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Investigation of sailing yacht aerodynamics using real time pressure and sail shape measurements at full scale

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Abstract

The steady and unsteady aerodynamic behaviour of a sailing yacht is investigated in this work by using full-scale testing on a Stewart 34. The aerodynamic forces developed by the yacht in real time are derived from knowledge of the differential pressures across the sails and the sail shape. Experimental results are compared with numerical computation and good agreement was found.

Introduction

Sail aerodynamics is an open field of research in the scientific community. Some of the topics of interest are knowledge of the flying sail shape, determination of the pressure distribution across the sails, and the determination of the aerodynamic forces developed by the sails. These studies can be carried out by using different methods, the most common being numerical methods, wind tunnel testing and full scale testing.

When dealing with yacht racing the main objective is to have good prediction of the forces in order to improve the performance. This is usually obtained through velocity prediction programs. In the wind tunnel, forces are obtained by mounting the models on a force balance [3]. Research efforts in past years have been on deducing the aerodynamic forces in full scale and in real time. The use of dynamometers and load cells for determining forces has been explored also in full scale by Masuyama [10]. In 2011 Augier et al. [1] conducted a full scale validation experiment for their "fluid structure interaction" numerical model in which loads on the rig were computed. A successful method for force determination has been implemented at the Yacht Research Unit by Le Pelley et al. [8]: pressure and sail shape measurements, obtained at different sail sections are interpolated and integrated across the entire sails to get the aerodynamic forces.

The current work, carried out at the Yacht Research Unit of the University of Auckland, is aimed at improving the equipment and post-processing techniques of the full-scale measurement for sailing yacht testing, in order to allow a wider range of application, and to provide a better understanding of sail aerodynamics in actual sailing conditions. The current paper presents an investigation of the effects of rig tension (in particular shroud tension) on yacht performance. Results are presented and discussed for steady and dynamic conditions, and compared with the predictions of a Dynamic Velocity Prediction Program (DVPP) developed at the University of Auckland [2].

FEPV System

Force Evaluation via Pressures and VSPARS (FEPV) is a system being developed by the University of Auckland which combines sail shape (VSPARS software) and pressure measurements (YRU pressure system) across the sails to obtain the aerodynamic forces in real time.

VSPARS for sail shape measurement

Visual Sail Position and Rig Shape (VSPARS) is a system that was developed at the YRU by Le Pelley and Modral [7]; it is designed to measure sail shape and can handle large perspective effects and sails with large curvatures using off-the-shelf cameras. The shape is recorded using several coloured horizontal stripes on the sails. A certain number of user defined point locations are defined by the system, together with several section characteristics such as camber, draft, twist angle, entry and exit angles, bend, sag, etc. All these outputs are then imported into the FEPV system and appropriately post-processed. The number of coloured stripes used is arbitrary, but it is common practice to use 3-4 stripes per sail. In this study 3 stripes were used in order to keep the system "light" and have an accurate reproduction of the entire sail.

Pressure Measurement System

When measuring pressures across a sail, several choices have to be made: the type of recording (single side measurement or differential measurement), number of taps, tap locations, recording frequency, etc.

In the present study it was decided to measure the differential pressures across the sails directly, which avoided the issue of recording the free-steam static pressure, which is known to be difficult [4]. Therefore taps with in-loco transducers were used, and differential pressures were recorded by connecting one side of the transducers to the suction and the other to the pressure side of the sail. Appropriate geometry of the taps was chosen, together with appropriate sail-cloth patches covering the taps, to minimize the interference with the flow. This geometry is the result of previous studies carried out by Flay & Millar [4].

The number of taps used in this study was restricted to 24, arranged in 3 rows of 8 taps placed close to the VSPARS stripes. This is a low number of taps compared to previous studies [9] but is consistent with the choice of the authors to have a lightweight system that could be applied easily to every sail. An appropriate interpolation of the pressures across the sail (as is done by the FEPV system) leads to a reasonably accurate reproduction of the real span-wise pressure distribution along the sail. The chord-wise location of the taps was chosen in order to capture the main features of the pressure distribution, such as the leading edge suction peak.

