Foiling A-Class Catamarans
Application of Cutting-Edge Technologies to Improve Sailing Performance

Multi-objective optimizations, combined with experienced aerodynamic design, is the most efficient strategy to face challenging designs as the improvements of fast foiling catamarans performances in regatta

"Foiling" is the term used to describe a condition in which a sailboat is lifted up from the water by lifting surfaces. The solutions adopted in the last America's Cup class catamarans gave a strong impulse to the evolution of smaller multihull classes. The A-Class catamaran has benefited from these experiences and have shown significant improvements in the last few years.
The A-Class is a small high-tech catamaran that is considered the fastest single-handed racing dingy in the world. It has very simple rules that stimulated a continuous technological evolution during the years. Figure 1 compares an old 90's A-Cat (top) with the winner of the world championship 2016 (Figure 1).
In 2009 new rules were introduced with the (vain) attempt to penalize flying configuration. The result is to make the foil dimensioning a strongly constrained design problem for which efficient implementation of multi-objective optimizations might represent the key strategy to design configurations able to broaden the range of sailing conditions in which flying boats are faster than conventional ones.


Figure 1 – Evolution of A-Cat in the last 20 years

The study here reported focuses on the geometric parameterization strategy, adopting a mesh morphing technology based on Radial Basis Functions (using the tool RBF Morph), and on its integration within a multi-objective optimization environment (managed by modeFRONTIER).

Geometric parameterization
The geometric parametrization based on RBF mesh morphing consists in implementing shape modifiers, amplified by parameters that constitute the variables of the problem, directly on the computational domain. New geometric configurations are obtained imposing the displacement of a set of mesh regions (e.g. walls, boundaries or discrete points within the volume) by using algorithms, based on RBFs, that are able to smoothly propagate the prescribed displacement to the surrounding volume. This approach offer several advantages: there is no need to regenerate the grid, the robustness of the procedure is preserved, its meshless nature allows to support any kind of mesh typology and the smoothing process can be highly parallelizable. The morphing action, furthermore, can be integrated in any solver offering the very valuable capability to update the computational domain "on the fly" during the progress of the computation.

The definition and the execution of a morphing action is, in RBF Morph, completed by three steps:

setup – it consists in the manual definition, from the program GUI, of the domain boundaries within which the morphing action is limited to, in the selection of the source points where fixed and moving mesh regions are imposed, and in the definition of the required movements of the points used to drive the shape deformation;

fitting – during this process, the RBF system, derived from the problem setup, is solved and stored into a file ready to be amplified. This operation has to be performed only once for every RBF problem. Stored RBF solutions are very light (in terms of files dimension) compared to storing all the created morphed mesh;

smoothing – the smoothing action (surfaces and volumes morphing according to arbitrary amplification factors) is first performed applying the prescribed displacement to the grid surfaces and then smoothly propagating the deformation to the surrounding domain volume. It can be performed combining several RBF solutions, each one defined by a proper amplification factor, to constitute the parametric configuration of the computational domain.

Figure 2 reports an example (in this case applied to the sail of an A-Cat) of an RBF problem setup.

RBF implementation and constraints definition
A-Class rules state that all foils have to be inserted from the top of the hull (to prevent the adoption of T-foils) and that the minimum distance between the tips must always be larger than 1.5 m (to limit the span of surfaces contributing to the vertical lift). The maximum beam of the boat, including appendages in all positions, must be lower than 2.3 m. In order to insert the foils, furthermore, a minimum value of the angle δ, assuming L-shaped foils, is required (Figure 3).

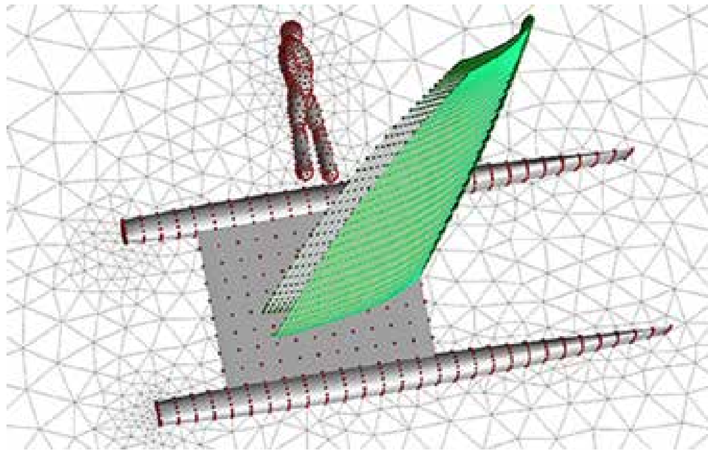
Figure 2 – Fixed (red) and moving (green) source points of an RBF setup

