Ocean Engineering 90 (2014) 93–103

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Detached Eddy Simulation of a sailing yacht

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ARTICLE INFO

Article history:
Received 20 November 2013
Accepted 30 July 2014
Available online 21 August 2014

Keywords:
Sailing yacht
Sail aerodynamics
Delayed Detached Eddy Simulation
DES
Leading edge vortex
Pressure distributions

ABSTRACT

Wind tunnel experiments on a 1:15th model-scale yacht were modelled with Detached Eddy Simulations, which allowed drawing the topology of the turbulent structures in the sail wake discovering new flow features. Simulations were performed with two different grids and three different time steps. It was found that a leading edge vortex grows from the foot to the head of the spinnaker (foresail), where it deflects downstream forming the tip vortex. The twist of the spinnaker leads to a mid-span helicoidal vortex, which has a horizontal axis almost parallel to the apparent wind and rotates in the same direction of the tip vortex. Vortical spanwise tubes are released from the trailing edge of the mainsail (aftsail) and the spinnaker and roll around the tip and the mid-span vortex of the spinnaker. Vortical tubes are also detached intermittently from the sails' feet and these break down into smaller and smaller structures while convecting downstream. For comparison, we also performed a Reynolds-averaged Navier–Stokes simulation. The comparison between forces and pressure distributions computed with different grids and time resolutions, different turbulence models, and measured with flexible and rigid sails showed similar trends; differences between numerical results were smaller than those between experimental results.

1. Introduction

Foresails are thin airfoils where the flow separates at the leading edge due to the sharpness of the edge and reattaches further downstream, leading to a high suction peak on the sail surface and contributing significantly to the overall thrust force. This flow feature is known as leading edge vortex (LEV) (Maxworthy, 2007) and it occurs on insect wings (Birch and Dickinson, 2001) and bird wings (Videler et al., 2004) at low Reynolds numbers (*Re*), and on delta wings at high *Re* (Gursul et al., 2007). The general features are also similar to those of the long laminar separation bubble known on thin airfoils with a sharp leading edge (Owen and Klanfer, 1953) but while the LEV is a coherent flow structure, the laminar separation bubble results from the time average of an unsteady flow field.

Downstream of the reattachment point, a boundary layer develops and the sail curvature leads to a second suction peak. Highly cambered sails show significant trailing edge separation due to the adverse pressure gradient downstream of this second suction peak. The sharp leading edge suction peak and the second smoother suction peak due to the sail curvature are typical of sails and unusual on airfoils. Fig. 1 shows the typical flow and pressure fields where a highly cambered spinnaker (foresail) and a flatter and smaller mainsail (aftsail) are used.

Differently from aircraft wings, sails are significantly twisted and cambered both chordwise and spanwise leading to a characteristic wake, which is not found on typical aeronautical wings. The flow field in the wake is measured with difficulty and experimentally while it can be computed numerically. The relatively high *Re* and the complex 3D geometry make direct numerical simulations unfeasible and therefore turbulence must be modelled. Reynolds-averaged Navier–Stokes simulations (RANS) have been performed since 1996 on downwind sails (Hedges et al., 1996) and, since then the agreement between numerical and experimental forces has increased in parallel with the growth of computational resources. The number of grid cells increased by about one order of magnitude every three years, Hedges et al. used a number of grid cells of the order 10^3, three years later Miyata and Lee (1999) used a number of grid cells of the order 10^4, and ten years later Viola (2009) used a number of grid cells of the order 10^7.

Richards and Lasher (2008) and Viola and Flay (2011) compared surface pressure distributions computed with RANS to those measured in wind tunnels. They found good agreement on the mid sections of the sails but larger differences on the highest sail

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http://dx.doi.org/10.1016/j.oceaneng.2014.07.019
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sections, where the suction peak near the leading edge was underpredicted by RANS.

While RANS allows a reasonable estimate of the pressure distributions, it does not allow an in-depth understanding of the turbulent structures in the wake. Therefore we performed Detached Eddy Simulations (DES), where the turbulence is modelled with RANS in the boundary layer and Large Eddy Simulation in the wake. As far as known by the authors, the present paper presents the first published investigation on sail aerodynamics performed with DES. However, it must be noted that Braun and Imas (2008) stated that DES was used in the design process of an ACC-V5-class yacht for the 32nd America's Cup, though no results were presented; Wright et al. (2010) presented few results achieved with DES but no details were provided to verify the validity of the simulation. In the present paper, the wind tunnel test on a spinnaker with both RANS and DES, using different grids and time steps, are presented.