FEPV Data Analysis

The FEPV system uses a Matlab code to handle the output data from the pressure and sail shape measurement systems. The main objective is to accurately interpolate the sail shape and the pressures across the sail and to combine them to obtain the aerodynamic forces developed by the yacht, and this is described below.

Firstly, starting from the VSPARS output, the sail sections are reproduced numerically; secondly the head and foot positions are determined, and finally a user-defined high resolution sail shape (50 x 100 cells) is obtained with appropriate interpolations. Once the sail geometry has been defined, the discrete pressure measurements are taken as inputs and interpolated to find the complete pressure distribution over the sails. The correct choice of interpolation to use (linear, spline, cubic) is very important. Indeed, wrong interpolations can lead to incorrect chord-wise pressure distributions, not catching some features such as the leading edge suction, or altering the trailing edge pressure. At this point a complete sail pressure map is defined as shown in figure 1:

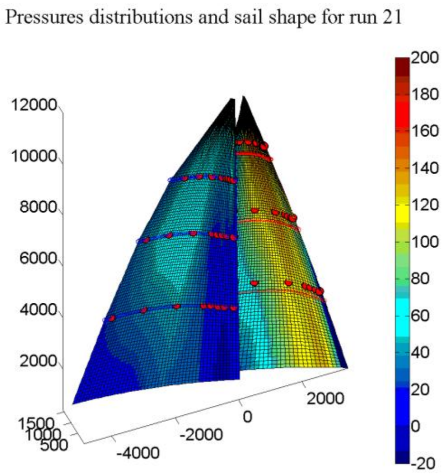

Figure 1.Typical pressure distribution across two sails

Forces and moments developed by the sails in each direction are determined using the cross-product theorem. This theorem proves that the magnitude of the normal calculated using the cross product of two diagonals of a quadrilateral is equal to twice the projected area in each direction. Therefore the forces from each panel in the direction of interest are simply given by the product of the pressure by the normal vector to the panel. The moment contribution of each panel is then obtained from knowledge of the panel distance from the yacht's moment reference centre. Forces and coefficients can be obtained in real-time and plotted on a "force versus run number" plot in order to compare directly different trims while testing (figure 2).

Other features can be investigated, and other outputs can be plotted by the user before running the code. The processing time varies between 2 and 6 seconds for each run, depending on the processor capabilities and the number of outputs displayed. Keeping in mind that pressures and sail shape are averaged over 30s to 60s, this is a reasonably small time lag for a real-time testing.

The FEPV system is fully automatic (in steady investigations) providing the correct definition of the input is done. The only input to be prompted before running the software is the number of the runs (each run corresponds to a particular trim) to be considered and the outputs desired. Good planning of the sail testing then allows the system to be a valuable real-time tool for force computation. The FEPV system is also a useful tool for the investigation of unsteady aerodynamics. At the end of the run it is possible to investigate the relationships between variables, such as pressures and/or forces with the pitch and roll angles, both in the time domain and the frequency domain. The accuracy of the FEPV system has been validated previously through wind tunnel testing at the Yacht Research Unit [8]. Current results have been compared with the predictions from a dynamic velocity prediction program, as is shown in the results section below.

Full scale testing

In this section an application of the FEPV system is described. The sails for a Stewart 34yacht have been equipped with VSPARS stripes and pressure taps. The system also includes GPS, sonic anemometer and an Inertial Measurement Unit located at the top of the mast and boat instruments. The test was performed in good and steady weather on the Hauraki Gulf, Auckland, with a breeze between 10 and 18 knots.

In this investigation the effects of the shroud tension on the measured yacht performance were investigated. It is a common belief among Stewart 34 sailors that they sail better with really slack shroud tensions. The authors wanted to validate this by using the FEPV system. In order to have reliable results, only one variable was changed during the tests, namely the cap shroud tension. Four settings were used and compared: "tight", "medium", "slack" and "fully slack" setting. All the other parameters were kept constant. Three different headings of the yacht were tested, namely: optimal heading (called VMG for simplicity), Pinching (heading a few degrees higher than VMG) and Footing (heading a few degrees lower than VMG). Therefore it was possible to compare the different shroud settings for all cases, although the VMG heading is the most representative. The tests were composed of two set of runs: the first 12 runs were on port tack (all the configurations), and after a break (downwind sailing to avoid high tidal streams areas) another 12 runs on starboard tack were carried out.

