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Full-scale flying shape measurement of offwind yacht sails with photogrammetry

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ABSTRACT

Yacht downwind sails are complex to study due to their non-developable shape with high camber and massively detached flow around thin and flexible membranes. Numerical simulations can now simulate this strong Fluid-Structure Interaction, but need experimental validation. It remains complex to measure spinnaker flying shapes partly because of their inherent instability, like luff flapping. This work presents full-scale experimental investigation of spinnaker shapes with simultaneous measurement of aerodynamic loads on the three sail corners, with navigation and wind data. The experimental set-up and photogrammetric method are presented. Results are analysed in the whole range of apparent wind angle for this sail. The spinnaker shape shows dramatic variations and high discrepancies with the design shape. The photogrammetric measurement produces the full 3D flying shape with a satisfactory accuracy. Even if only steady state results are given here, this new system enables time-resolved measurement of flying shapes and thus flapping of spinnakers to be investigated, which is valuable for yacht performance optimisation. On top of sailing yacht applications, the method is useful in any application where a non-developable 3D shape is to be determined, and particularly when it results from the Fluid Structure Interaction of a flexible structure with a complex flow.

1. Introduction

Performances achieved by recent racing yachts demonstrate the massive improvements made in yacht design, materials and fabrication. In hull design, rigging design or sail design, more and more detailed research and development are used to be competitive. Understanding the physics and thus the behaviour of racing yachts have been enabled by many experimental studies combined with advanced computational resources reached nowadays. In sail design, from traditional and empirical manufacturing, the best sail designers now use high technology materials and important research and development tools (Braun and Imas, 2008; Ranzenbach et al., 2013).

The need of acquiring flying shapes is also stressed by Ranzenbach and Kleene (2002). The shape while sailing -also called flying shape-gives valuable information for validation of numerical simulations, for comparison of shapes at different apparent wind angles (AWA) and with the design shape -drawn by the sailmaker.

On the water, sail shapes and performance measurements have already been carried out by the sail dynamometer boat Fujin (Masuyama, 2014). Another sail dynamometer boat called DYNA had a flying shape measurement system described in Clauss and Heisen (2005). However those sail dynamometer boats mainly focused their experiments on upwind situations. A sail analyser method called Visual Sail Position And Rig Shape (VSPARS) is developed by the Yacht Research Unit at the University of Auckland (Le Pelley and Modral, 2008). North Sails has also developed their own tool called Advanced Sail Analyser (ASA). However, all those systems are based on a strong hypothesis for accurate measurements: the stripes painted or glued on the sail, are supposed to remain in a horizontal plane, which is not always the case for flying sails on a large range of apparent wind angles.

For downwind conditions, the physics is by far more complex than in upwind conditions due to strongly coupled Fluid-Structure Interaction between a highly curved flow and light sail cloth. Compared to upwind conditions, soft and flexible offwind sails have an inherent unsteadiness even in conditions considered “stable” (with no gust, no wind shift, on flat water and fixed trimming). This phenomenon can be spotted as a flapping at the leading edge, also called luffing. Some numerical simulations can now model the dynamic behaviour of downwind sails (Durand et al., 2014; Lombardi et al., 2012). However those simulations need validation from experiments to be confidently used in sail design optimisation. Different tools have been used to measure flying shapes of downwind sails during wind

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tunnel experiments at smaller scale: Coordinate Measuring Machine (Ranzenbach and Kleene, 2002), Photogrammetry measurement (Fossati, 2009) with custom built Infrared cameras and Renzsch and Graf (2013). Nevertheless for wind tunnel experiments, some rules of similitude are violated. Not only is there a too small Reynolds number (about 4. 10^6 for full scale testing and 4. 10^5 for a 1/10th model) but also a different ratio of fabric weight to wind pressure is encountered as well as a different ratio of membrane stress to wind pressure. Thus full-scale experiments would complete the validation. At full scale, we have previously investigated pressure evolution during luffing (Deparday et al., 2014; Motta et al., 2015).

To measure the shape of a thin flexible surface several methods have been developed. Photogrammetry and videogrammetry using dot projection has been used on solar sails by NASA (Pappa et al., 2003). Stereophotogrammetry permits to measure deformations of a flexible wing in a wind tunnel (Black et al., 2010). But only small displacements and wrinkles are measured. Thin flexible surfaces like a spinnaker can have large displacements, in an order of magnitude of 1–5 m. Techniques to measure the displacement of a surface exist e.g. the optical profilometric technique measuring free-surface deformations using fringe pattern projection (Cobelli et al., 2009). However for those methods a controlled environment is required. Salzmann and Fua (2011) developed a model using a deforming mesh corresponding to the size of the object and only one camera. Nevertheless given the large area of the spinnaker, it is not guaranteed the whole sail is in the field of view of only one camera fixed on the deck of the sailing yacht. Those last years laser measuring tools like LIDAR (LIght Detection and RAnging) have been improved and can be used to measure flexible sails. However because of the large time necessary to scan the whole sail, dynamic measurement might be difficult to obtain. The sampling rate and the accuracy can significantly decrease with moderate cost laser measuring tools. Considerable work needs to be achieved to obtain accurate data, like the custom patented system developed by Fossati et al. (2015a) using a “Time-Of-Flight” radar to detect flying shapes. It will be used on their sail dynamometer boat (Fossati et al., 2015b).