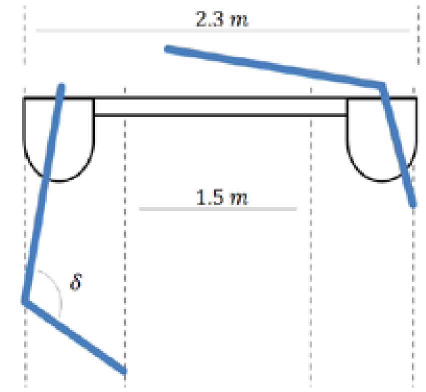

Figure 3 – Scheme of foils constraints

The reference geometry, that has been made parametric for the optimization, was generated by two straight segments smoothly blended in the junction region. The connection with the hulls is located at the external side and both inner and outer segments are oriented inboard. The foils segments are generated by a straight untwisted extrusion of the well-known NACA 63-412 laminar airfoil. The inner section is assumed to have a constant chord while the outer is tapered.
Seven shape modifiers have been setup: four to control lengths and angles of the foil segments (Figure 4), one to set the chord of the inner segment, one for the taper ratio of the outer segment and one to control the foils sweep angle. The last parameter is not exactly a shape parameters. It is a trim that has a direct effect on the horizontal angle of incidence of the foils. Its morphing action is implemented as a rotation of the foils along an axis perpendicular to

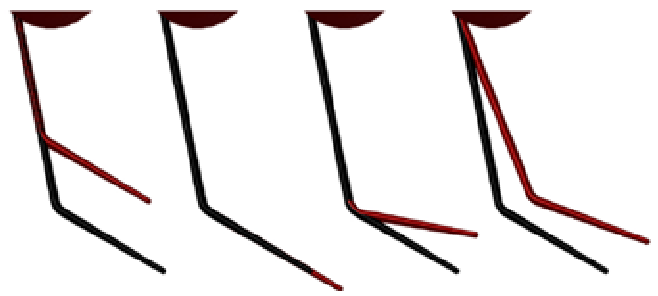
Figure 4 – Foils front shape modifiers

Figure 5 – Planform shape modifiers

the boat symmetry plane and passing near the hull/foil junction. The morphing actions are applied in sequence and limited to a volume surrounding the foils region.

Setup of numerical configuration

The operative conditions of sailing boats appendages depend on the equilibrium of the forces and moments acting on the system. To define the design conditions of the A-Cat foils, some simplifications has been, however, adopted. The equilibrium of vertical forces is assumed to be mainly dominated by the weight of the boat and the crew. The modulus of the other components, derived from the 6DoF equilibrium, varies in a range that is, in general, smaller than the range of possible crew weight. It is then considered acceptable, for design purpose, to assume a fixed target vertical component of lift to be generated by the foils. Similar assumptions are accepted for the side force since it is mainly limited by the maximum righting moment generated by the helmsman at the trapeze (for a fixed known centre of buoyancy and height of the sail centre of effort). The task is to identify the shape of the foils that, while respecting the imposed constraints and generating the required lifting force, minimize the drag. The selected variables of design were:

1. total foil draft;
2. outer segment cant angle (angle δ of Figure 3);
3. angle of the inner segment respect to vertical;
4. inner segment chord (at constant thickness);
5. outer segment taper ratio;
6. foils sweep angle.

The amplification factors of the RBF solutions are defined combining the design input variables in order to fulfil the constraints imposed by the class rules (e. g. when the cant angle δ is modified, the outer segment is scaled according to an amplification factor that recover the limits reported in Figure 3).