With full scale testing it is impossible to control all factors and inevitably some of these affect the results. These include: tidal stream, waves, variation in wind speed, alignment of the instruments with the boat centreline, calibration and zero recording of the pressure taps. These had to be taken into account during the post-processing, and can possibly explain some unexpected results as outlined below

Results

In this section the results from the full-scale tests are presented and discussed. Results in terms of driving force coefficient (CF_x) and heeling moment coefficient (CM_x), as directly outputted from the FEPV system, are shown in figure 2 (for all the port tack runs). These outputs, together with the complete pressure map distribution over the sails (figure 1) give rapid feedback on the vessels performance.

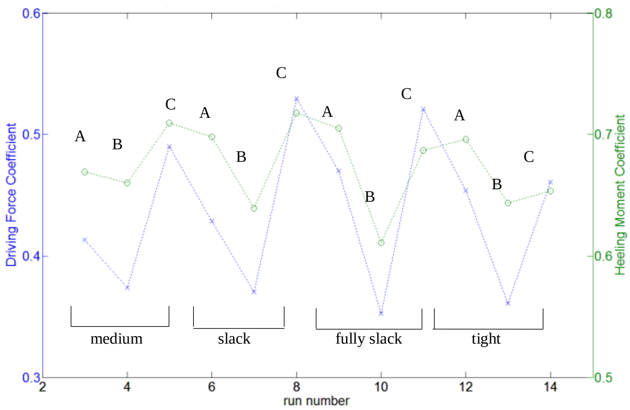

Figure 2.Drive force and heeling moment coefficients for all port tack runs. A = VMG runs; B = pinching runs; C = footing runs

For instance, from figure 2 it can be deduced that VMG runs lead to both higher CF_x and CM_x than the correspondent pinching runs, but lower than the footing ones, as expected. Moreover, it is possible to state immediately that the highest CF_x is obtained with a slack shroud setting.

A deeper analysis can lead to more accurate conclusions. It is a common belief among Stewart 34 sailors that the yachts sail faster with really slack shroud tensions. Indeed, slack shroud tension theoretically increase the velocity made good (VMG) by allowing the masthead genoa to be trimmed tighter and the yacht to point higher.

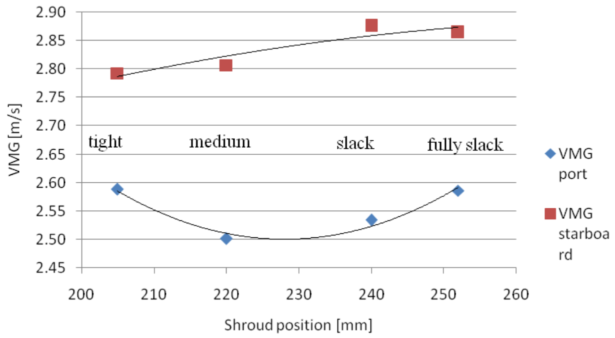

Figure 3.Velocity made good variation with shroud tension

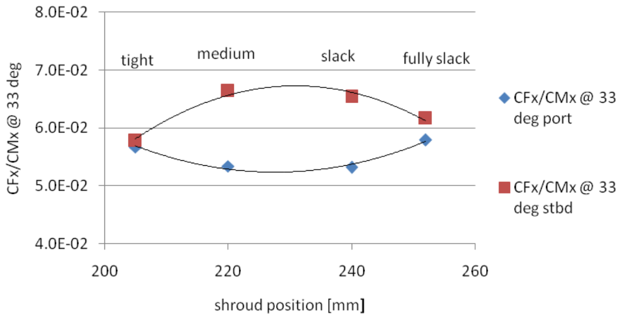

Figure 4 (a)