To obtain a 3D-shape of a flying spinnaker, we decided to use a photogrammetry process. In Mausolf et al. (2011), full-scale flying shapes of spinnakers were captured using a photogrammetry process with 4 cameras placed on motorboats all around the sailing yacht, which requires manpower. In addition with independent and spaced cameras, synchronization is hard to obtain with all the cameras and with the other time-resolved data. Moreover they are on moving spots relative to the sailing yacht, which is not convenient for time-resolved flying shape measurements. Furthermore rigid-inflatable boats create waves and can hamper experiments.

Moreover, those last couple of years have witnessed an increase in the quality of cameras and a considerable cost reduction. High resolution cameras are now more affordable for experiments. If the positions of cameras are unknown, a minimum of 3 photographs is required for photogrammetry measurement. However for redundancy and better accuracy, more photographs are needed. We decided to use six High Definition cameras with wide fields of view to see the sail from different angles. They were fixed on the sailing yacht on the deck. The actual locations of the cameras do not need to be a priori known for flying shape reconstruction. At last, placing cameras on deck avoids occlusion issues with the mainsail.

In this paper, we present a full-scale testing where aerodynamic loads and flying shape are simultaneously measured. Those data are time-resolved to be used for validation of numerical models and to better assess unsteady aerodynamics of offwind sails taking into account luffing for example. We present here the experimental setup and the first steady results in the whole range of apparent wind angle for this sail, from AWA ≈ 60° up to AWA ≈ 140°. The accuracy of the photogrammetric flying shape acquisition system is discussed. Then flying shapes are compared between each other. We present a new method for comparison using the volume distribution. It displays the 3D camber of the sail, i.e. the depth of the sail from the plane created by the 3 corners of the spinnaker (head, tack and clew). The last section gives a comparison between the design shape and the flying shapes.

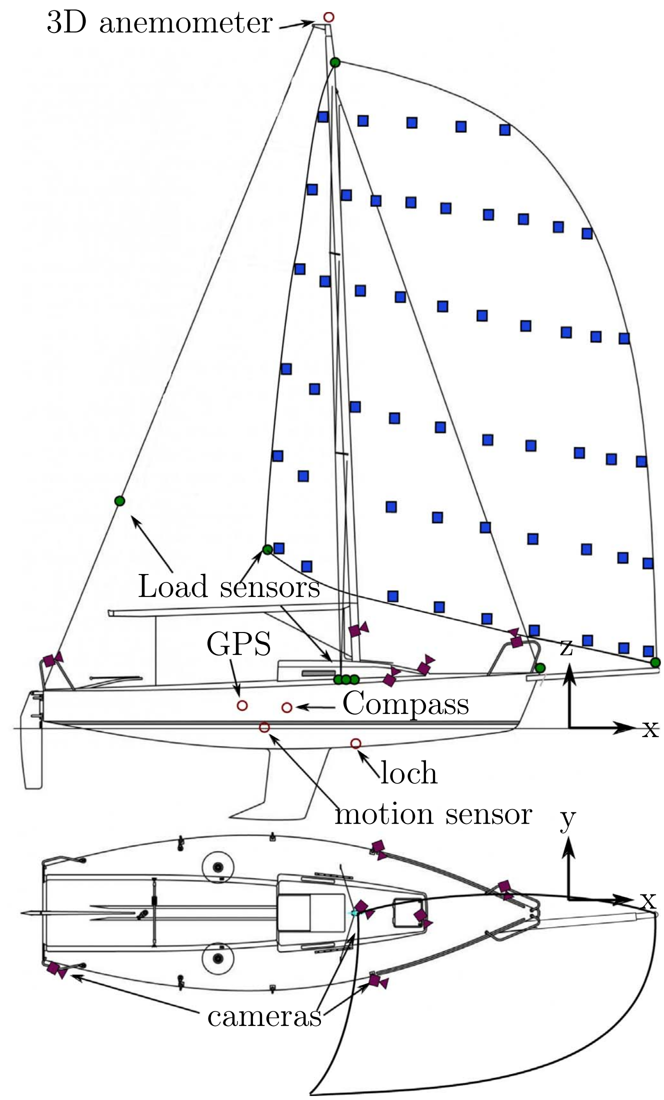

Fig. 1. General arrangement of the experimental set-up on the J/80. 11 load sensors (green discs), 6 cameras (purple objects), and wind and boat sensors (red circles). Sail markers (blue squares). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Experimental setup

While sailing downwind, we simultaneously measured the flying shape of the spinnaker as well as the loads on the rigging and on the corners of the spinnaker, the motion of the boat and the navigation parameters including the wind. We used a J/80 class yacht, an 8 m one-design cruiser racer. A tri-radial spinnaker with a surface of $S = 68.5\ m^2$ with a 12 m long rounded luff was hoisted. Fig. 1 presents the general layout of the experimental setup..

A repeatable procedure was applied during experiments. All data were recorded “on the flow”, at their own rate using a dedicated real-time acquisition system, Compact Rio from National Instruments. That is, as soon as a sensor acquires a new measurement, the value is transmitted to the real-time acquisition system which instantaneously timestamps the received value. Fig. 2 presents the centralisation of all data. It shows that only the Compact Rio clock is used to timestamp different data or to trigger a laser flashing on the sails to synchronise