Ocean Engineering 163 (2018) 136–147

Contents lists available at ScienceDirect

Ocean Engineering

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

Review

A Fluid-Structure Interaction case study on a square sail in a wind tunnel

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ARTICLE INFO

Keywords:
Fluid structure interaction (FSI)
Sail
CFD
FEA
Wind tunnel
Benchmark

ABSTRACT

A Fluid-Structure Interaction (FSI) conventional case study is proposed to be used as a benchmark for numerical analyses. Experimental tests were carried out to provide targets for comparisons; in particular, the study regarded the estimate of the deformed configuration ("flying shape" in the sailing field) of a square sail under a uniform flow regime in a wind tunnel facility. Several tests have been carried out at different wind velocities. The sailcloth has been characterized by means of mono-axial tensile tests obtaining Young's and shear moduli as well as Poisson's coefficients, which have then been used as input parameters for numerical analyses. Test results are considered a benchmark target deserving challenging aspects for numerical simulations in spite of the selected simple test geometry and conditions. Numerical tests have been carried out by means of a commercial software (ADINA™). Analyses used a strongly coupled partitioned approach between a Finite Volume Method (FVM) based on Reynolds Averaged Navier Stokes (RANS) equations, whereas a Finite Element Method (FEM) has been adopted for the structural field. A comparison has been eventually carried out assessing different numerical models. A good overall agreement between experimental and numerical results has been obtained by suitably setting FSI simulation algorithms.

1. Introduction and state of the art

Sails are a clear example of a Fluid-Structure Interaction (FSI) issue: from a structural point of view, they can be considered as very thin and flexible pretensioned membranes, undergoing large displacements because of the pressure field induced by the wind. This charming research field has been growing in the last 50 years exploiting experimental and numerical techniques of investigation. A rather extensive literature can nowadays be found on this topic. Nevertheless, only a few important works will be reported in the following for the sake of briefness.

Early studies were conducted considering separately the fluid-dynamic field and the structural one. From the experimental point of view, such early works were conducted in wind tunnel environments. Because of the impossibility of scaling the thickness of a sail by keeping the same mechanical properties of the real-scale structure, sail models are much stiffer than corresponding prototypes, and sometimes they are directly built on purpose with even stiffer materials in order to avoid any structural deformation. Thus, only the flow regime around the rigid (or quasi-rigid) sail plan is studied. Interesting results can be found in (Wilkinson, 1984). In this work, the Author studied the interaction effects of a mast on a rigid sail in a bi-dimensional case by varying some parameters such as mast's dimensions, sail's camber ratio and wind Angle of Attack (AoA). He also identified typical flow regions around a mainsail. A further important study is reported in (Flay, 1996), where a three-dimensional model was tested for the first time in a wind tunnel under twisted flow conditions, thus taking advantage of the real wind velocity profile and the variation of AoA along the sails' height. More recently, in (Fossati and Muggiasca, 2013), the aerodynamic behaviour of a 3D scaled model was characterized by means of wind tunnel tests. The study allowed the characterization of aerodynamic forces using a forced motion technique to assess the aeroelastic response of the sail plan. A representation of the aeroelastic effects was proposed, showing a hysteretical loop behaviour of the aerodynamic coefficients. Finally, in (Querad and Wilson, 2007), the Authors carried out a study on a mainsail comparing wind tunnel tests with numerical results obtained by using a commercial RANS solver (ANSYS CFX). Further numerical analyses showed that including the hull shape significantly improves the predictions.

An increasing number of full scale experimental tests have been published in recent years (Stackpole, 1985). described the tests carried out on a dynamometer-boat built at the Massachusetts Institute of Technology already decades ago. The 10.7 m boat with an internal frame connected to the hull by six load cells configured to measure forces and moments acting on rigging and sails. Additional sensors provided data about wind angles and speed at various height from sea level, heel and pitch angles, and boat speed. A more recent work was

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https://doi.org/10.1016/j.oceaneng.2018.05.056
Received 5 December 2017; Received in revised form 27 May 2018; Accepted 28 May 2018

presented by (Motta et al., 2013), where aerodynamic forces and sail shape measurements using High Resolution Cameras (HRC) were simultaneously collected on a mainsail and a spinnaker concurrently used. It is also worth mentioning a new 10 m dynamometer-boat recently built by the Politecnico di Milano, endowed of sensors on mast, rigging and sails, and of cameras for sail shapes measurements. In (Fossati et al., 2015), the concept design and the building process of the boat are described. It is pointed out by Fossati's group that sails flying shapes can be investigated using pressure taps positioned on the sails and cameras. In addition, the boat has been equipped with load cells to measure the overall forces and moments transmitted by sails and rig to the hull. Some preliminary results are also reported (Rizzo et al., 2009). designed and installed a mast and rigging monitoring system on a very large sail ship to collect data during service. While sea trials measured data are more difficult to be obtained, analysed and interpreted, the information gathered during service life is extremely valuable to calibrate design methods using data from actual loading scenarios.

