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Numerical study of a flexible sail plan submitted to pitching: Hysteresis phenomenon and effect of rig adjustments

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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 analyse the system's dynamic behaviour and the effects of motion simplifications and rigging adjustments on aerodynamic forces. 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. It is shown that the hysteresis phenomenon dissipates some energy and that the dissipated energy increases strongly with the pitching reduced frequency and amplitude. The effect of reducing the real pitching motion to a simpler surge motion is investigated. Results show significant discrepancies with under-estimated aerodynamic forces and no more hysteresis when a surge motion is considered. However, the superposition assumption consisting in a decomposition of the surge into two translations normal and collinear to the apparent wind is verified. Then, simulations with different dock tunes and backstay loads highlight the importance of rig adjustments on the aerodynamic forces and the dynamic behaviour of a sail plan. The energy dissipated by the hysteresis is higher for looser shrouds and a tighter backstay.

1. Introduction

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 non-linear, 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 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 of yacht motion due to waves. To account for this dynamic behaviour, several Dynamic Velocity Prediction Programs (DVPPs) have been developed, (e.g. Masuyama et al., 1993; Masuyama and Fukasawa, 1997; Richardt et al., 2005; 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

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Nomenclature

A	pitching oscillation amplitude (deg[1])
C	sail plan chord at z_{CE} (from head-sail leading edge to mainsail trailing edge) (m)
C_x	driving force coefficient
C_y	heeling force coefficient
f_r	flow reduced frequency
F_x	driving force (N)
F_y	side force (N)
M_x	heeling moment (Nm)
M_y	pitching moment (Nm)
P_{TOT}	total power of aerodynamic forces (W)
P_{LOOP}	dissipated power: power contained in the hysteresis loop (W)
$P_{V_{BS}}$	useful power: power driving the boat forward (W)
S	total sail area (m^2)
(O,X,Y,Z)	Inertial frame defined for an upright boat (origin O at the mast step, X the yacht direction pointing forward, Y athwartships (upright) pointing portside (left), Z vertical pointing upwards) (m)
(O,x,y,z)	Boat frame defined for a pitched and heeled boat (x yacht direction pointing forward, y athwartships (heeled) pointing portside (left), z along mast pointing upwards) (m)
T	pitching oscillation period (s)
V_{AW}	apparent wind speed (ms^{-1})
V_{BS}	boat speed (ms^{-1})
V_{TW}	true wind speed (ms^{-1})
V_r	flow reduced velocity
Z_{CE}	instantaneous altitude of the centre of aerodynamic forces in the inertial frame (m)
z_{CE}	instantaneous z coordinate of the centre of aerodynamic forces in the boat frame (pitched and heeled) (m)
β_{AW}	apparent wind angle (deg[1])
β_{eff}	effective wind angle (deg[1])
β_{TW}	true wind angle (deg[1])
ϕ	heel angle (deg[1])
θ	trim angle (deg[1])
α	heading angle (deg[1])
ρ	fluid density ($kg\ m^{-3}$)
τ	phase shift (s)
$_O\left\{\begin{matrix}\vec{F} & (N)\\ \vec{M} & (N\ m)\end{matrix}\right.$	Aerodynamic force matrix: resultant and moment written in O
$_O\left\{\begin{matrix}\vec{\Omega} & (rad\ s^{-1})\\ \vec{V} & (ms^{-1})\end{matrix}\right.$	Boat kinematic matrix: rotation and velocity written in O

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).

In a previous work (Augier et al., 2013), the aero-elastic behaviour of the sail plan subjected to a simple harmonic pitching was numerically investigated. This study has shown hysteresis phenomena between the aerodynamic forces and instantaneous apparent wind angle. A comparison between a rigid structure and a realistic soft structure showed that the hysteresis still exists for a rigid structure but it is lower than when the structure deformation is taken into account. However, in this first work (Augier et al., 2013), the question whether this hysteresis could be represented by a simple phase shift between both oscillating signals was not clearly elucidated. Moreover, the energy exchange associated with the hysteresis phenomenon was not determined. Hence, the first aim of the present work is to investigate further this hysteresis phenomenon, to quantify the phase shift between aerodynamic forces and apparent wind angle, and to determine and analyse the associated energy.

Most studies of the unsteady effects due to yacht pitching have considered a 2D simplified problem and thus approximated the pitching motion by a translational oscillation aligned with the yacht centreline (e.g. Fitt and Lattimer, 2000; Gerhardt et al., 2011). Then, the usual procedure is to decompose this surge motion into oscillations perpendicular to and along the direction of the incident flow, which results in oscillations of apparent wind angle and speed respectively (Fig. 8). The second aim of this work is to investigate the effects of such simplifications in the yacht motion, this is considered by comparing the results obtained with the sail plan subjected to different types of motion.

The third aim of this work is to address the effect of various rig and sail trims and adjustments commonly used by sailors on the unsteady aero-elastic behaviour of the sail plan subjected to pitching. This is investigated by comparing the results obtained with several docktunes and backstay tensions which are typically used while racing a 28-foot (8 m, J80 class) cruiser-racer.

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 FSI model is briefly presented in Section 2. The methodology of the dynamic investigation is given in Section 3. In the continuity of a previous work (Augier et al., 2013), Section 4 gives further precisions on the dynamic behaviour with a particular attention to the energy exchange related to the hysteresis phenomenon. The analysis of pitching motion decomposition in simple translations is given in Section 5 and the effects of various dock tunes and backstay loads are presented in Sections 6.1 and 6.2. 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 commonly 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 stresses and shape of sails according to the loading in dynamic conditions. 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.

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[1] In degrees when a value is mentioned in the text and in radians in all formulae.

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