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Dynamic behaviour of a flexible yacht sail plan

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ABSTRACT

A numerical investigation of the dynamic Fluid–Structure Interaction (FSI) of a yacht sail plan submitted to harmonic pitching is presented to address both issues of aerodynamic unsteadiness and structural deformation. The FSI model – Vortex Lattice Method fluid model and Finite Element structure model – have been validated with full-scale measurements. It is shown that the dynamic behaviour of a sail plan subject to yacht motion clearly deviates from the quasi-steady theory. The aerodynamic forces presented as a function of the instantaneous apparent wind angle show hysteresis loops, suggesting that some energy is exchanged by the system. The area included in the hysteresis loop increases with the motion reduced frequency and amplitude. Comparison of rigid versus soft structures shows that FSI increases the energy exchanged by the system and that the oscillations of aerodynamic forces are underestimated when the structure deformation is not considered. Dynamic loads in the fore and aft rigging wires are dominated by structural and inertial effects. This FSI model and the obtained results may be useful firstly for yacht design, and also in the field of auxiliary wind assisted ship propulsion, or to investigate other marine soft structures.

1. Introduction

It is now well-known that deformations actively or passively endured by aerodynamic and hydrodynamic lifting bodies have a significant effect on the flow dynamics and the performance of the system. A huge amount of work has been devoted to insects' and birds' flight, (Mountcastle and Daniel, 2009) or to fishes swim (Fish, 1999; Schouveiler et al., 2005), for example for applications in Micro Air Vehicles (MAV) and more generally in the biomimetic field (for a review, see Shyy et al., 2010). From this abundant literature, it has been shown that the dynamic behaviour of the flow and the structural deformation must be considered to better understand the mechanisms involved in lifting and propulsive performances (Combes and Daniel, 2001). For example in the field of insect flight, Shyy et al. (2010) have underlined the necessity to consider the dynamic phenomena to properly estimate aerodynamic coefficients.

Fluid–Structure Interaction is also of interest for some compliant marine structures, such as wave attenuation systems (Lan and Lee, 2010) or in the field of Ocean Thermal Energy Conversion (OTEC) where soft ducts made of a membrane and stiffeners may be interesting for the cold water pipe (Yeh et al., 2005; Griffin, 1981). To reduce fuel consumption and emissions in maritime transport, wind assisted propulsion is more and more considered for ships (Wellicome, 1985; Low et al., 1991; Dadd et al., 2011).

When analysing the behaviour of yacht sails, an important difficulty comes from the Fluid–Structure Interaction (FSI) of the air flow and the sails and rig (Marchaj, 1996; Garrett, 1996; Fossati, 2010). Yacht sails are soft structures whose shapes change according to the aerodynamic loading. The resulting modified shape affects the air flow and thus, the aerodynamic loading applied to the structure. This Fluid–Structure Interaction is strong and nonlinear, because sails are soft and light membranes which experience large displacements and accelerations, even for small stresses. As a consequence, the actual sail's shape while sailing – the so-called flying shape – is different from the design shape defined by the sail maker and is generally not known. Recently, several authors have focused on the Fluid–Structure Interaction (FSI) problem to address the issue of the impact of the structural deformation on the flow and hence the aerodynamic forces generated (Chapin and Heppel, 2010; Renzsh and Graf, 2010).

Another challenging task in modelling racing yachts is to consider the yacht behaviour in a realistic environment (Charvet et al., 1996; Marchaj, 1996; Garrett, 1996; Fossati, 2010). Traditional Velocity Prediction Programs (VPPs) used by yacht designers consider a static equilibrium between hydrodynamic and aerodynamic forces. Hence, the force models classically used are estimated in a steady state. However, in realistic sailing conditions, the flow around the sails is most often largely unsteady because of wind variations, actions of the crew and more importantly because

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Nomenclature

A	pitching oscillation amplitude (deg)
C	sail plan chord at z_a (from head-sail leading edge to mainsail trailing edge) (m)
C_x	driving force coefficient (dimensionless)
C_y	heeling force coefficient (dimensionless)
f_r	flow reduced frequency (dimensionless)
S	total sail area (m^2)
T	pitching oscillation period (s)
V_{AW}	apparent wind speed (m s^{-1})
V_{TW}	true wind speed (m s^{-1})
V_r	flow reduced speed (dimensionless)
z_a	height of the centre of aerodynamic force (m)
$\underline{F}$	force vector (dimensionless)
$\underline{R}$	residual vector (dimensionless)
$\underline{u}$	position vector (m)
$[C]$	damping matrix (dimensionless)
$[K]$	stiffness matrix (dimensionless)
$[M]$	inertia matrix (dimensionless)
β_{AW}	apparent wind angle (deg)
β_{eff}	effective wind angle (deg)
β_{TW}	true wind angle (deg)
ϕ	heel angle (deg)
θ	trim angle (deg)
ρ	fluid density (kg m^{-3})
τ	phase shift (s)