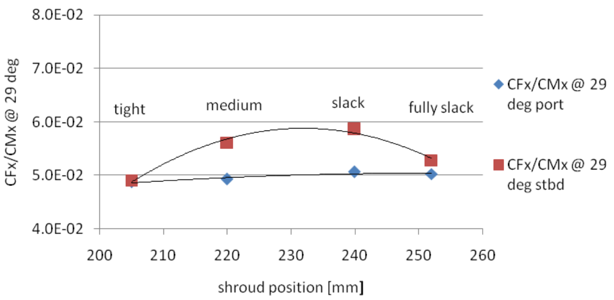

Figure 4 (b)

Figure 4.Driving force coefficient / heeling moment coefficient variation with shroud tension, for (a) VMG and (b) pinching headings.

In figure 3 the velocity made good is plotted for all the shroud settings for VMG headings on both port and starboard tack. For the runs on the port tack a minimum boat speed is achieved for the medium to slack shroud setting. On the starboard tack however, a maximum boat speed is achieved for the medium to slack shroud setting. The difference between the trends on the two tacks could be caused by effects that are not corrected for when determining boat speed, such as different wind speed or sea state.

In order to better investigate the effect of the shroud tension on the yacht performance, results in terms of driving force and heeling moment are presented herewith. Figure 4 shows the variation of the ratio of the driving force coefficient on heeling moment coefficient (CF_x/CM_x) with the shroud position. The ratio CF_x/CM_x is a good predictor of performance. In most of the cases it is higher when sailing with medium or slack shrouds for all the headings (footing results not included). This is not surprising, as these are the settings that are usually considered as optimal by sailors.

Full scale testing with the FEPV analysis approach also allows unsteady aerodynamics to be investigated. Interesting results on sailing aerodynamics in unsteady conditions have been obtained by Lozej [9] in full scale and Fossati in model scale [5]. Taking as reference those works, particular attention has been paid to the relationship between the driving force and the pitching motion of the boat when sailing upwind. All the boat motions were recorded through the logging equipment mounted on board. Results of the spectral analysis of a specific run are presented below, namely a VMG run on starboard tack with slack shroud tension and head-on waves. Pressures and pitching motion were recorded at sampling rates of 4 Hz and 30 Hz respectively

When sailing upwind into head-on waves a significant correlation between the driving force and the pitching motion of the boat with a phase shift was expected. This is confirmed by figure 5. The driving force coefficient spectrum shows a high peak at a similar frequency to the pitch angle. Note that the recording time of about 90s is very low for getting really accurate results with a spectral analysis. This can explain the other peak in CF_x spectrum present at lower frequency, and the non-zero values at different frequencies, which are probably due to noise in the signal.

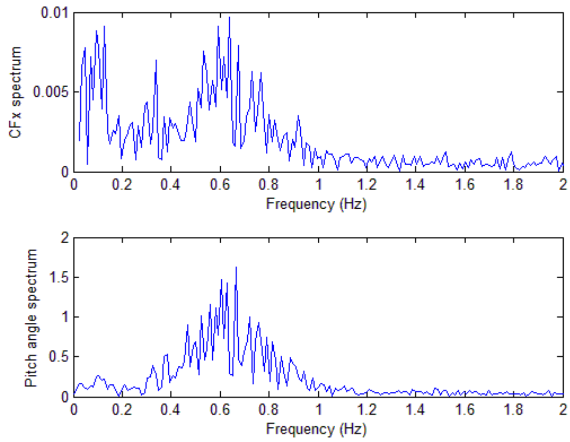

Figure 5.CF_x and pitch angle spectra

According to Fossati [5] the AWA and pitch angle are also related when sailing upwind. Results from the full scale test confirm that if the bow rises the AWS decreases, while both the driving force and AWA increase, and when the bow dips, CF_x and AWA decrease.

