind speed and angle, with wind speed corrected by the IMU to remove the effects of boat motion, as shown in Figure 4.

A GPS was used to log boat location and speed over ground, and the boat's own instrumentation system logged the speed through water, wind speed and direction. All of this data was gathered by a custom-made data acquisition unit on an industrial computer using an iPad as a remote interface.

The tests were undertaken in perfect conditions on the Hauraki Gulf, New Zealand. This is a predominantly sheltered area of water and exposed to moderate tidal currents. True wind speed was 10-15kts with a slight sea. The SE wind direction enabled most of the tests to be conducted in an area with an insignificant tidal flow.

The main impediment to the testing was the condition of the sails used. Through necessity, they were very stretched old racing sails and as such it was very difficult to sail on the wind in the fresh breeze without significant overpowering, especially for some of the harder trim cases. An effort was made to sail at a consistent wind angle in all cases which lead to significant luffing on the headsail and backwinding on the mainsail.

## Results

Figure 5 shows the differential pressure distributions on both tacks for the mainsail sweep, for the mainsail and headsail middle stripes respectively. The lack of a suction peak can be clearly seen, as a result of the boat having to sail too close to the wind for the headsail to have attached leading edge flow, and from the backwinding of the mainsail. However, whilst the pressure distributions may not be desirable for sail analysis, the FEPV method should still be able to determine the forces and moments produced by the sails.

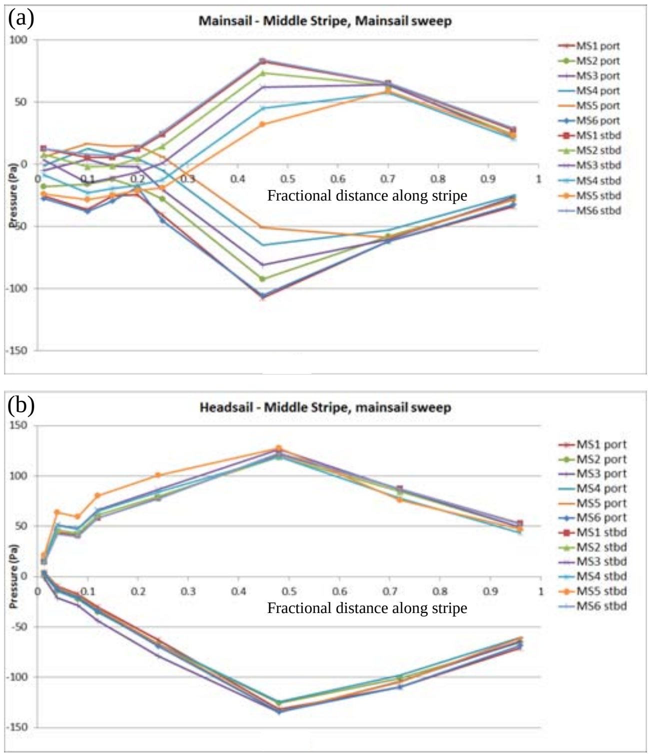


Figure 5. (a) Mainsail and (b) headsail differential pressure distributions along the middle stripe of each sail for a typical test.

The sail shapes were recreated using the VSPARS system and the results were run through the FEPV code. In this analysis, only the driving force (Fx) and roll moment (Mx) calculated by the FEPV code have been considered.

As an example, the results for the jib sweep on starboard tack are shown in Figure 6. Port tack results show very similar trends. Trim positions 0 through 5 are progressive easing of the genoa sheet, and trim position 6 is the same as position 0, giving an indication of the repeatability of the results. The mainsail was trimmed to optimum for the first jib position and then fixed throughout the test. All values in figures 6 & 7 have been non-dimensionalised by dividing by the corresponding values at the initial trim 0 setting so that comparisons can easily be made.