As regards numerical simulations applicable to sail design, many different approaches (both where the FSI coupling is considered or not) have been adopted in the last decades. Early studies made use of non-viscous fluid-dynamic software. Subsequently, because of the increasingly available computational power, further studies have been developed using viscous RANS solvers, able to predict more complex types of flow. One of the first numerical FSI analyses is reported in (Boote and Caponnetto, 1991), where the authors wrote a complete procedure for the design of sailing yacht masts and rig. For the calculation of the aerodynamic forces, a software was realised by the authors based on the lifting surface theory. For the stress analysis, another dedicated program was developed starting from a multi-purpose Finite Element (FE) code operating in the non-linear domain (Trimarchi and Rizzo, 2009). presented a Matlab™-FEM code specifically developed for deformation analysis of sails, modelled with Constant Strain Triangles (CST) membrane elements. A weakly coupled FSI analysis of a mainsail was carried out coupling the FE code with an aerodynamic panel code. Among more recent works employing RANS codes, the study presented in (Trimarchi et al., 2010) is worth mentioning. In this work, the Authors showed the importance of using structural shell elements in FE analysis to capture the wrinkling phenomena in sails simulations. Indeed, its influence on aerodynamic performances, especially in downwind sails, is significant. A strongly coupled partitioned approach was used to solve FSI.

(Renzsch and Graf, 2011), described the implementation of a numerical procedure to couple a commercial RANSE software (ANSYS CFX) with a structural code, developed to study the behaviour of spinnakers. The structural code is based on the use of membrane elements adopting wrinkling models. A comparison with experimental tests developed in a wind tunnel was also carried out. Recently (Sacher et al., 2015), proposed an optimization procedure of the trimming of the mainsail of an IMOCA yacht (International Monohull Open Classes Association) in upwind conditions. They tested their procedure both carrying out experimental tests as well as using numerical simulations coupling RANS and FEM codes: a general good agreement was found despite inherent errors in the numerical model and uncertainties of measurements.

In this paper, a simplified case study has been developed on a square woven sailcloth in a wind tunnel. The sail undergoes large displacements to validate the prediction performances of the numerical computations for this kind of problems. Despite its simplicity, the proposed test case includes several challenging aspects and allows adjusting the simulation set-up and the modelling strategies in full detail. The selection of a simple geometry is also mandatory when new approaches or solvers are investigated on complex problem like the definition of the sail flying shape. Anyhow, further cases could be developed in the future studying more realistic and complex sail geometries by considering the rig as well. It is believed that the proposed test case is suitable to validate numerical models used in this work and providing benchmark targets for further research activities.

2. Sailcloth's mechanical properties

Even if a rather wide literature is available regarding fluid-dynamic and FSI experiments, very few works regarding sails' mechanical properties can be found, at least in open literature. The work presented in (Satchwell, 1984) can be considered a milestone in this field. The primary intent of that study was to carry out a procedure to assess mechanical characteristics of sailclothes. Standard uniaxial tensile tests on non-specified “popular” types of woven sailcloth specimens (most probably Dacron®) have been carried out to assess Young's and shear moduli, Poisson's coefficient as well as tensile strength of the fabric (McMillan, 2009). published a work on the effects of UV light and moisture on the strength of sail materials. Specimens were subjected to an intense treatment, exposing them to UV rays and air with 100% of relative humidity. Tensile tests were performed on the treated specimens and compared with results obtained from new specimens. Results were reported in terms of loss of strength, but no data were provided in terms of elastic moduli. A study on a new sailcloth called Dilon-Organza (since engineered from Dilon spinnaker fabric and Organza, a dress-making fabric, sewn together in the warp and fill directions) was published by (DeWalt, 2014). Cloth specimens were tested for stretch resistance along warp and fill directions, damage from flutter testing and tensile strength after exposure to UV light. Different results were reported in this work, yet, no data were provided in terms of elastic moduli of the material.

To the best of the authors' knowledge, no other systematic studies - except commercial information of fabric makers - are available so far in open literature about sailclothes characterization.

Because of the difficulty in finding adequate mechanical properties of sailclothes to be used as input parameters in FE structural calculations, some preliminary experimental tests have been carried out at the Engineering Materials Laboratory of the Department of Civil, Environmental and Architectural Engineering of the University of Genoa. It should be outlined that complete and accurate figures of mechanical properties of the clothes material is of primary importance to accurately predict the structural response. North Sails Italia Company provided specimens used for the mechanical characterization and for the wind tunnel test. In the following, a brief description of the tensile tests is reported. Further details can be found in (Ghelardi, 2017).

2.1. Tensile tests description

North Sails Italia Company provided a woven sailcloth manufactured in Dacron® having a density of 235 [g/m^2]. For woven sailclothes, it is reasonable to assume an orthotropic nature of the material. Therefore, the fabric was tested with fibres oriented at 0°, 90° and 45°, i.e. along fill, warp and bias directions, for a total of three specimens, in order to obtain the complete mechanical characterization of the material. Such hypotheses are particularly valid in the present work because the geometry and the loading conditions adopted in the FSI test are rather simple. In case of actual sails, more complex anisotropic models may be more representative of the structural behaviour. Namely, measurements provided elastic moduli in warp/fill directions E_w and E_f, the corresponding Poisson coefficients ν_{wf} and ν_{fw}. Specimens' dimensions are reported in Fig. 1.

Mono-axial tensile tests up to the breaking point were carried out using a Zwick Roell Z020 testing-machine. Machine measurements might be subjected to an error of 1% according to its calibration certificate. Data have been acquired and conditioned providing, as a result, force-strain plots. Afterwards, Young's moduli have been estimated using actual geometries of each specimen measured on purpose.

To evaluate the Poisson's coefficients, ν_{wf} and ν_{fw}, a contactless photographic technique has been used to measure the transversal deformation of the specimens with respect to the acting direction of the load. A mono-axial load has been applied with the same test-machine