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Wind-tunnel pressure measurements on model-scale rigid downwind sails

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ABSTRACT

This paper describes an experiment that was carried out in the Twisted Flow Wind Tunnel at The University of Auckland to measure a detailed set of pressure distributions on a rigid 1/15th scale model of a modern asymmetric spinnaker. It was observed that the pressures varied considerably up the height of the spinnaker. The fine resolution of pressure taps allowed the extent of leading edge separation bubble, pressure recovery region, and effect of sail curvature to be observed quite clearly. It was found that the shape of the pressure distributions could be understood in terms of conventional aerodynamic theory. The sail performed best at an apparent wind angle of about 55°, which is its design angle, and the effect of heel was more pronounced near the head than the foot. Analysis of pressure time histories allows the large scale vortex shedding to be detected in the separation region, with a Strouhal number in the range 0.1–0.3, based on local sail chord length.

1. Introduction

Modern yacht sails are aerodynamically very efficient but the flow field around sails is largely unknown. Knowledge of the flow features that make sails aerodynamically efficient will allow the performance of sails and also the aerodynamic efficiency of sail-like airfoils for other applications to be enhanced further.

The aerodynamics of sails has mainly been investigated with force measurements (Richards et al., 2001; Le Pelley et al., 2002; Fossati et al., 2006a, 2006b; Hansen et al., 2006) in wind tunnels (Flay and Jackson, 1992; Flay, 1996; Le Pelley et al., 2001), while only a few authors have recently measured sail pressure distributions (Richards and Lasher 2008; Viola and Flay, 2009, 2011). The flow field around sails has been examined primarily through numerical simulations and, therefore, it is very important to validate such simulations with accurate measurements of local quantities such as surface pressure distributions, instead of only comparing them to global quantities such as forces.

Sail pressure distributions can be measured in model-scale from wind tunnel tests and in full scale (Viola and Flay, 2011). The state-of-the-art experimental technique is based on flexible sails – including semi-flexible single-skin fibreglass sails used by Richards and Lasher (2008), and common spinnaker sailcloth used by Viola and Flay (2009, 2010) – where pressure taps are attached to one side of the sail and pressures are measured on the other side of the sail through holes in the sailcloth. This technique allows realistic sail trims in different sailing conditions to be modelled, but is limited by (i) the unknown blockage effect due to the tubes and pressure taps, (ii) the alteration of both the static sail shape and the dynamic behaviour of the sails by the mass and stiffness of the tubes and pressure taps, (iii) the low accuracy in the reconstruction of the sail flying shape.

The observed differences between the pressure distributions measured with this technique in the wind tunnel, and those measured in full-scale or computed numerically are expected to be partially due to the presence of tubes and pressure taps.

A novel technique is presented in this paper, where the effect of the pressure taps is eliminated and the effect of the tubes on the flow field is minimised. Also, the sail is rigid allowing the flying shape to be detected with high-accuracy.

This paper describes pressure distributions measured on the rigid asymmetric spinnaker in a wind tunnel, which are discussed and compared to pressures measured on soft flexible sails, and also to numerical simulation results. The pressure profiles along the sail chord on the leeward side enable interesting flow characteristics that were found in previous works (Collie, 2006; Viola and Flay, 2011; Viola et al., 2014) to be determined, such as

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Nomenclature

AWA	apparent wind angle (°)
c	sail section chord (m)
c_{av}	average sail chord (m)
$Cp = \frac{p - p_\infty}{q_\infty}$	pressure coefficient (–)
f	frequency (Hz)
h	Yacht model height (m)
p	sail surface pressure (Pa)
p_∞	reference static pressure (Pa)
q_∞	reference dynamic pressure (Pa)
$Re = \frac{U_\infty h}{\nu}$	Reynolds number (–)
$St = \frac{fc}{U_\infty}$	Strouhal number (–)
U_∞	reference velocity (m s^{-1})
x	chord-wise coordinate (m)
ν	fluid kinematic viscosity (m s^{-1})

leading edge separation bubble (sharp suction peak), sail curvature suction, and trailing edge flow separation (pressure plateau). Helpful insights into sail aerodynamics are obtained from this investigation, which are explained using conventional aerodynamic and aeronautical knowledge of the aerodynamics of thin wings (e.g. Glauert, 1926; Abbot and von Doenhoff, 1959; Hoerner and Borst, 1975). Further details are given in the subsequent sections.

