Fluid-structure interactions of anisotropic thin composite materials for application to sail aerodynamics of a yacht in waves

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1 INTRODUCTION

In recent years technological innovations has allowed large improvements to be made in sail design and construction. Sails and in particular kite-sails have application for sport, ships' auxiliary propulsion and even power generation. Sails are divided into upwind and downwind sails (Fig.1), where upwind sails operate as lifting surfaces with small angles of attack whereas traditional downwind sails acted as drag device. New designs of downwind sails have reduced the area of separated flow and increased the lifting behaviour of the sails. In order to capture the lifting behaviour and regions of separation present in both types of sail careful application of computational fluid dynamic analysis tools are required. Solutions of the Reynolds averaged Navier-Stokes equations (RANSE) are often used as a part of the design process of high performance sailing yachts. The examination of how well CFD predicts the performances of the sail against wind tunnel data was established in the past by several studies [1, 2], and good agreement was generally found.

Fig. 1 - Upwind and Downwind Sails

From a structural perspective, sails are thin anisotropic laminates with a variable distribution of reinforcement. Due to the small thickness, elasticity and boundary conditions, the flying shape of the sail is variable, and the sail operates in the large displacement – small strain regime. A nonlinear finite element approach involving anisotropic shells or membranes is therefore required. As a fabric, the structural behaviour of the sail is affected by wrinkling. This phenomenon is related to buckling, and causes the development of out of plane deformations when one of the principal stresses vanishes. The development of wrinkling, often neglected in sail analysis, affects large areas of downwind sails and affects the tension distribution within the material, slightly changing the final
deformed shape.

From an engineering perspective sails are therefore a typical example of fluid structure interaction (FSI), where pressures generated by sails depend on the sail's equilibrium shape. The equilibrium shape is a function of the applied load, structural stiffness and boundary conditions, as for example battens and rigging. A solution has therefore to be searched iteratively, interchanging data from a fluid solver to a structural solver. The study of FSI applied to sails was carried out in the past by several authors. However, due to the complexity of the phenomena involved and computational effort required, this problem is far from being solved. If the application of RANSE solver showed good prediction performances in the past, much more work seems to be needed related to the structural behaviour of sails and coupling. In fact when modelling the sail structural behaviour very simplified models have been adopted in the past, the reliability of which has not been really assessed. In a previous work [4] a simple structural model was developed, and some weaknesses were found and underlined. The present paper discusses some initial investigations and future guidelines in order to get a more detailed description of the physics involved in sail FSI. Three main fields are therefore covered: the use of CFD in order to accurately capture flow features and a comparison with experimental results; structural modelling; and approach to coupling.

2 CFD INVESTIGATIONS

The flow on sails is complex, due to the presence of the mast geometry and sharp edges. Separation bubbles and vorticity generation are to be expected even in the simpler upwind sail case. In this situation the sail works as a thin wing profile subjected to relatively small angles of attack. The bluff-body type of wake behind the mast results in the formation of separation regions over the forward portion of both aerofoil surfaces.

In addition, trailing edge separation is expected, due to the adverse pressure gradient towards the rear of the aerofoil upper surface. An important reference in this analysis is given by Wilkinson's [5, 6]. In these experiments, carried out in Southampton in the early 80's, a lower third section of a typical yacht mainsail with a mast was tested in the wind tunnel. Measurements were carried out in terms of velocity profiles, pressures and separation bubble lengths. In the case analysed later the ratio of mast diameter to sail chord was 4.03% with a camber to chord ratio of 12.5%. The angle of incidence of the sail was 5 degrees at a Reynolds' number of 709000. The camber distribution represents that of a NACA a=0.8 mean line. The sail was constructed from a 5 mm thick rigid aerofoil of 2.11m span and 0.7m chord, fitted horizontally across the wind tunnel. Pressure measurements were performed with pressure tapings at mid span. Results from these experiments suggest that a mainsail can be ideally divided into 9 regions, where different flow features can be identified, as in Fig.2:

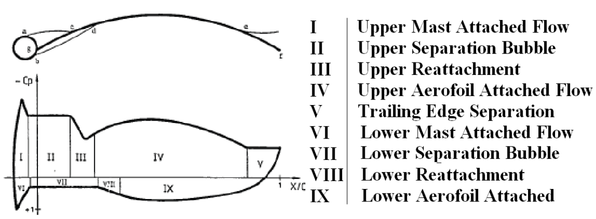

Fig. 2. Wilkinson's flow regions

Separations bubbles are widely developed on the sail surface, and they are induced by the presence of the mast both on leeward and windward side, and at the trailing edge leeward side. In Fig.2 a universal pressure distribution is represented, where it is possible to appreciate that the influence of such bubbles in terms of pressure coefficient is quite important and it cannot be neglected. Results in terms of boundary layer velocity profiles are given at specified locations as in Fig.3.

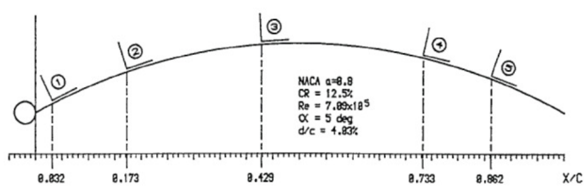

Fig. 3 - Wilkinson's measurements locations

These experiments are a good starting point as a validation exercise, and they have been used in the past by several authors [7, 8]. In particular, Paton's analysis was performed with the commercial RANSE solver ANSYS CFX, the package which has been used also for the present analysis.

In the past potential codes were also used for this kind of analysis [9, 10]. Although this could be an effective way to get easy and fast results, the inability to capture separation bubbles is an important an unacceptable source of error, as shown in Fig.2-b.

An initial multiblock structured - hexaedral mesh with O-Grid around the mast has been chosen, as in Fig.4. With such a mesh it is generally possible to expect central symmetry at all mesh points, this preserves second order accuracy. However, in the future investigations will be also carried out on hybrid meshes. With hybrid meshes the computational effort in the outer domain is slightly reduced, with a degree of accuracy which can be on a par with structured meshes [11]. However, in the literature structured meshes have been chosen for sail analysis [1, 4]. A mesh independency analysis is reported for 4 different meshes, the characteristics of which are reported in terms of spacing and average y+ over the whole mast-sail geometry:

Table 1. Analyzed meshes.

Mesh	Total n. elem.	Vertical on mast	Vertical on sail	Horizontal on mast	AVG y+
1	140.532	0.4	0.2	0.7	9
2	149.838	0.4	0.1	0.7	6.4
3	151.611	0.4	0.1	0.5	8.4
4	178.725	0.2	0.05	0.5	3.9

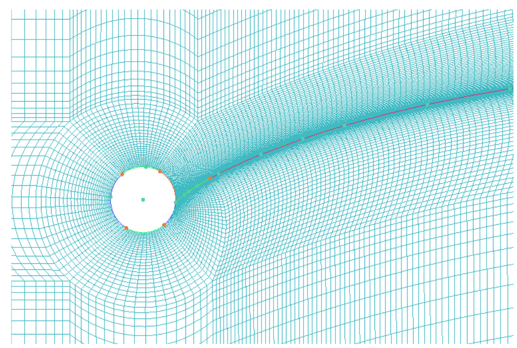

Fig. 4 – Mesh in the mast region

Generally sail flows are modelled as fully turbulent, with a typical inlet free stream turbulence of 5%. However, Wilkinson's experiments suggest that the mast flow is always below transition, meaning that the boundary layer on the mast is laminar. Transition is estimated within the last 25% of separation bubble length, as in Fig. 5. On the other hand, Collie [12] suggests that for real sail flows transition to turbulence could be accelerated by surface roughness and fittings at the head of the sail.