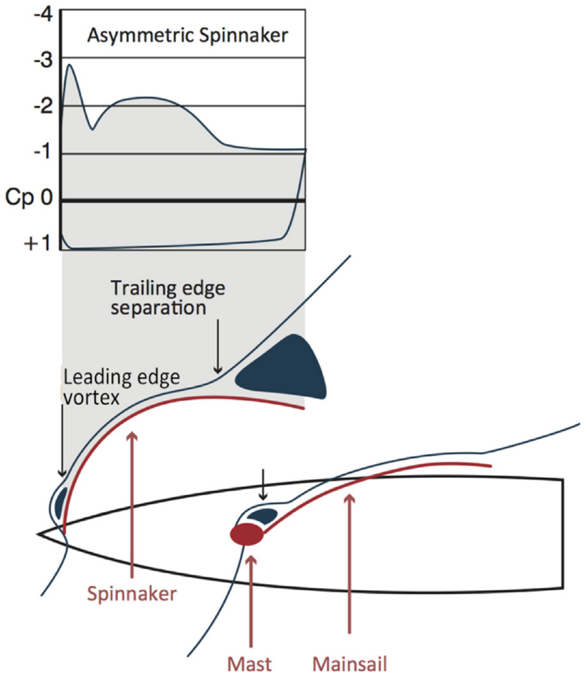

Fig. 1. Typical flow and pressure distributions in downwind conditions.

The paper is structured as follows: in Section 2, the experimental tests are introduced and the numerical simulations modelling the experiments are described, including details of the equations solved, the boundary conditions, the grids and the time steps tested, and the hardware used to run the simulations. In Section 3, the general flow field computed with the numerical simulations is presented, and details of the near-wall region and of the sail wake are discussed. Forces and pressures computed with the different simulations are compared with the experimental data. In Section 4, the key findings of the research are summarised.

2. Method

2.1. Wind tunnel tests with flexible sails

A 1:15th model-scale AC33-class yacht equipped with flexible sails was tested at the Auckland University wind tunnel. Fig. 2 (left) shows the model during the wind tunnel test. The tunnel has a 3.5-m-high and 7-m-wide open jet section, where the floor and the roof extend downstream for 5.1 m and 4.8 m, respectively. The 2.3-m-high model was placed on the wind tunnel floor at 2.7 m downstream from the open jet section. A flexible spinnaker and a mainsail were mounted on a model scale yacht, which included the hull and the rigging, at 55° apparent wind angle and 10° heel angle. Viola and Flay reported the force (2009) and pressure (2010) measurements. The mean flow velocity was $U_\infty = 3.5$ m/s, equivalent to a dynamic pressure $q_\infty = 7.5$ Pa. The boundary layer on the

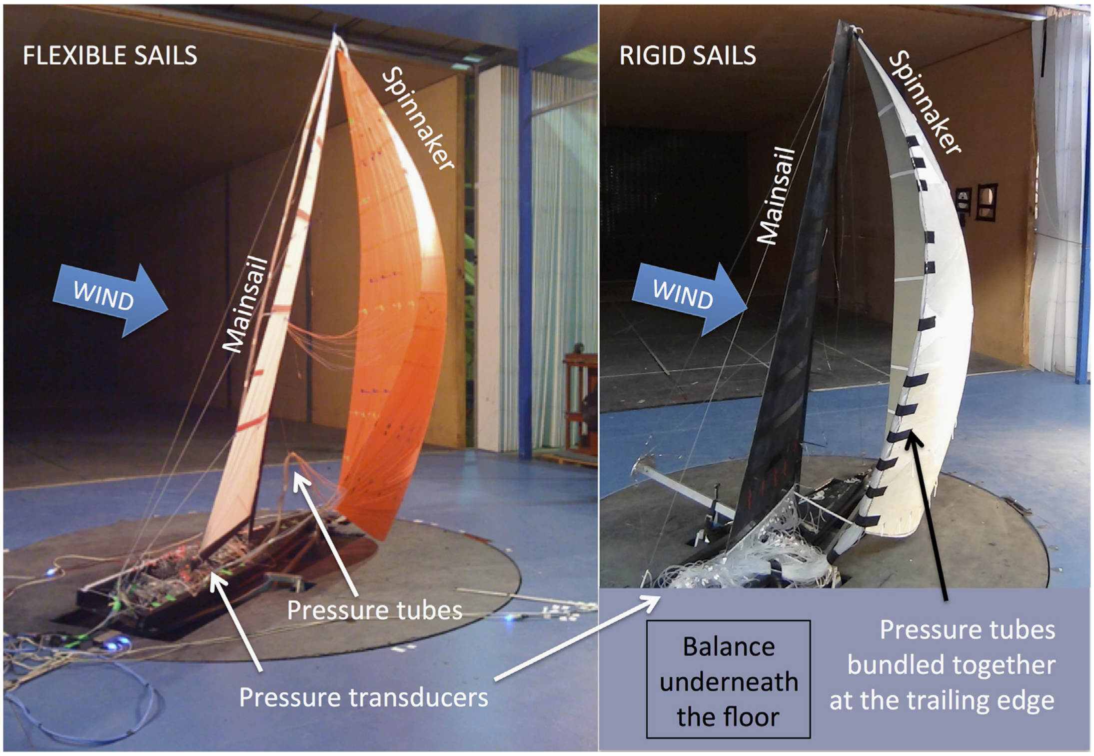

Fig. 2. Wind tunnel tests performed with flexible sails (left) and rigid sails (right).