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The leading-edge vortex of yacht sails

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ABSTRACT

It has been suggested that a stable Leading Edge Vortex (LEV) can be formed from the sharp leading edge of asymmetric spinnakers, which are high-lift sails used by yachts to sail downwind. If the LEV remains stably attached to the leading edge, it provides an increase in the thrust force. Until now, however, the existence of a stable and attached LEV has only been shown by numerical simulations. In the present work we experimentally verify, for the first time, that a stable LEV can be formed on an asymmetric spinnaker. We tested a 3D printed rigid sail in a water flume at a chord-based Reynolds number of ca. 10^4. The sail was tested in isolation without hull and rigging. The flow field was measured with Particle Image Velocimetry (PIV) over horizontal cross sections. We found that on the leeward side of the sail (the suction side), the flow separates at the leading edge reattaching further downstream and forming a stable LEV. The LEV grows in diameter from the root to the tip of the sail, where it merges with the tip vortex. We detected the LEV using the γ criterion, and we verified its stability over time. The lift contribution provided by the LEV was computed solving a complex potential model of each sail section. This analysis indicated that the LEV provides more than 20% of the total sail's lift. These findings suggest that the maximum lift of low-aspect-ratio wings with a sharp leading edge, such as spinnakers, can be enhanced by promoting the formation of a stable LEV.

1. Introduction

Sails are thin wings with a relatively sharp leading edge. A common configuration for downwind sailing includes two sails: the mainsail and the spinnaker (Fig. 1). The mainsail, which is on the rear of the yacht, has both the leading edge and the lower edge attached to rigid structures (the mast and the boom, respectively). Conversely, the spinnaker, which is in the front of the yacht, is attached to the boat only by the three corners. The free, sharp leading edge leads to flow separation at any non-zero angle of attack (Fig. 2). This is one of the key features of yacht sails that makes them different from conventional wings. In fact, the flow at the leading edge is similar to that of a plate at incidence (Viola and Flay, 2015). Flow reattachment occurs somewhere downstream of the leading edge, forming a region of separated flow. This region is short in the chordwise direction, but it extends from the base to the tip of the sail (Viola et al., 2013). When sailing downwind, the most efficient fore sails are asymmetric spinnakers, which are highly-cambered, highly-twisted and low-aspect-ratio sails. The maximum camber in both the chordwise and spanwise directions is typically higher than 20% and 50% of the chord length, respectively. The twist angle between the root and top section is higher than 20°, and the aspect ratio is between 1.5 and 2. These sails are designed to allow the maximum lift, and the drag has little effect on the yacht performance because it is almost perpendicular to the sail course.

The large camber enables high lift, but it also leads to trailing edge separation. The rear separated region could cover more than half of the chord. Since the extent of it is easier to identify than the smaller leading edge separated area, the length of the rear region is typically used to inform the sail designer on where the sails' shape can be enhanced. However, virtually all of the driving force is generated near the leading edge. Thus, small changes in the fluid dynamics of the leading edge separated region can result in significant gains in performance. This work aims to gain new insight on the flow in this section.

The impact of this work, however, extends beyond sail design. In particular, there is an increasing interest for very thin wings, and also membrane-wings, for Unmanned Aerial Vehicles (UAV). These operate at moderate Reynolds numbers (*Re*) of the order of 10^4 - 10^5. At this *Re* regime, either a large angle of attack or a high camber must be used to generate lift. Therefore, the flow around this highly cambered sail is relevant for the design of UAV wings.

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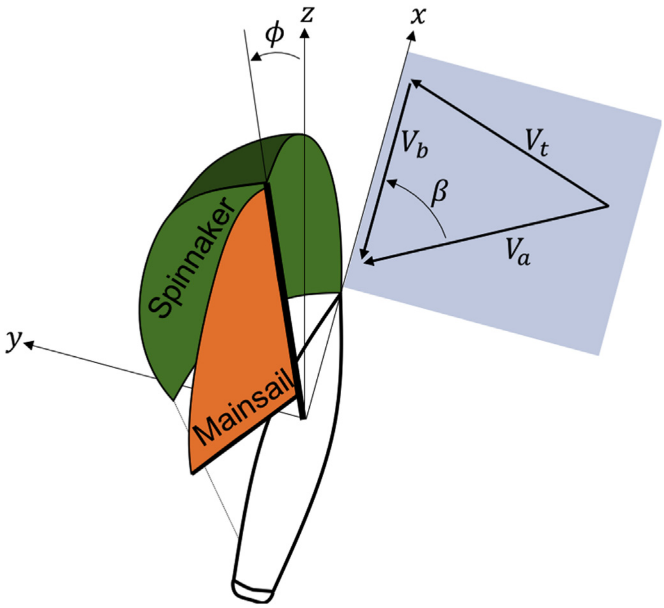

Fig. 1. Bird eye view of a yacht sailing downwind, where ϕ is the heel angle in the vertical plane perpendicular to the yacht, V_b is the wind due to the boat speed, while V_t and V_a are the true and apparent wind, respectively; β is the apparent wind angle.

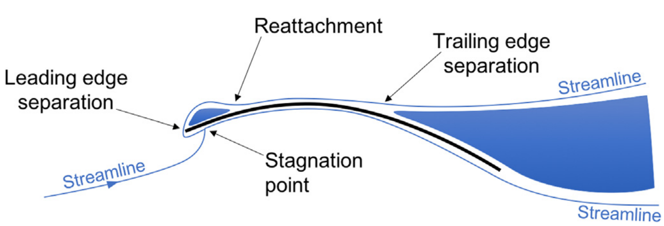

Fig. 2. Schematic view of the flow over a horizontal section of a spinnaker.

