FULL SCALE INVESTIGATION OF ONE-DESIGN CLASS CATAMARAN SAILS

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Abstract. This work is concerned with an experimental campaign carried out on a Tornado class catamaran. Full scale pressure measurements were taken on the boat mainsail both on the pressure and on the suction sides. Pressure taps were applied on the main sail accurately trying not to modify the flow field nor the flexibility of the sails. The distribution of the pressure taps is such that an accurate map of the mean pressure distribution on the sail surfaces has been reconstructed. Every pressure tap was coupled with a pressure transducer and the pressure values were acquired through an electronic scanning system, so that they can be considered to be simultaneous. Static pressure coefficient distribution over the sail span will be presented, giving an insight into the flow structure over the sails and precious information for validation of CFD codes.

NOMENCLATURE

AWA Apparent Wind Angle
AWS Apparent Wind Speed
CFD Computational Fluid Dynamics
Cp Pressure coefficient
CpR Pressure difference coefficient
GPS Global Positioning System
p Static pressure
p_ref Pressure Reference
SoG Speed over Ground
TMG Track Made Good
TWA True Wind Angle
TWS True Wind Speed
ρ Air density

subscripts
P.S. Pressure side pressure
S.S. Suction side pressure

1. INTRODUCTION

The use of numerical tools in the design process of yachts is experiencing a great increase. Recent improvements in computer performance allow the use of Computational Fluid Dynamics for designing hulls, appendages and sails, making possible the replacement of some experimental investigation. However, CFD simulations are not always feasible and still need refinement for some specific applications. Sail performance characteristics, for instance, are usually accurately predicted for upwind sails, whereas for downwind sails many problems arise due to separated flow [1,2]. Therefore experimental investigations still remain of paramount importance either as the only feasible tool for some applications or in order to provide precious data for validation of CFD codes.

The choices that can be made when adopting an experimental approach are mainly two. One of them is to measure sail forces with a balance and therefore to determine total quantities such as drive and side force coefficients, lift and drag coefficients, heel moment etc. This can be done either on full-scale boats during navigation [3,4], or in wind tunnels on scaled models [5,6]. Such methods make it possible to sort out the performance of a single sail or of a specific set of sails, but also can be used in a comparative procedure in order to work out the optimal shape among different sail geometries for a given sailing condition. The second approach consists of detailed measurements taken directly on the sail surface, close to the sail, or even in the sail wake [7]. Static pressure can be measured by suitably applying pressure taps on the sail surface and the velocity field around the sail can be analysed by means of aerodynamic pressure probes [8] or hot-wire anemometers. The advantage of the latter method is that it allows the nature of the flow over the sails and the way in which it is affected by changes in sail shape to be deeply understood.

To the authors’ knowledge detailed information on the static pressure distribution on sail surfaces is not available. The aim of this work is to provide some information on the matter by means of measuring techniques used in experimental research activities at the Department of the Mechanical Engineering of the University of Cagliari, and using instrumentation available from the market place.

However, some problems make it difficult to achieve reliable results when adopting such an approach. The pressure distribution on a sail is characterised by very low values (few millimetres of water) that require pressure transducers with a suitably low full-scale value.

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in order to obtain accurate measurements. The difficulty of finding pressure transducers with this characteristic in the market place is increased by the fact that the transducers need also to be miniaturised. In fact there are a variety of transducers with the appropriate full-scale values for industrial applications, but they are not usable in our situation because of their dimensions. The need for keeping the size of the devices used as small as possible is of great importance and is a direct consequence of the necessity to set the transducers as close as possible to the pressure taps. This in fact allows the pressure values to be acquired while avoiding the use of long pneumatic lines, which would result in low response frequency not suitable for this application. Furthermore, this leads to an acquisition system where every pressure tap is coupled with a pressure transducer, and the pressure values are acquired through electronic scanning, not pneumatic scanning, so that they can be considered to be simultaneous. Hence, to obtain detailed information on the pressure distribution over the sail surface, a large number of pressure taps is required and therefore a large number of pressure transducers. This has to be realised bearing in mind that the measuring system should not interfere with the flow field and not affect the flexibility of the sails. The following sections deal with these problems and with the way they have been worked out.

2. MEASUREMENT SYSTEM

The mainsail of a Tornado class catamaran has been instrumented in order to make pressure measurements on his surface. Pressure taps have been applied on both sides of the sail, so that they allow measurements at the same time of the pressure distributions over the pressure and suction sides. Specifically, 25 pressure taps have been distributed on each side of the sail, as shown in figure 1.

As it may be noted from the figure, the pressure taps are arranged in 6 rows for each side and the rows in one side are staggered from those on the other side and placed far apart enough to avoid interferences with the flow.