2. Experimental arrangement

A rigid 1/15th scale model of an AC33-class spinnaker has been tested at the University of Auckland Yacht Research Unit (YRU) Twisted Flow Wind Tunnel which has an open jet with a test section 7 m wide and 3.5 m high. The tests were performed in uniform flow (without twisting vanes) with a turbulence intensity of maximum 3%. The reference wind speed was approximately $U_\infty = 3.5$ m/s giving a Reynolds number based on the average spinnaker chord c_{av} equal to $Re = 2.3 \times 10^5$. The solid spinnaker and mainsail were mounted on a yacht model (rig and hull), which was mounted on a turntable to adjust the apparent wind angle (AWA). The model was mounted on fore and aft bearings to enable the heel angle to be varied. Fig. 1 shows two photographs of the model during the tests. In particular, Fig. 1(b) shows the tubes carrying the pressures from the sail leech to the transducers in the cockpit; note also that to reduce deflection, the rig was reinforced by a deck spreader to windward due to the heavy spinnaker model, and the actuator used to adjust heel angle can be seen on the left hand side.

The solid model spinnaker was built as part of a master's research project at the YRU by Brett (2012), with the flying shape recorded from a sailcloth model spinnaker previously studied at the YRU (Viola and Flay, 2009). The selected shape was recorded for a trim giving the maximum driving force with a non-flapping sail at an AWA of 55° and 10° of heel. The geometric parameters of the sail shape are given in Table 1. Unfortunately the shapes of the rigid asymmetric spinnaker and the soft sail were not perfectly identical, and this has implications on the pressure comparisons discussed in Section 4.

The solid sail is a 5 mm thick epoxy fibreglass sandwich where the core is a corrugated plastic material featuring a high density of individual pressure-tight flutes, which provide the pneumatic tubes to carry the pressure signal from the measurement locations to the sail leech. Thin plastic tubes are connected to each flute on the sail leech to carry the pressures to the pressure transducers in the model cockpit. One-millimetre holes were drilled through the sail and tape was used to close one side in order to measure the pressures on the other side. A sketch of a pressure tap in a section of the solid spinnaker model is shown in Fig. 2. The sail model is as thin as possible with a 45° chamfer on the leading edge to mimic the very low thickness of a real sail. The rigid sail had a mass of about 10 kg, and it was observed that its shape could distort due to self-weight. The implications of this are addressed later in the paper when the results are discussed.

2.1. Measurement system and experimental procedure

All transducers were pneumatically connected to a reference static pressure measured with a Pitot-static probe located 9.1 m upstream of the model, 0.5 m below the wind tunnel roof. A total of 175 pressure taps were arranged along five horizontal sections located at fractions 1/8, 1/4, 1/2, 3/4 and 7/8 of the mitre height, which is the line equidistant from the leading and trailing edges of the sail. The distance between consecutive pressure taps ranges

Table 1
Parameters of the aerodynamic profile on each section (see definition in Fig. 2).

Section	1/8	1/4	1/2	3/4	7/8
Curve (mm)	1490	1510	1380	892	525
Chord (mm)	1260	1276	1203	820	488
Twist (°)	23	27	34	37	40
Camber (mm)	350	346	277	140	73
Camber (%)	28	27	23	17	15
Draft (%)	55	56	52	50	49
Entry angle (°)	63	63	56	48	50
Exit angle (°)	39	40	50	47	45

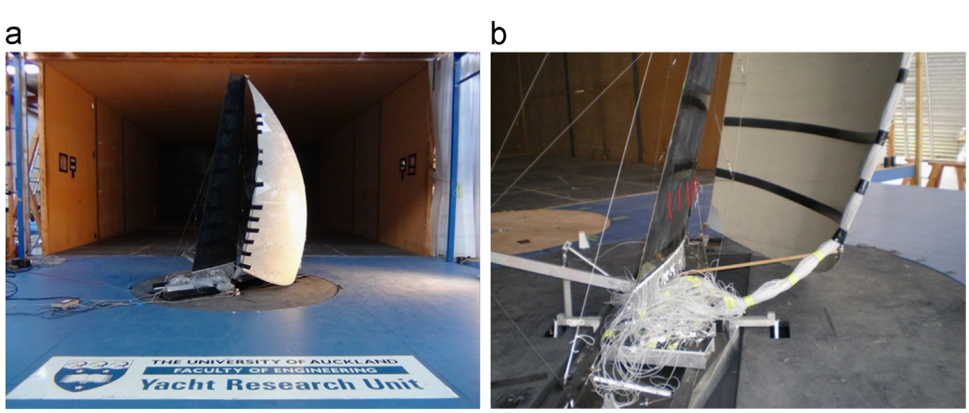

Fig. 1. Photographs of the rigid spinnaker setup in the wind tunnel; (a) general view from downstream; (b) close-up view from behind the yacht model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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