Advances in sailing yacht performance analysis and optimization

PROGRESSI NELL'ANALISI PRESTAZIONALE E OTTIMIZZAZIONE DI YACHT A VELA

L'analisi numerica e l'ottimizzazione di uno yacht da gara richiede l'integrazione di sistemi CAD, codici CFD, generatori di mesh per trattare problemi altamente non lineari con un elevato numero di variabili, senza tralasciare i fondamentali aspetti dell'aerodinamica.

In questa prospettiva modelli CFD sempre più accurati e VPPs (Velocity Prediction Programs) vengo utilizzati dai progettisti per una stima delle prestazioni delle imbarcazioni.

ES.TEC.O. ha svolto un intenso lavoro di ricerca in questo campo, per sviluppare strumenti all'avanguardia che possano essere disponibili anche come web service per piccoli uffici di progettazione. Questo articolo presenta due esempi tecnici (studio delle forma di una vela e VPP) e si chiude con una breve descrizione dei servizi web per progettisti e costruttori di yacht e vele.

The numerical analysis and optimization of a racing yacht is a complex task that requires the integration of CAD systems, mesh generators, CFD codes as well as performance prediction tools. Moreover, in marine applications, the nature of the physical problems is highly non-linear and many variables affect the performance of the system. Various components have to be taken into account: free-surface effects, lifting bodies, laminar to turbulent transition. When we simply consider the aerodynamic analysis of a sailplane, the deformation owing to aerodynamic forces must be taken into account in order to perform the analysis on the so-called "flying shape".

Towing tank and wind tunnel have been used for decades and are still considered the most reliable tools, however, there are some drawbacks. In fact, a boat operates at the interface between two fluids and it is impossible to reproduce the same conditions of the full scale phenomenon on a scale model. There are proven techniques how to convert the measurements taken from models to full scale, however, there is a remaining degree of uncertainty.

Models for the numerical computation of forces may have different accuracy and involve different computational cost depending on the analytic approach used: empirical correlations are fast but require specific tuning, not to be generally inaccurate, whilst CFD models (commonly used by the America's Cup design teams) are much slower but more accurate. The availability of ever faster computers at reasonable prices makes the second option feasible and offers a bright future, even for small and medium-sized design offices.

VPPs (Velocity Prediction Programs) are used by yacht designers to evaluate the performances of boats.

These tools are able to find the equilibrium condition and the optimal trim of the boat, taking into account the effects of all forces acting on the system: hydrodynamic forces on hull and appendages, aerodynamic forces on sails, heeling moments owing to sail force and righting moment of the boat. VPP accuracy is strongly linked to the implemented force models, hence coupling with a CFD code is necessary to achieve good results.

ES.TEC.O. has done extensive research in the yacht design field, to develop cutting edge tools and to make them available, as a web service, even to small design offices. In this article, two research works are presented: the study of a sail flying shape and the development of a time-dependent velocity prediction program. Finally, a brief overview of a web service for yacht designers and sail makers completes the article.

Aero-elastic analysis of sails

The aerodynamic study of the sail exposed to the wind is a very challenging topic for yacht designers. Flying shapes are not easily predictable: performance estimation and sail design are mainly based on experience or costly experimental measurements.

From a physical point of view, this is a classic and well defined aero-elastic problem since the sail shape depends on the pressure loads and on the air flow around sails which strongly influence each other. The numerical problem involves membrane finite element analysis with geometric non-linearities, coupled to CFD volumes finite RANSE models.

The flow is characterized by intrinsic unsteadiness and by massive separation downstream the sails, and sail displacements are influenced by local properties of the material (fabric pattern orientation, sail battens, reinforcement patches). Moreover, as displacements are usually large, the computational grid needs to be updated. It is hence mandatory to provide the CFD solver with a robust algorithm able to deform the mesh accordingly.

At a first stage, the problem was studied only on the CFD side, to verify whether the simplifications introduced make sense from a quantitative point of view.