A schematic drawing of the components necessary to realize a pressure tap is represented in figure 2. In order to create a flat and even surface, a brass foil 0.2 mm thick has been glued on the measuring side. On the other side of the sail a Plexiglas plate of 15x15 mm and a thickness of 3 mm has been stuck and connected to the pressure transducer through a PVC tube. The pressure tap hole is 1 mm.

The pressure transducers used are differential ones, miniaturized, amplified and temperature compensated. They are the PCLA 02X5D2 type, produced by SensorTechnics. The operating pressure range is ±2.5 hPa; the output is proportional to the supply voltage and ranges between 0.25 V to 4.25 V when the supply voltage varies between 4.5 V and 5.5 V. Therefore the supply voltage is realized and kept steady by means of a voltage regulator, so that output voltage variations are avoided. Figure 2 illustrates the way in which the transducers have been mounted on the sail. They have also been sealed and waterproofed.

All pressure transducers have been accurately tested and calibrated in the operating pressure range. Druck DP 610LP pressure calibrator has been used for the calibration. This device is equipped with a reference low pressure transducer (pressure range of ±2.5 hPa and ±0.05% FS accuracy). The pressure transducers show a linear characteristic and be stable in time and with respect to temperature variation. Therefore, it is only necessary to apply signal corrections for zero drift and pressure reference variations before and after each test run.

Figure 1. Distribution of pressure taps on both sides of the sail and photo of the instrumented sail

Figure 2. Schematic drawing of the pressure taps and transducer arrangement
Data are sent to four data loggers, each having 16 single-ended input channels. These types of data loggers are specific for standalone configurations and allow data to be stored in MMC or SD removable memory cards. This is a significant advantage, since it allows the use of a laptop computer during the test runs to be avoided, which may have been a problem given the hard environmental conditions.

The boat (a Tornado class catamaran) has been equipped with an anemometer, a GPS antenna and a compass, so that the apparent wind angle and apparent wind speed, the boat heading and the boat speed could be measured. Therefore, taking into account the leeway angle, the real wind speed and real wind angle can be calculated (figure 3).

During the test runs the flying shape of the sail was acquired with digital cameras in order to be able to measure it after processing the images with a software.

![Figure 3. Velocity triangle.](image)

3. TEST RUN AND RESULTS

Experimental tests have been carried out in order to verify whether the GPS antenna, anemometer and compass, as well as the pressure transducers on the sail were working properly. The boat type (a dinghy) and the configuration taken during navigation obliged the anemometer, the compass and the GPS antenna to be positioned on the bowsprit. In fact, positioning the anemometer on the masthead would have produced an error on the apparent wind speed and angle due to many reasons. First of all, because of the significant heel angle occurring on upwind configurations, to which the results reported in this paper are referred. Moreover, the potential interaction between the boat rig and the flow field can not be neglected. Last but not least, the rig finite length and the main sail load is responsible of a tip vortex which modifies the flow field close to the masthead [8].

Figures 4 and 5 show the quantities measured during the test runs out on the sea. In detail, two consecutive starboard and port tacks relative to an elapsed time of about 1200 s are represented. The data coming from the anemometer, GPS antenna and compass were digitalised and stored on a data-logger with a sampling time of 2 s. The data acquired from the anemometer (Figure 4), measured with respect to the boat axis but corrected taking into account the leeway angle, show that the apparent wind direction is almost constant and about 30° for the starboard tack and -50° for the port tack. On the other hand the apparent wind speed varies between 9 and 13 m/s. The graphs clearly show when the tack has occurred (at about 520 s), i.e. close to the sudden variation in the AWA and the temporary reduction in the AWS. From figure 5 it can be noticed that a sharp decrease in the boat speed and a significant variation on the boat course (measured by the GPS with respect to the North) have occurred simultaneously. Furthermore, the sensitivity of the boat to the apparent wind speed variation can be highlighted. As soon as the AWS decreases, the SoG substantially reduces, for example at approximately 300 s and 800 s.

![Figure 4. Apparent wind speed and angle.](image)

![Figure 5. Speed Over Ground and Track Made Good.](image)
From these data, considering the velocity triangle (figure 3), it is possible to calculate the speed and angle of the true wind, as reported in figure 6. As it can be seen, the TWA is about 60° during the starboard tack and about -80° during the port tack, whereas the TWS is affected by the AWS variations and is 6 m/s and 8 m/s on average for the starboard and port tack respectively. This information allows us not only to understand the boat behaviour with respect to the apparent wind, but also to identify the steady operating conditions that can be considered in order to analyse the pressure field on the sail surface. The time segment between 600 s and 800 s seems to be particularly suitable since all the quantities mentioned above have small variations. Evidence of this is given in figure 7, where the voltage signal vs. time from two transducers on the two sides of the sail is reported. During the time segment [600-800 s] both voltage signals are constant and therefore can be considered to represent an almost steady flow configuration on the sail. However, analysing the whole period of the test run, other time segments during which the same steady conditions occur can also be identified. For instance, during the time segment between approximately 400 s and 520 s all the quantities are stable and almost constant. Moreover, the difference between the voltage signals of the two transducers (figure 7) allows the identification of the pressure and suction sides, which are swapped after tacking (approximately at 520 s).