1.1. The flow of sharp-edge sails

When the leading edge of a wing is sharp and the incidence angle is high, the flow separates forming a strong shear layer. This results in the production of vorticity that is accumulated in the separated region. The integral of the vorticity in this region leads to a circulation that has the same sign as the circulation of the sail; thus this vorticity contributes to the generation of lift. However, vorticity cannot be accumulated indefinitely. It can be either shed downstream with the main flow stream, or it must be somehow extracted. At the leading edge of genoas and jibs, which are higher aspect ratio sails than spinnakers and are used to sail upwind, the vorticity is continuously shed downstream in the form of vortices that roll on the surface of the airfoil toward the trailing edge (Viola and Flay, 2011a, 2015; Nava et al., 2016). The time-averaged flow field shows flow reattachment somewhere downstream of the leading edge, and a thick boundary layer that grows towards the trailing edge.

Recent Detached Eddy Simulations (DES) (Viola et al., 2014) have revealed that a stable attached LEV might also occur on the asymmetric spinnakers of sailing yachts. This was anecdotally anticipated by Bethwaite (1993), who sketched the LEV on the asymmetric spinnaker of high-performance dinghies. The LEV is a coherent vortex formed by the roll up of vorticity, generated at the leading edge. The vorticity is not continuously shed downstream, but is instead convected towards the centre of the vortex. If the vorticity is somehow extracted from the axis of the vortex, it is possible to achieve a stable LEV that remains attached to the leading edge indefinitely. The vorticity is typically extracted by axial flow inside of the vortex core, towards the wing tip. A stable LEV grows in the direction in which the vorticity is extracted. The vorticity and circulation of the LEV can significantly increase the lift and thus it is exploited on both man-made and natural flyers (Ellington, 1999; Srygley and Thomas, 2002; Garmann et al., 2013; Jardin and David, 2014). Remarkably, it has been identified across a wide range of *Re*. In laminar flow conditions, it has been found on autorotating seeds (Lentink et al., 2009), and on the wings of insects (Muijres et al., 2008) and small birds (Lentink et al., 2007). In transitional and turbulent flow conditions, it has been found on larger bird wings (Hubel and Tropea, 2010), fish fins (Borazjani and Daghooghi, 2013) and delta wings (Gursul et al., 2005, 2007). In helicopter rotors (Corke and Thomas, 2015) and wind turbines (Larsen et al., 2007), the LEV is a powerful but undesirable flow feature. This is due to the large angle of attack oscillations. At every period, the LEV is shed downstream leading to a lift overshoot above the quasi-static maximum lift and to an abrupt, and dangerous change in the pitching moment. Conversely, in biological flyers and delta wings, the LEV provides an essential source of lift augmentation.

This work aims to provide experimental evidence that a stable LEV can occur on asymmetric spinnakers, corroborating the numerical evidence. Moreover, the work aims to quantify the contribution of the LEV to sails' performances.

1.2. A benchmark for downwind sails

The asymmetric spinnaker where the LEV was identified with DES (Viola et al., 2014) is considered in this work. The aerodynamics of this sail have been widely investigated in the last decade and this makes it one of the best available benchmarks for downwind sails. The geometry and the experimental, and numerical data are available on the Edinburgh DataShare (datashare.is.ed.ac.uk). This sail was designed for the AC33 class, which was proposed for the 33rd America's Cup. This class has never been adopted, as the 33rd America's Cup was eventually disputed with multi-hulls (ruled by the Deed of Gift). A 1:15$^{\text{th}}$-scale model of this sail was tested in a wind tunnel at 55° apparent wind angle and 10° heel angle. The apparent wind angle is the supplementary angle between the wind velocity experienced by the yacht and the sailed course. The forces (Viola and Flay, 2009) and pressures (Viola and Flay, 2010) on the sail surfaces were recorded for a range of sail trims, and also compared with those measured on similar sails. The sail trim that allowed the maximum driving force, was used to build a rigid sail with embedded pressure taps and both forces, and pressures were measured in a wind tunnel (Bot et al., 2014). This sail trim was also modelled with Reynolds-averaged Navier-Stokes (RANS) simulations (Viola and Flay, 2011b) and with DES (Viola et al., 2014). A 1:3$^{\text{rd}}$-scale prototype was built and tested on water on a Platu25-class yacht (Viola and Flay, 2012), where surface pressures were measured. A three-way comparison between the pressures measured in a wind tunnel, on water and with RANS was presented in Viola and Flay (2011b). While a comparison between wind tunnel tests performed with flexible and rigid sails, and DES, was presented in both Bot et al. (2014) and Viola et al. (2014). The pressures from these three approaches showed a qualitative agreement, with the pressures computed numerically lying in between those measured with the two experimental techniques.

1.3. Overview of the present work

In order to test in highly controlled flow conditions and to identify the main mechanisms enabling the formation, and stability of the LEV, the asymmetric spinnaker is tested in isolation (without the mainsail and the hull). Consider the chord measured on a section at 3/4th of the mitre from the base of the sail, where the mitre is the line on the sail surface equally far from the leading and trailing edge. Based on this reference chord, the Reynolds number of the sail tested in this work is $Re = 1.3 \times 10^4$. The actual flow of a real sail is certainly more complex than the one of this simplified model. The enhanced turbulent mixing and boundary