On-Water Pressure Measurements on a Sailing Yacht

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1 INTRODUCTION

Sail aerodynamics has been widely investigated in the last half century and it is common practice to characterize it by aerodynamic force components, whilst pressure on sails is rarely measured. In fact, in model-scale, pressure measurements are complicated because sails are flexible in order to be trimmed, the weight of the pressure transducers affects the sail shape, and the dimension of the transducer affects the flow field. When solid and thick sails are adopted to support the transducer weight, the sails can only be trimmed with difficulty. In full-scale, pressure measurements are complicated because of the unsteady wind environment and the large number of parameters involved.

The atmospheric boundary layer is fully turbulent and does not usually provide a steady wind environment. The sails are flexible and the shapes change with the wind speed. The boat heels and pitches continuously due to the waves and the wind. The differential pressure across a sail is 3 orders of magnitude smaller than the absolute value of the pressure. In fact, atmospheric pressure is between 95,000 Pa and 105,000 Pa, whilst the differential pressure across sails is of the order of magnitude of the dynamic pressure, which is roughly 15 Pa in a 5 m/s wind. Hence, the required accuracy of the pressure instrumentation is of the order of magnitude of one Pascal. To increase the accuracy, the differential pressure across the sail instead of the absolute pressure can be measured. If the pressure distributions on the windward and leeward sides of the sail need to be measured individually (instead of only the differential values between the two faces), a reference pressure is necessary. In particular, to relate the pressures with the test conditions, the undisturbed far field conditions should be chosen as reference static and dynamic pressure. Ideally, a differential pressure transducer should be connected through pressure tubes to the far field and to the sail. Because this is impossible, a stable reference pressure, possibly representative of the far field pressure, should be found somewhere onboard the vessel. It should be noticed that an incoming atmospheric disturbance can change the atmospheric pressure by several Pascal per minute. Hence, the far field pressure can change significantly during the acquisition period. The vertical pressure gradient due to hydrostatic effects is of the order of 10 Pa/m. Hence, on a 10 m high mast, the static pressure at the top of the sail is roughly 100 Pa larger than the pressure at the bottom of the sail height. The differential pressure across the sail varies linearly with the dynamic pressure and thus with the square of the wind speed. Hence, when a gust increases the wind speed by 1m/s, the dynamic pressure increases by roughly 5 Pa. Moreover, the dynamic pressure is higher at the highest sail sections than at the lowest sail sections, due to the atmospheric boundary layer.

The difficulties above were overcome in the present paper, which discuss the pressure distributions on the sails of a 24-foot sailing yacht. Differential pressures were measured, with the reference pressure being the pressure inside the yacht cabin, which was supposed representative of the far field static pressure. The reference dynamic pressure was measured with Pitot static probes located at several locations onboard. The pressure on three horizontal sail sections of the mainsail and genoa were measured for different sail trims.

2 EXPERIMENTAL SETUP

The yacht Aurelie was used for the test. She is a Sparkman & Stephens 24-foot cruising yacht with a Bermuda rig (one mast and triangular sails), designed in the late 1960s by Sparkman & Stephens. The pressure distribution was measured on 3 sections of each of the two sails: mainsail and genoa (Figure 1).

Pressures were measured on the sails with a system developed by the YRU, which has 512 channels, and each of them can acquire up to 3,900 samples per channel per second. The transducers have a pressure range of ±450 Pa and a resolution of 9.25 mV/Pa. All the transducers were pneumatically connected to a reference static pressure. The system is made of 4 boxes, which contain 64 transducers each. To simplify the measurement setup, only 42 transducers were used and hence, only one box was necessary. The box was connected to a laptop, which ran the acquisition software. A standard marine battery supplied 12 V DC to the pressure system. Pressure was averaged over 120 seconds and was sampled at 100 Hz.

The reference pressure was measured in a locker inside the yacht cabin, which was connected with a 10 m length tube to the box. The locker helped avoid that the static pressure measurement being affected by cabin ventilation. Each transducer was connected to a pressure tap through a tube, which was stuck onto the sails with adhesive tape. The pressure taps were truncated cones with a base diameter of 20 mm and a height of 5 mm (figure 2). The pressure tap on the top of the cone was connected to a stainless steel tube lying flat against the sail, to which the PVC pressure tube was connected.