Mean pressure values characteristic of a certain operating condition are obtained by time averaging the pressure measurements of each pressure transducer.

Figure 6. True wind speed and angle.

Figure 7. Voltage signal vs. time for two transducers

Taking into account the incident flow variation (figure 4), the mean pressure can be considered meaningful since it is calculated over a large number of pressure samples, as the sampling frequency was equal to 20 Hz. By suitably extrapolating the mean pressure values obtained from the pressure transducers on the sail, it is possible to obtain the pressure distribution over the whole sail surface, including leech, luff, foot and head of the sail. Figure 8 shows the maps of the pressure coefficient distribution on both the pressure and suction sides. The pressure coefficient has been calculated as follows:

$$C_p = \frac{P - P_{ref}}{\frac{1}{2} \cdot \rho \cdot AWS^2}$$

(1)

Where $P_{ref}$ is the atmospheric pressure applied to the reference port of all transducers and AWS is the mean value of the apparent wind speed calculated over the time interval considered. The pressure coefficient distribution on the pressure side (right hand side on figure 8) reaches the greatest values in the centre of the sail, whereas the load decreases close to the leech. The distribution is fairly smooth with a gradient in the x direction and shows a core of high pressure at mid-height. An analogous distribution with similar pressure contours characterizes the suction side. The lowest pressure values occur near the luff all over the sail height. The pressure increases towards the leech where the highest pressure values occur.

The same pressure distributions have been obtained without significant variations over different time intervals, and other test runs carried out in upwind configurations. From the pressure distribution it is possible to obtain the pressure coefficient resulting from the difference between the pressure and suction side:

$$C_{pk} = \frac{P_{ps} - P_{ss}}{\frac{1}{2} \cdot \rho \cdot AWS^2}$$

(2)

The map of such coefficient (figure 9) is particularly meaningful because it provides accurate information on the aerodynamic force on the sail, and together with the flying shape of the sail allows the lift and drag coefficients to be calculated, as well as the drive and side force coefficients.
The contour plots of the pressure coefficient distribution provide a complete representation of the aerodynamic load on the sail but do not allow the pressure distribution over the chord to be clearly understood. Therefore the authors have tried to represent the pressure distribution over the chord at three different sail heights. Figure 10 reports the pressure coefficient distribution over the chord at 10%, 50% and 80% of the sail height respectively. Even though the pressure distribution over the whole sail surface has been obtained by means of an extrapolation of the raw data, the graphs in figure 10 clearly show the different loads on the three sections considered. The highest load is reached at mid-height and the pressure difference coefficient $\Delta Cp$ (figure 11) is higher than 1.5 over 50% of the chord length, with the maximum value of the aerodynamic load at about the 30% of the chord. On the other sections the load is lower and in particular at 80% of the sail height the pressure coefficient is lower than 1 all over the chord length. This is a very important indication, since highlights the fact that the head of the sail slightly contributes to the resultant aerodynamic force due to the reduced load and not just because of the small sail surface. This can be explained with the small camber on the upper part of the sail. Hence, it confirms the importance of designing a sail with a bigger area on the upper part but most of all the importance of increasing the camber and twisting the upper part of the sail in order to slightly increase the incidence flow angle.


4. CONCLUSIONS

Modern aerodynamic sail design and the improvement of the aerodynamic performance of sails cannot be limited to the evaluation of global forces by means of balances in wind tunnels nor to the evaluation of boat performances during navigation. The analysis of the flow field close to and downstream of the sails, as well as the pressure field on the sail surface has been considered really interesting. In this paper the measurement technique of the pressure on the sail surfaces of the mainsail of a Tornado class catamaran in upwind configuration has been illustrated. The experimental campaign has been carried out by using miniaturised pressure transducers with the proper full-scale value and data loggers for data storage.

The data from the anemometer and the GPS have allowed the speed and angle of the true wind to be determined. The variation with time of these quantities gives an idea of the variations that may occur during races and how much they affect the boat performance.

The pressure distribution on both sides of the sail has been reported as dimensionless static pressure coefficient. It clearly shows the aerodynamic behaviour of the sail. More specifically, a smooth distribution of the aerodynamic load and a higher load in the central part of the sail has been noted. The load is lower in the boundary regions and especially in the tip of the sail. This behaviour emphasizes the importance of major attention on the design of the higher part of the sail, for example by applying 3D design criteria able to twist this part of the sail and therefore slightly increasing the aerodynamic load.

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