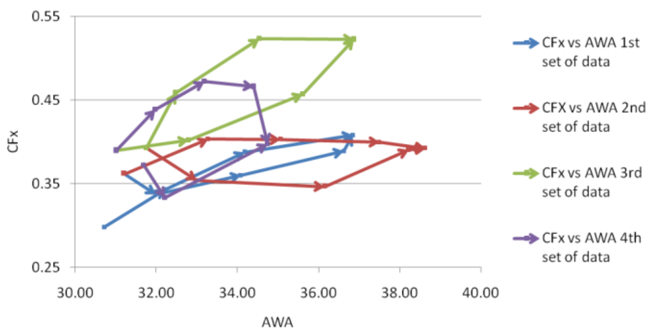

Figure 6.CF_xvariation with AWA

Of particular interest is the relationship between CF_x and AWA. As an example, in figure 6 four full cycles (named “set in the graph”) of pitching motion of the boat are considered. To each pitch angle there is a corresponding value of AWA and CF_x.

Therefore four full cycles of CF_x variation with AWA can be identified, as shown in figure 6. As stated above CF_x increases with the AWA. Moreover it is evident that there is a hysteresis loop in the graph, which indicates a shift in phase between the two variables. If the drive force and the apparent wind angle were exactly in phase, the loop would collapse into a single line. CM_x and AWA show a similar trend which is in agreement again with the results of Fossati.

<u>Dynamic Velocity Prediction Program Predictions</u>

The results obtained so far have been compared to previous research in order to verify their validity. In addition, a Dynamic Velocity Prediction Program (DVPP) developed by Bordogna [2] at the Yacht Research Unit was used to simulate the variation in the aerodynamic forces basing on the recorded experimental motions of the boat. This DVPP is based on the “unsteady thin aerofoil theory” developed by Gerhardt [6] and is aimed at predicting the velocity of a yacht sailing upwind when subjected to a periodic pitching motion. This DVPP code was firstly validated by running a test without waves. After this validation, the experimental motions from the full scale tests were used as input for the DVPP. For a complete set of results refer to [2]. Run 21 is shown as an example in figure 7.

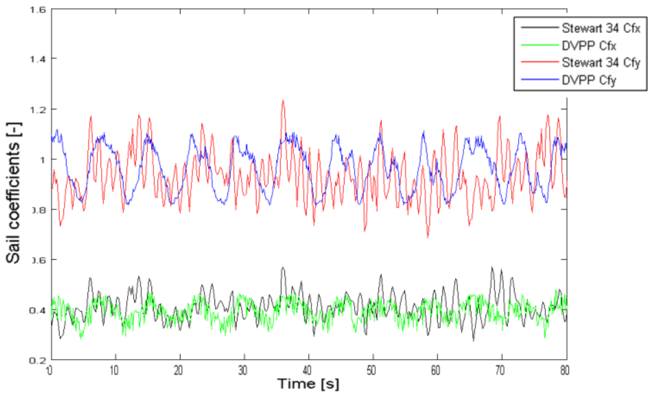

Figure 7:DVPP results for run 21 and comparison with full-scale testing

The DVPP takes as input a periodic pitching motion, thus the average values of maximum pitch angle, wave frequency and wave height were inserted. In the DVPP the flow around the sails is assumed to be two-dimensional; therefore ‘sail slices” of the mainsail and headsail are considered. The middle sections of both sails were chosen as representative of the entire sails. In figure 7 the driving force and side force coefficient as measured on board the Stewart 34 and calculated by the DVPP are compared over a recording time of 80 seconds. The boat was sailing upwind with head waves with a significant pitching motion.

Although some discrepancy in results is present (these are discussed in [2]) the results agree quite well. In particular the measured and calculated sail force coefficients agree well in magnitude.

Conclusions

A system for the investigation of sailing yacht aerodynamics using real time pressure and sail shape measurements at full scale has been developed. Aerodynamic forces and yacht performance can be evaluated in real time.
An application of the system, called FEPV, for the investigation of the effects of rig tension on the yacht performance is shown and the results are in good agreement with performance based on sailing experience. The system proved to be an effective tool to obtain a fast and accurate feedback of yacht performance.

The system can be used for the investigation of unsteady sail aerodynamics. The relationship between pressure/aerodynamic forces and pitching motion when sailing upwind has been investigated and the results have been compared to a dynamic velocity prediction program, which showed good agreement.

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