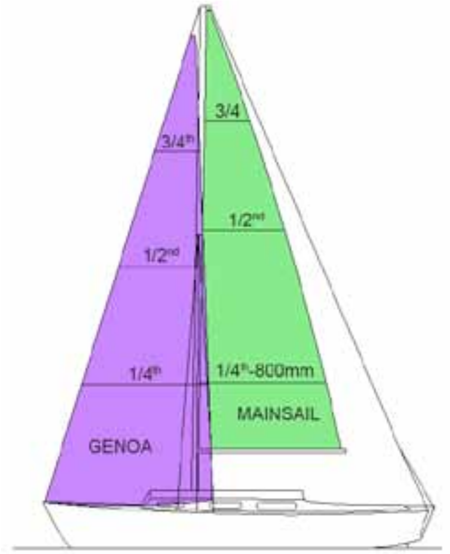

Figure 1: Sailplan of Aurelie.

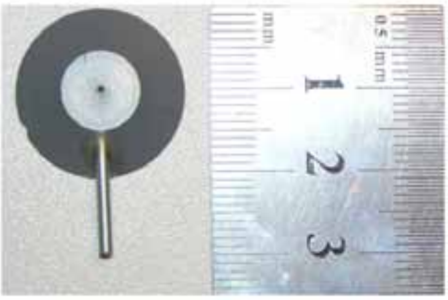

Figure 2: Pressure tap.

Pressure taps were placed on 3 horizontal sections of the two sails (figure 1). To simplify the experiment, one sail face at a time was measured. Each test condition was repeated on both tacks. Hence, the same sail face was firstly the windward face and then the leeward face. To verify the correspondence of the test condition from one tack to the other, while measuring the pressure on one sail face, a few pressure taps were used to measure the pressure on the other face. Moreover, for each test, 4 pressure taps measured the pressures around the mast, two on the windward side and two on the leeward side respectively.

Static and dynamic pressures were measured with three Pitot static tubes located on the windward side of the yacht. Two of them were fixed to the shrouds at two different heights. These were oriented approximately 35 degree to windward of the boat's heading. The third one was fixed on a pole, which held the probe roughly 1.5 m away from the boat stern on the windward side. This latter probe was free to pivot into the wind direction and was found to be the most reliable of the three of them. The differential pressure between the total probe on the pole and the cabin reference static pressure was taken to be the reference dynamic pressure. The measurements were performed in roughly 4 m/s of breeze.

3 RESULTS AND DISCUSSION

The following results are shown in terms of pressure coefficients Cp, defined as the difference between the pressure measured on the sail surface p and the reference pressure inside the cabin p_0, divided by the reference dynamic pressure q measured by the poled Pitot static tube. Note that the vertical axis is reversed in the following figures, showing negative values above and positive values below. Cp is plotted versus the non dimensional chord length (x/c).

A general trend of Cp along a sail section can be described. Figure 3 shows a schematic diagram of Cp along a generic section of the genoa and the mainsail. The correlated flow field is also shown. The apparent wind velocity Va is determined by the sum of the boat velocity Vb and the atmospheric true wind Vt.

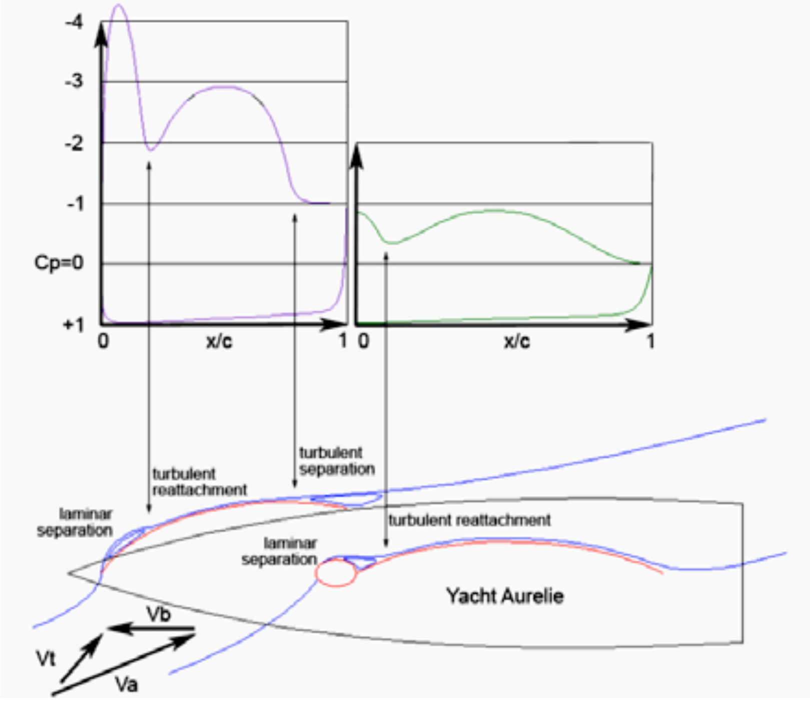

Figure 3: Schematic diagram of the pressure distributions over the genoa and the mainsail, and the corresponding flow field.