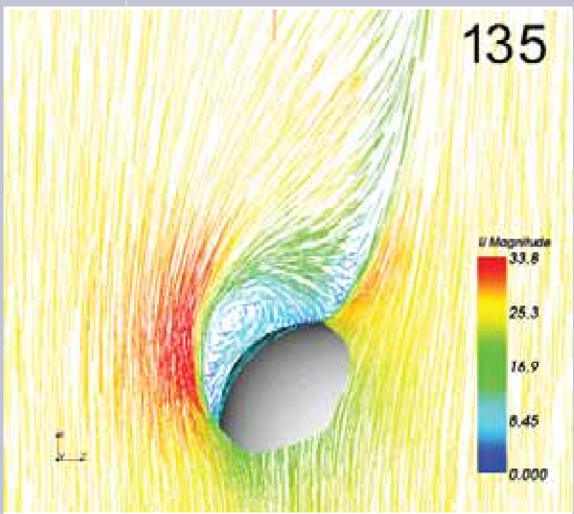

Figure 1: CFD analysis of a rigid spinnaker for validation purposes

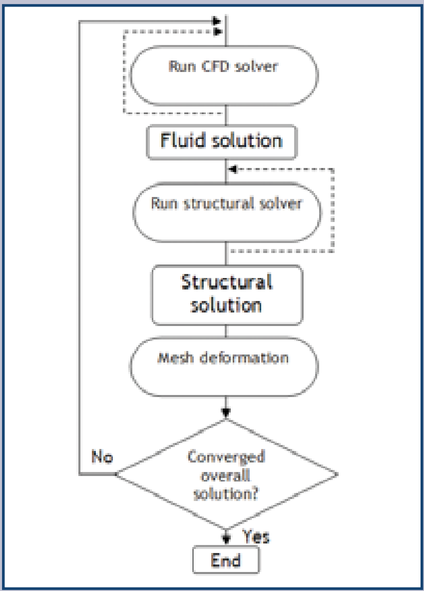

Figure 2: Logic flow of the aero-elastic simulation on sails

For this purpose, results from numerical simulations were compared with experimental data obtained from a study of a rigid spinnaker model in a wind tunnel.
Given the spinnaker rigid, it was possible to address the problem regardless of the structural analysis and of the atmospheric boundary layer which do affect the results on a real spinnaker.

A realizable k–e model was used (inlet turbulence setting based on the honeycomb flow conditioning in the wind tunnel). An industrial code (ANSYS CFX) and an open source code (OpenFOAM) were employed. The results show that in spite of the simplification introduced, the numerical models are able to catch the basics of the flow behaviour apart from the zone where the separation bubble starts increasing in dimensions at an angle of attack around 135 degrees.
In a second phase, the entire fluid structure interaction problem was undertaken by using an ad hoc structural solver for membrane analysis, coupled with a CFD open source code customized to address sails aerodynamic problems (stays, sheets, halyards and masts definition, sail trimming parameterization, calculation of effective sails thrust and heel forces and more). An ALE (Arbitrary Lagragian Eulerian) approach was used.
To verify reliability and robustness of the coupled solvers, an optimization problem was set up.
In this phase, an isotropic and homogeneous material for the sails fabric was used. The aim was to test how the CFD and structural solvers work together rather than testing quantitatively the results.
All computations were run on a 64 cpu Linux Cluster. A queuing system (SGE) + parallel evaluations of designs allowed a profitable use of the computational capacity. The problem consisted in maximizing the overall sails thrust force and minimizing the overall heel sails force, by changing mainsail and spinnaker trimming.
The optimization process was defined and run using modeFRONTIER, through the following steps:

1) the space of the input variables is explored by a full factorial design of experiments;
2) the research area is refined where necessary;
3) a response surface meta-model is constructed, in this way, input variables and output variables are linked by an analytical model;
4) the optimization problem is solved by using the meta-model instead of the coupled solvers;
5) the optimization results are validated running the real solvers on a limited set of optimum designs.

In this way, less than 50 runs were sufficient to solve the problem.

Time dependent velocity prediction program

The dynamic behaviour of a yacht represents complicated phenomena. There are unsteady features which govern both, the hydrodynamic and the aerodynamic forces and moments. Nevertheless, there is a strong demand for understanding these phenomena, and for developing means that correctly predict them. For example, as regards racing yachts, it is important to reduce tacking and gybing time losses, and to better accelerate under gusty wind. Presently, one can assess (at least partially), unsteady performances by doing tank tests, or CFD simulations. Unfortunately, both techniques are very expensive, time consuming, and, in some cases, still in an early development stage.
The idea underlying the development of the dynamic model presented here, is to build a tool that focuses on the global dynamic behaviour. Thus trying to assemble all forces and moments that act on the sailboat system, although sometimes, only roughly approximated. The solution time for such an approximate global model is very fast, so that is could be used in real-time simulations on board, or for sailboat-simulators.
The aim of the research project is to develop a complete and flexible platform for dynamic analyses and performance prediction, useful not only for research but also for yacht design activities. The tool is integrated into an optimization scheme, demonstrating how certain interesting, typically unsteady phenomena could be investigated for better performances.
As an example of usage of this model, an optimization scheme was implemented. Given the possibility to
evaluate the dynamic behavior of the yacht, it is interesting to optimize the tacking maneuver. In the present model, there is no fine control over the sails performances, which are governed by the steady aero coefficients. What can be done in order to modify the behavior during the maneuver, is to change the rudder history.
The performance prediction tool was integrated within the modeFRONTIER optimization platform. The tack