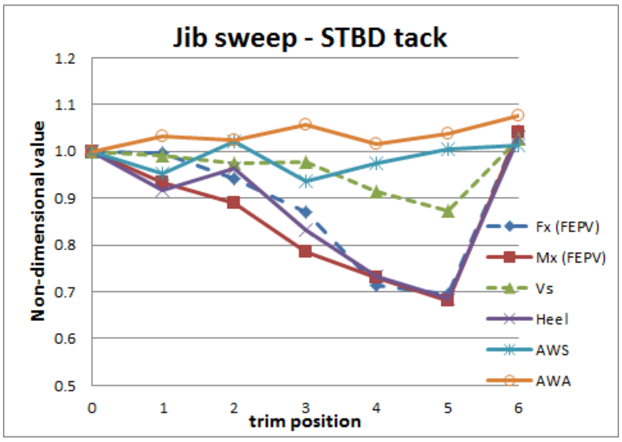


Figure 6. Performance variation with sail trim for the jib sweep

There is a clear trend of decreasing boat speed with jib ease, as would be expected. The excessive depth of the sail meant that it could not be adequately flattened for the conditions, so that even the tightest setting was under-trimmed. The shape of the curves between roll moment (Mx) and heel angle, and between drive force (Fx) and boat speed (Vs) agrees well considering the variation in apparent wind speed (AWS) and apparent wind angle (AWA).

While in the example shown in figure 6, the boat speed followed the trend in drive force this wasn't always the case, particularly if there was a significant change in heel angle. For example with the main sweep, figure 7, the boat speed increased even though the drive force decreased, possibly due to a greater reduction in heel angle than drive force. This aspect is still under investigation.

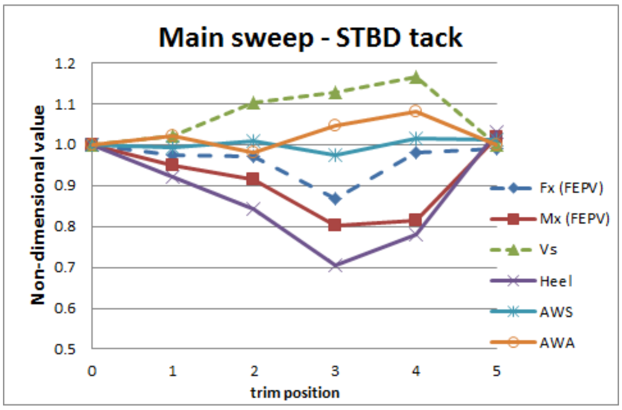


Figure 7. Performance variation with sail trim for the main sweep

However a more reliable correlation was observed between the measure heeling moment and the heel angle. Figure 8 shows the measured heel angle plotted against the measured aerodynamic roll moment from FEPV for all the runs conducted on starboard tack. If the righting moment curve for the yacht is known, the hydrodynamic rolling moment caused by flow past the hull and appendages can then be estimated.

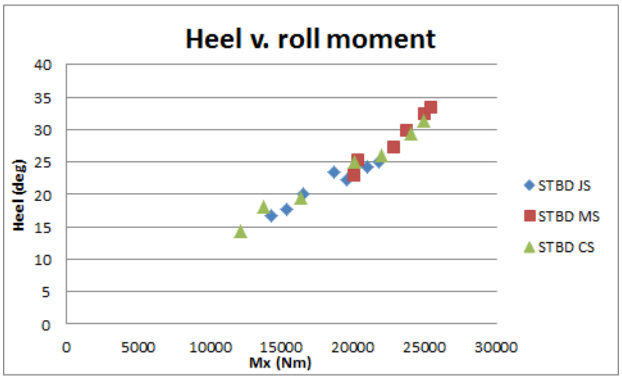


Figure 8. Heel angle plotted against roll moment for all starboard tack runs

## Conclusions

A system of deriving aerodynamic force and moment data at full-scale has been developed. The system uses sail shape and differential pressure data in order to estimate sail performance with only minimal modification to the yacht itself.

The system proved to function well at full-scale, and provided repeatable measurements of aerodynamic performance. Using only a small number of pressure transducers, the system is simple and cheap enough to be used as an aerodynamic analysis tool by yacht racing teams.

The next step in this project is to process the FEPV output from the full-scale testing with a VPP in order to compare boat performance predictions with those measured on the water. Further testing is also planned with new sails.

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