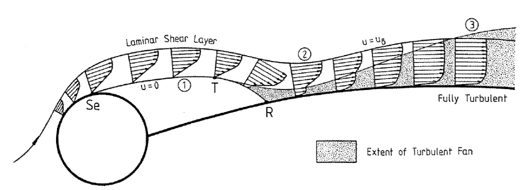

Fig. 5 – Wilkinson's observed transition

For the simulation SST turbulence model with automatic wall treatment was chosen, since it is considered as the most suitable for both upwind and downwind sails [12]. This is generally accepted in sail analysis literature, and just a few authors chose different turbulence models. Simulations were carried out for fully turbulent cases and for cases with transition. Unfortunately convergence becomes very difficult in the case with transition, and residuals remain about values of 10^{-4} both for steady or unsteady cases. For this reason results presented here relates to the fully-turbulent case, and further investigations will be carried on in the early future.

Velocity profile comparisons are presented in Fig.6, where results from Wilkinson's experiments, Paton's analysis and the current analysis (mesh 4) are compared. As expected, the error decreases with the distance from the separation bubble. A remarkable mesh-sensitivity was experienced, and the four meshes analyzed seem to be in the range of convergence for this case. Further increasing or decreasing spacing caused severe convergence issues.

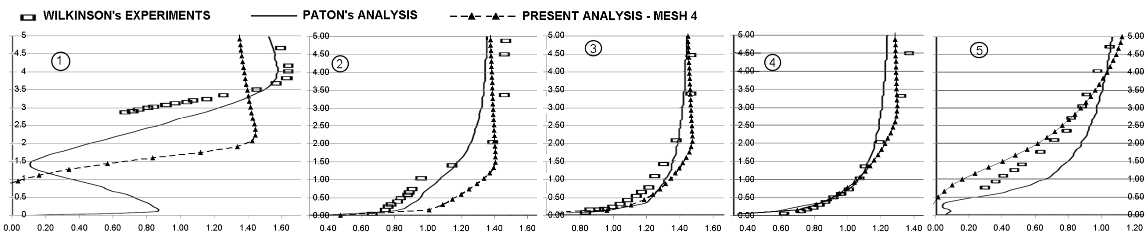

Fig. 6 – Velocity profiles comparison – results for Mesh 4

A comparison of Cp values is reported in Fig.7. The general behaviour is captured, but errors are quite important in correspondence to separation regions. In Fig.8 a comparison between the present and Paton's analysis was performed in terms of relative error:

$$ERROR = \frac{Cp_{Wilkinson} - Cp_{calculated}}{MIN(Cp_{Wilkinson} - Cp_{calculated})} \qquad (1)$$

Error values from present and Paton's analysis seem to be comparable over the whole sail chord, except in the leeward separation bubble region. Here Paton over estimates the pressure value, where the current analysis under estimates it.