of yacht motion due to waves. To account for this dynamic behaviour, several Dynamic Velocity Prediction Programs (DVPPs) have been developed, e.g. by Masuyama et al. (1993), Masuyama and Fukasawa (1997), Richardt et al. (2005), and Keuning et al. (2005) which need models of dynamic aerodynamic and hydrodynamic forces. While the dynamic effects on hydrodynamic forces have been largely studied, the unsteady aerodynamic behaviour of the sails has received much less attention. Schoop and Bessert (2001) first developed an unsteady aeroelastic model in potential flow dedicated to flexible membranes but neglected the inertia. In a quasi-static approach, a first step is to add the velocity induced by the yacht's motion to the steady apparent wind to build an instantaneous apparent wind (see Richardt et al., 2005; Keuning et al., 2005) and to consider the aerodynamic forces corresponding to this instantaneous apparent wind using force models obtained in the steady state. In a recent study, Gerhardt et al. (2011) developed an analytical model to predict the unsteady aerodynamics of interacting yacht sails in 2D potential flow and performed 2D wind tunnel oscillation tests with a motion range typical of a 90-foot (26 m) racing yacht (International America's Cup Class 33). Recently, Fossati and Muggiasca (2009, 2010, 2011) studied the aerodynamics of model-scale rigid sails in a wind tunnel, and showed that a pitching motion has a strong and non-trivial effect on aerodynamic forces. They showed that the relationship between instantaneous forces and apparent wind deviates – phase shifts, hysteresis – from the equivalent relationship obtained in a steady state, which one could have thought to apply in a quasi-static approach. They also investigated soft sails in the same conditions to highlight the effects of the structural deformation (Fossati and Muggiasca, 2012).

To better understand the aeroelastic behaviour, a numerical investigation is achieved with a simple harmonic motion to analyse the dynamic phenomena in a well-controlled situation. This paper addresses both issues of the effects of unsteadiness and structural deformation on a yacht sail plan with typical parameters of a 28-foot (8 m, J80 class) cruiser-racer in moderate sea. An unsteady FSI model has been developed and validated with experiments in real sailing conditions (Augier et al., 2010, 2011, 2012). Calculations are made on a J80 class yacht numerical model with her standard rigging and sails designed by the sail maker DeltaVoiles. The dynamic results are compared with the quasi-steady assumption and the dynamic force coefficients are also compared with the experimental results obtained by Fossati and Muggiasca (2011) for a rigid sail plan of a 48-foot (14.6 m) cruiser-racer model. The FSI model is presented in Section 2, and the experimental validation is presented in Section 3. The methodology of the dynamic investigation is given in Section 4. The core of the paper (Section 5) presents and analyses the simulation results regarding variation of force coefficients and loads in the rig due to pitching. In the last section, some conclusions of this study are given, with ideas for future work.

2. Numerical model

To numerically investigate aero-elastic problems which can be found with sails, the company K-Epsilon and the Naval Academy Research Institute have developed the unsteady fluid-structure model ARAVANTI made by coupling the inviscid flow solver AVANTI with the structural solver ARA. The ARAVANTI code is able to model a complete sail boat rig in order to predict forces, tensile, and shape of sails according to the loading in dynamic conditions. The numerical models and coupling are briefly described below. For more details, the reader is referred to Roux et al. (2002) for the fluid solver AVANTI and to Hauville et al. (2008) and Roux et al. (2008) for the structural solver ARA and the FSI coupling method.

2.1. The inviscid fluid solver: AVANTI

Flow modelling is based on the Vortex Lattice Method (VLM). This method is suitable for external flows where vorticity exists only in the boundary layers on the lifting surface and its wake. In the lifting surface model, the vorticity is represented by a non-planar doublet distribution along the lifting surface and the wake formed by the vortex shedding at the trailing edge is represented by a vortex sheet. This method is basically made up of two parts: a lifting body problem and a wake problem. These two problems are coupled by means of a kind of Kutta condition that has been derived from the kinematic and dynamic conditions along the separation lines. Usually, these lines are reduced to the trailing edges although more complicated situations have sometimes been considered. Except when writing this Kutta condition, the flow is assumed to be inviscid. The lifting problem is solved by means of a boundary integral method: the surface of the body is represented using panels of rectangular shape which are used to satisfy the potential slip condition. Specifically, a doublet strength is associated with each panel, and the strength of the doublet is adjusted by imposing that the normal velocity component at the surface of the body must vanish at control points. The aerodynamic force is computed with the doublet strength and local fluid velocity thanks to the doublet/vorticity equivalence introduced by Hess (1969) (see also Huberson, 1986). The wake is modelled by means of the particles method itself developed by Rehbach (1977) and then Huberson (1986). According to this method, the vorticity