The windward side of the two sails is a low speed region. Hence, Cp is near 1.0 over the whole section. The leeward side of the genoa shows a suction peak at the leading edge, which is followed by a quick pressure recovery with a local minimum suction at around 10% of the chord. The pressure recovery is related to the laminar separation bubble formed behind the sharp leading edge of the luff, which reattach after the turbulent transition [1,2]. The reattachment location is just in front of the local maximum pressure location [2]. Downstream of the re-attachment, the pressure decreases again due to the section curvature, showing a second suction peak at a location between 20% and 40% of the curve length. After the pressure recovery, the pressure becomes constant due to the trailing edge separation [3].

The leeward side of the mainsail shows similar trends to the genoa, but the laminar separation occurs on the mast, and the turbulent reattachment occurs at around 10% of the mainsail chord.

Between the leading-edge suction peak and the pressure recovery due to the reattachment, the pressure is almost constant. The Cp trends over the mainsail are in agreement with the measurements performed on a 2D mast/mainsail section by Wilkinson [4].

Figure 4 shows the Cp measured over the 3 sections of the mainsail versus the position x along the chord c. The 3 curves are obtained with different trims of the mainsail sheet, which mainly changes the angle of incidence of the sail. The trim #0 in Figure 4 optimises the boat speed, while trim #-1 and #+1 are achieved easing and tightening the sail respectively.

Figure 5 shows the Cp over the 3 genoa sections for 5 genoa-sheet trims. Only the Cp over the leeward side of the genoa is plotted. The trim #1 optimises the boat speed, while trim #0 is achieved easing the sail and trims from #+2 to +4 are achieved increasingly tightening the sail.

Figure 4 and 5 show that when the sails are eased, the ideal angle of attack is reached and there is no leading edge suction peak, whilst when the sails are tightened, the trailing edge separation occur forward along the chord and both the leading edge and the trailing edge suction peaks are dumped.

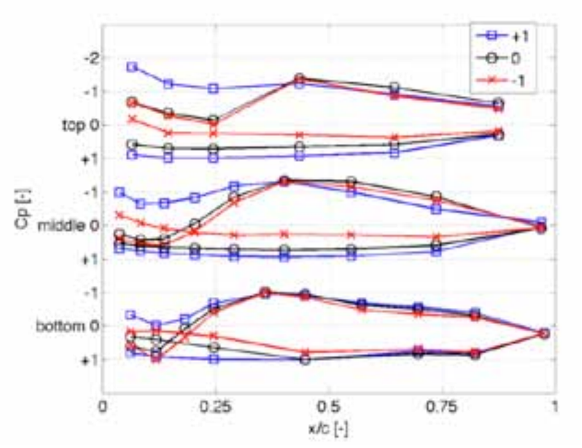

Figure 4: Cp over the leeward and windward sides of the mainsail for 3 trims.

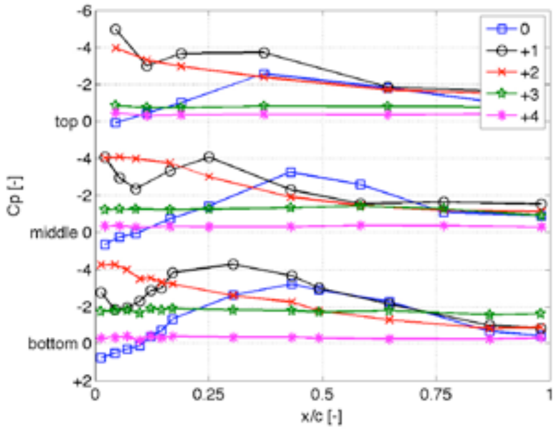

Figure 5: Cp over the leeward side of the genoa for 5 trims

4 CONCLUSIONS

The present paper shows pressure distributions on a full-scale genoa and mainsail. The pressure coefficients and the related flow field over a generic genoa and mainsail section are shown in the form of a schematic diagram. The measured pressure on the mainsail and the genoa are presented for different sail trims. The present results show that the sails are trimmed to the ideal angle of attack or slightly above to achieve the maximum speed. In the latter case, the sharp leading edge leads to separation and, hence, to the presence of a leading edge bubble. The high adverse pressure gradients can lead to trailing edge separation.

5 REFERENCES

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