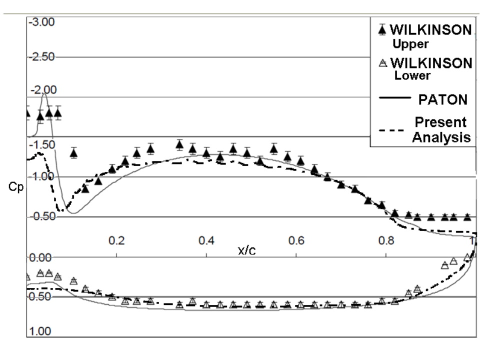

Fig. 7 - Cp values comparison

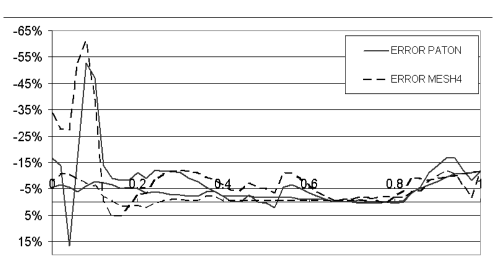

Fig. 8 – Errors. Comparison with Paton's Analysis

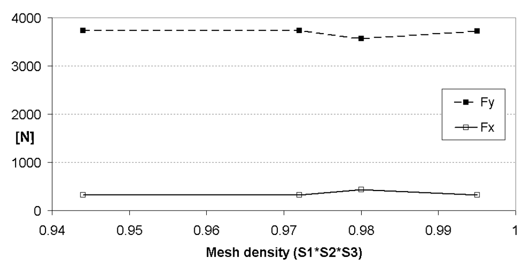

Fig. 9 – Mesh sensitivity over calculated forces

In Fig.9 values for Forces are plotted over a mesh density parameter, obtained by multiplying the spacing in Table1.Calculated forces are relatively stable. On the other hand, in Fig.10, Cp plots are reported on the same scale as Fig7 for the four analyzed meshes. In this case it is remarkable the difference between the treatment of the separation bubble pressure, which is always poorly estimated, but the finer mesh seems to better capture the flow features experienced by Wilkinson. The relative stability of measured forces in Fig.9 can therefore be explained looking at Fig.10, observing that the integral of all calculated Cp curves have similar values.

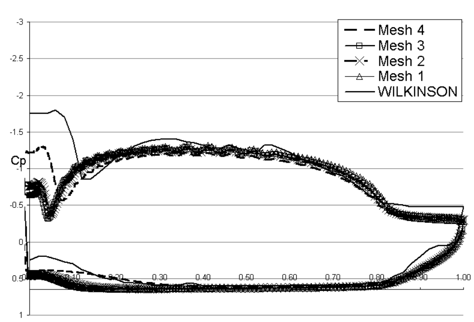

Fig. 10 – Mesh sensitivity over calculated Cp

The degree of flow complexity goes higher when considering the interaction with the jib and the generation of large tip vortices. These constitute a loss of momentum from the flow, and consequently they induce a force, which is the major contributor to the total drag [13]. Therefore, calculations will be carried out on complete mast sail geometries and results will be compared with full scale wind tunnel data [14].

Downwind sails operate at very high angles of attack and adverse pressure gradients. This produces large amount of separation and recirculation. In addition, due to the high cambered sections, these sails exhibit large streamline curvatures, which directly impacts on the Reynolds stress tensor, which becomes anisotropic. Also the log-law wall does not hold for strong curvature: for convex curvature velocity profiles lie above the log-law, for concave curvature they lie below the log-law [12]. Investigations into downwind sails will be carried out in the near future.

3 STRUCTURAL INVESTIGATIONS

A Finite Element tool able to deal with nonlinear membranes and cables elements has been developed in a previous work [4]. The implemented elements are nonlinear constant strain triangles (CST) in large displacement-small strain regime [15]. As the element is nonlinear, its stiffness matrix is composed of an elastic stiffness matrix (linear) plus a geometric stiffness matrix (nonlinear effect): $\mathbf{K} = \mathbf{K}_E + \mathbf{K}_G$. For large displacement analysis, the problem becomes non-linear since the structure's stiffness (necessary to calculate displacements) is not defined *a priori* but it has to be calculated as a function of current nodal displacements. The problem is therefore solved with an iterative procedure. The elastic stiffness matrix is defined as a function of the undeformed geometry and the constitutive relationship; the geometric stiffness matrix is a function of the stress generated along sides by the element's deformation at the previous iteration. For a more detailed description, one should refer to [4]. In Fig.11 the stress distribution for a flat plate with a hole and for a spinnaker loaded with constant pressure are shown.

