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Sail aerodynamics: Understanding pressure distributions on upwind sails

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ABSTRACT

The pressure distributions on upwind sails is discussed and related to the flow field around the headsail and the mast/mainsail. Pressures measured on several horizontal sections of model-scale and full-scale sails are used to provide examples. On the leeward side of the sails, leading edge separation and turbulent reattachment occurs, sometimes followed by trailing edge separation. On the windward side, leading edge separation occurs on the mast/mainsail and, at low angles of attack, it can also occur on the headsail. Differences were found between the leading edge bubbles on the two sails. Pressure trends for different angles of attack are presented, and these can be explained in terms of standard aerodynamic theory, particularly in terms of short and long leading edge separation bubble types. It was found that the pressure distributions measured on mainsails at full- and model-scale showed good agreement on both the windward and leeward sides.

1. Introduction

Numerical fluid dynamic methods are widely used to investigate sail aerodynamics. Potential flow codes are normally used to investigate sail aerodynamics in upwind conditions, when a mainsail and a headsail are used and the flow is mainly attached. Conversely, Reynolds Averaged Navier–Stokes techniques, and more recently Large Eddy Simulations, are used to investigate sail aerodynamics in downwind conditions, where the effect of trailing edge separation is not negligible. Although numerical simulations are very effective in investigating sail aerodynamics, they always need to be carefully validated with physical experiments.

Experimental measurements on sails are typically performed in wind tunnels. It is common practice to use flexible sails, which allow the sails to be trimmed. Aerodynamic forces are typically measured with a balance attached to the model. However, pressure measurements allow a more reliable validation of numerical simulations than force measurements. In fact, different pressure distributions can provide the same global aerodynamic forces. However, pressures are rarely measured. In fact, model-scale sails must be light and thin, which makes it difficult for pressure taps to be used. As far as is known to the present authors, pressure distributions on model-scale three-dimensional headsails and mainsails in upwind sailing conditions have never been published. Conversely, pressure distributions on full-scale sails were measured the first time between 1915 and 1921 [10] and much later by the present authors [9], and also by others, e.g. [8,6].

In the present paper, pressure distributions on upwind sails were measured in a wind tunnel on horizontal sections of rigid pressure-tapped sails. Aerodynamic forces were measured with a 6-component balance placed below the model under the wind tunnel floor. The general pressure distributions on the headsail and the mainsail and the correlated flow fields are discussed. The pressure distributions are also compared with the recent full-scale tests performed by the present authors [9].

2. Method

The Yacht Research Unit (YRU) of the University of Auckland has developed an innovative pressure system capable of acquiring up to 512 channels at speeds up to 3900 Hz on each channel. The transducers have a pressure range of ±450 Pa and a resolution of 9.25 mV/Pa. Although initially developed for laboratory use, it has been modified for use on the water. Additional details of the pressure system are provided in Viola and Flay [9]. The system was used to measure the pressures on model-scale rigid pressure-tapped sails, which were designed for the America's Cup class 'AC33'. A 1/15th-scale mainsail and headsail were built as fiberglass sandwich structures. The core was made of a 2 mm thick polypropylene plastic sheet, which had 3 mm wide core

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