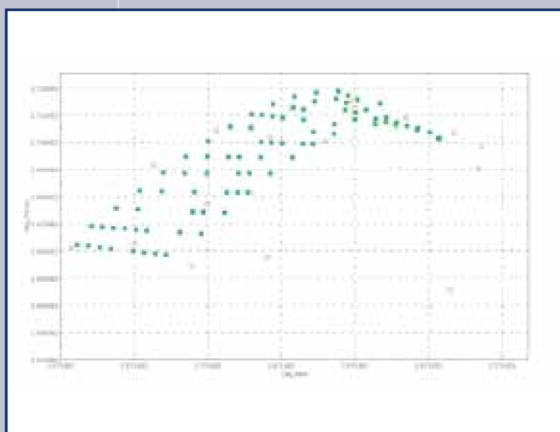

Figure 3: modeFRONTIER optimization of sail trimming - Scatter chart

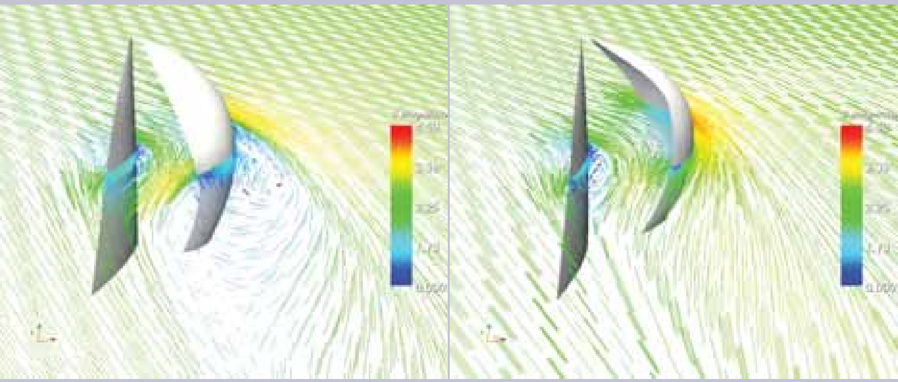

Figure 4: Initial VS Optimized sail trimming

maneuver is divided into three parts: an initial one, where the boat is governed by the control system (autopilot), keeping the course at a specified true wind angle. A central part where a motion law is assigned that controls the rudder angle during tack. The final phase then begins after tacking, where the boat accelerates, controlled again by the autopilot which steers the yacht at the same true wind angle of the first part, but on opposite tacks. A long time interval is considered (260 sec), in order to properly take into account the acceleration of the boat after the tack. The motion law imposed to the rudder angle is defined by a spline curve. This curve has five control points, which are positioned at five chosen, fixed time instants. The objective function is what we call Displacement

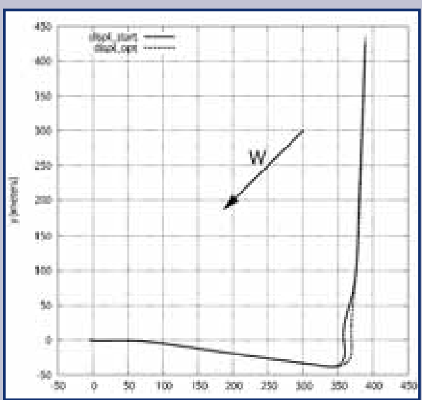

Figure 5: Boat tracks of initial and optimized tack

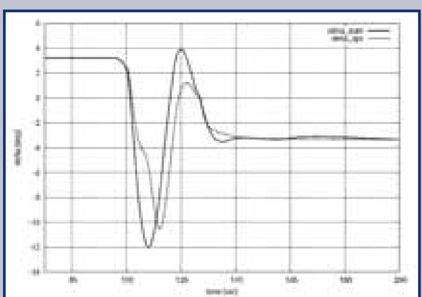

Figure 6: Rudder angle history of initial and optimized tack

Made Good (DMG), this is the distance sailed in the wind direction during a predetermined time interval. The optimization process looks for the maximum of the objective function. This was implemented within modeFRONTIER by defining a proper workflow (in-out variables, objective function, constraints, logic flow) and writing a series of scripts in order to run the simulation for each design candidate automatically.

The Multi Objective Genetic Algorithm has been used, starting from an initial population (Sobol DOE) of 16 designs and evolving for 100 generations, for a total number of 1600 designs tested. The total time of simulation was about 12.5 hours on a laptop PC. The difference in terms of objective functions from the maneuver used as starting point, determined reliable by the authors after analysis of the experimental data, and the final optimized is about 8 meters. This distance is more or less one boat length, when projected along the upwind yacht course, and represents a significant gain.

Sail4web, a web service for yacht designers and sail makers

In spite of the growing accuracy of CFD of the flow around hulls and sails, numerical analyses are not used, in a systematic way due to high cost of the software, with respect to the value of the product, and because of the complexity of the simulation process which requires different and specific knowledge.

ES.TEC.O. is implementing an on-line portal to provide yacht designers and sail makers with a tool that allows small and medium-sized companies to use numerical methods for fluid field prediction in an easy and reliable way. The service, named Sail4web, consists of three parts (free surface flow simulation around hulls and appendages, aero-elastic analyses of the sail plan and a Velocity Prediction Program (VPP)) that can be combined in various ways and according to the requested accuracy of the solution. At this stage of the development, a classical steady VPP is implemented and available online for registered users (www.sail4b.com). Further developments will include other modules for CFD simulations and the integration between CFD analyses and performance predictions.

References

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Authors' contacts:

Matteo Ledri
Rosario Russo
Mauro Poian
info@esteco.com
ES.TEC.O. srl Headquarters, Trieste – Italy
www.esteco.com
Enrico Nobile - nobile@units.it
University of Trieste - Italy

Figure 7: Sail4web screenshot – VPP polar plot