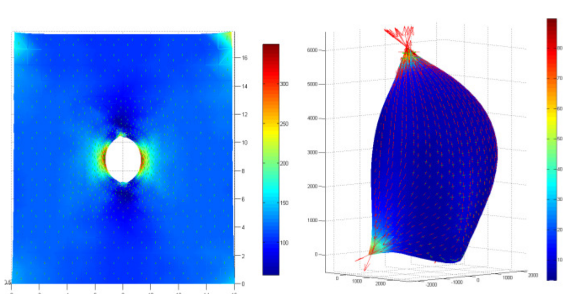

Fig. 11 - Stress distribution

The results from this work showed good agreement in some circumstances, for instance within plane or axis-symmetric comparisons versus analytical solutions [Error: 0.5 - 4% in terms of displacements and tension values]. On the other hand, poor answers were obtained by comparisons with experimental results. A wooden box was built and a Dacron membrane was fixed on the top, as in Fig.12-a. The box was made air-proof, and the Dacron fabric was fitted onto the box with fibres oriented along the box directions. Compressed air was pumped into the box and the pressure was measured by water columns, providing very accurate measurements in the range of interest. A laser device, able to measure distances, was used to obtain the fabric deformations. In Fig12 the experimental apparatus is shown with curves reporting the measured vs. calculated central section deformed shape. In this case, the maximum error is about 30%. It is worth to remark that the calculated deformed shape is not physical, since all the curvature is concentrated in the centre of the deformed membrane. Similar analysis, inflating the box with different pressures, leads to similar unphysical deformed shapes.

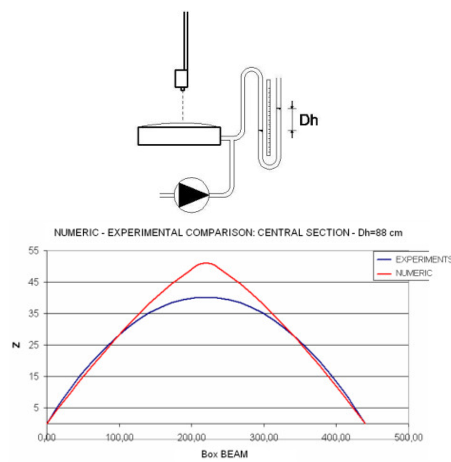

Fig. 12 - Experiments and numerical solution

The element formulation which has been implemented, or other similar formulations based on the CST, are attractive for their relative simplicity. For this reason, they have been widely adopted in structural-sail calculations and commercial codes [16, 17]. However, the main assumption of this model (a constant distribution of strain within the element) is very simplified, and the reliability of such elements is subjected to many uncertainties. More detailed formulations are available, derived from shell equations and imposing zero bending stiffness. In this case, assumptions on the elements are much more limited and the physical representation much more accurate. On the other hand, it should be remarked that for some combinations of loading and boundary conditions the use of such elements may lead to ill-posed problems. This is the case for example when wrinkling occurs, which is a buckling phenomenon controlled by the bending stiffness. When wrinkling occurs, the membrane model cannot react, and *ad hoc* wrinkling models have to be introduced [18, 19]. The use of shell elements, although with a very limited bending stiffness, is expected to overcome the problem and give much more accurate results. Furthermore, the possibility to include some bending stiffness is to be considered as a remarkable improvement for the modelling of modern sails, which are complex laminates with a certain amount of bending stiffness.

Shells are subjected to some issues when analyzing a structure, the thickness of which is very small compared to other dimensions, as it is the case for a sail model. In this case, 'locking' can occur. This makes the prediction of structural behaviour dominated by artificial, numerical effects and the actual mechanical/physical behaviour is not represented at all. Locking is characterized by a severe underestimation of the displacements, i.e. the structural response is too stiff. This can be overcome by the use of opportune interpolations between element's nodes, as it is done with MITC shell elements. For a more detailed description of shells, membranes and related problems one should refer to [20, 21, 22].

In the near future, a collaboration between the University of Southampton and INRIA-MACS will focus on applying MITC shell elements to a sail model.

4 COUPLING

Normally a Lagrangian (material) description of motion is adopted for structural algorithms, and computational domain follows the associated material particle during motion. On the other hand, an Eulerian description is generally adopted for the fluid algorithms, i.e. the computational grid is fixed and the continuum moves with respect to the grid. In the Lagrangian viewpoint material coordinates X are used, being permanently connected to the same material points. The motion of the material points relates the material coordinates X to the spatial coordinates x. For steady calculations it is possible to couple calculations by passing data between the fluid and structural solvers. In this fashion, a quasi-static approach may be used. The fluid mesh follows the structural deformation and an updated pressure's field is applied iteratively to an updated deformed shape of the sail until convergence.

In the previous work [4] coupling was performed between a structural solver and a vortex-lattice potential code [23], as already done by previous similar works [9, 16]. Therefore an updated pressure's field was applied iteratively to the initial geometry (design shape) of the sail. Convergence was achieved very well, as in Fig.13-14, where the norm of nodal displacement vector for every fluid-structure interaction step, the fluid calculation and the final deformed shape are reported.

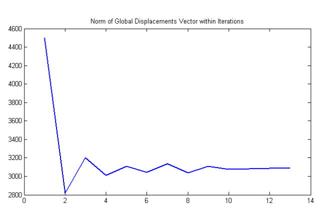

Fig. 13 - FSI - Norm of nodal displacements

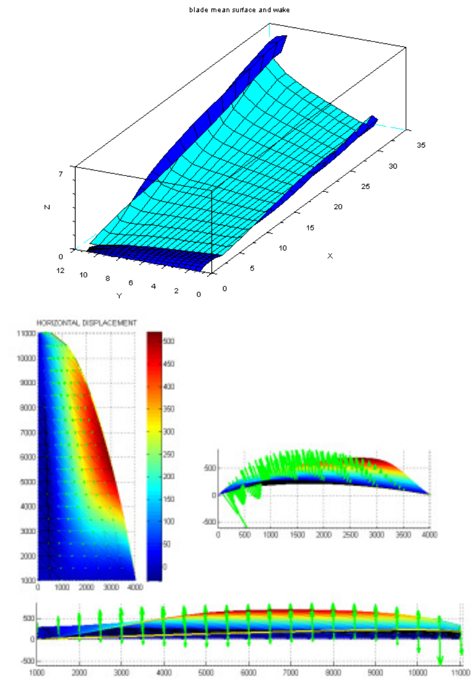

Fig. 14 - Final wake and deformed shape

When considering unsteady calculations, the quasi static approach cannot be used, and an Arbitrary Eulerian Lagrangian (ALE) approach becomes necessary. In this fashion the mesh deformation velocity is introduced, which is necessary in order not to neglect the convective term variation within the spatial derivatives: $\frac{df}{dt} = \frac{\partial f}{\partial t} + v \cdot \nabla f$. Detailed development of ALE techniques can be found in [24, 25].

5 WORK IN PROGRESS:

Much work is to be done in the fluid domain. Mesh sensitivity and calculation's instability was widely experienced in the present analysis. In the near future some new calculations will be compared with experimental results [14] performed on full scale three dimensional wind tunnel models. In this case the flow is expected to be completely turbulent, due to model fittings and the surface roughness. When this is done, investigations will be carried out on spinnaker type geometries. It is intended, that the analysis will start from simplified plane or cylindrical geometries, where it is possible to get experimental results for validation.

Measurements of a spinnaker's flying shape are generally not available, but effective data are expected to be available, courtesy of the University of Southampton's Wolfson Unit for Marine Technology and Industrial aerodynamics.

When sensible CFD analysis will be settle down, the use of an OpenSource software will be investigated, for instance OpenFoam. It is intended

that this would provide the possibility to access in a more flexible way all data fluxes necessary for coupling.
From a structural point of view investigation will be carried out with MITCNL shell elements, in order to assess the behaviour of such elements for a sail geometry. In particular, wrinkling capabilities will be observed. This is particular important for spinnakers, where tensions concentrations over seams cause important wrinkles.

At the present stage, MITCNL elements are isotropic. In order to model both upwind and downwind sails an orthotropic constitutive relationship will be necessary. Further, the analysis will consider the variable amount of reinforcement within different zones of the sail and all the sail fittings as reinforcements and cables on the sail's leech.
Experiments on sail materials have been performed in the past [4, 26], but since the rapid development of new fibres, those data will need some update in the future.

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