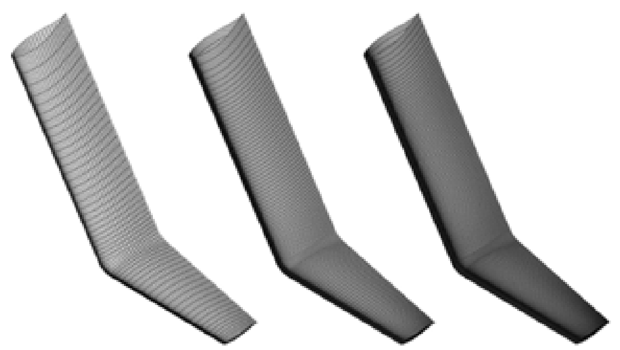

Figure 6 – Surface cells clustering for the three levels of grid

A multi-block structured hexahedral mesh was generated modelling a domain extended up to ten meters upstream and downstream the foils. Three levels of grid were generated (Figure 6) with the aim to evaluate the sensitivity of the solution on the grid dimension. The size of coarse, medium and fine meshes were approximatively 1, 7.5 and 25 millions of cells.

Figure 7 reports the solutions obtained, on the baseline geometry, with the three meshes in downwind configuration (VOF analysis trimming the sinkage to maintain the vertical lift component unchanged). The difference between the drag obtained with the coarse grid and the drag obtained adopting the fine mesh is in the order of 5% while the adoption the medium grid leaded to a difference limited to half percent. The coarse mesh was the one used in the optimization procedure.

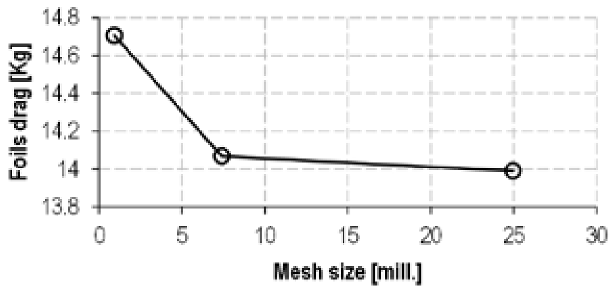

Figure 7 – Solution of the grid sensitivity to dimension

Steady incompressible computations, using a volume of fluid (VOF) technique to model the two-phases (air and water), were setup for the downwind analysis. The boat was assumed to sail at a heeling angle of five degree and at a speed of 15 knots. The sinkage was iteratively trimmed to define the attitude that generates the target vertical force. The total displacement was assumed equal to 170 Kg (empty boat weight plus crew). Considering around 30% of this value to be generated by the T-foils of the two rudders, the main foils were then assumed to contribute with the generation of 120 Kg to the sustainment of the boat. The operative leeway, that should be defined from the global equilibrium of forces and moments acting on the boat, was, here, kept fixed to 3 deg. The proper estimation of its value would have, in fact, significantly increased the computational burden since it requires to introduce an additional degree of freedom. The balance between the additional computational cost and the impact this simplification is expected to have on the optimization trend fully justifies, in our view, this choice.

The analysis in upwind sailing was performed at a speed of 10 knots and at a fixed attitude maintaining the computational domain unchanged. One hull is flying while the other one is floating and contributing to the sustainment. A single phase CFD analysis was setup assuming the top inviscid wall boundary of the domain (which, in order to partially account for hull/foil junction interference effects, includes a shape similar to the immersed hull) to represent the water free surface considered as planar (Figure 8). This simplification force to neglect effects as ventilation or hull boundary layer interference introducing uncertainties on the solution. It is, however, considered acceptable, for optimization purpose, since the aim to estimate the drag difference between candidate solutions is prevalent on the necessity of an accurate definition of the absolute value of drag. The missing drag component of the hull is recovered by an analytical formulation developed by a comparison with a matrix of CFD solutions obtained on the isolated demihull at several attitudes and displacements. The lift fraction obtained subtracting the lift generated by the foils from the boat operative displacement is used to feed the hull analytical drag model, whose output is added to the foils drag fraction to estimate the total drag. The accurate evaluation of the leeway angle is considered to be important in upwind sailing and adjusted by changing the inflow direction on the far field boundaries. Its operative value is estimated performing two preliminary analyses at two angles and then linearly extrapolating the final leeway angle at which the candidate geometry should generate the required target side force. If the target side force is not generated at the expected angle, the selected configuration is rejected because it does not perform in the linear region of the aerodynamic lift polar. The target side force (in our case defined equal to 70 Kg) was estimated from the equilibrium of moments around the sailing direction.

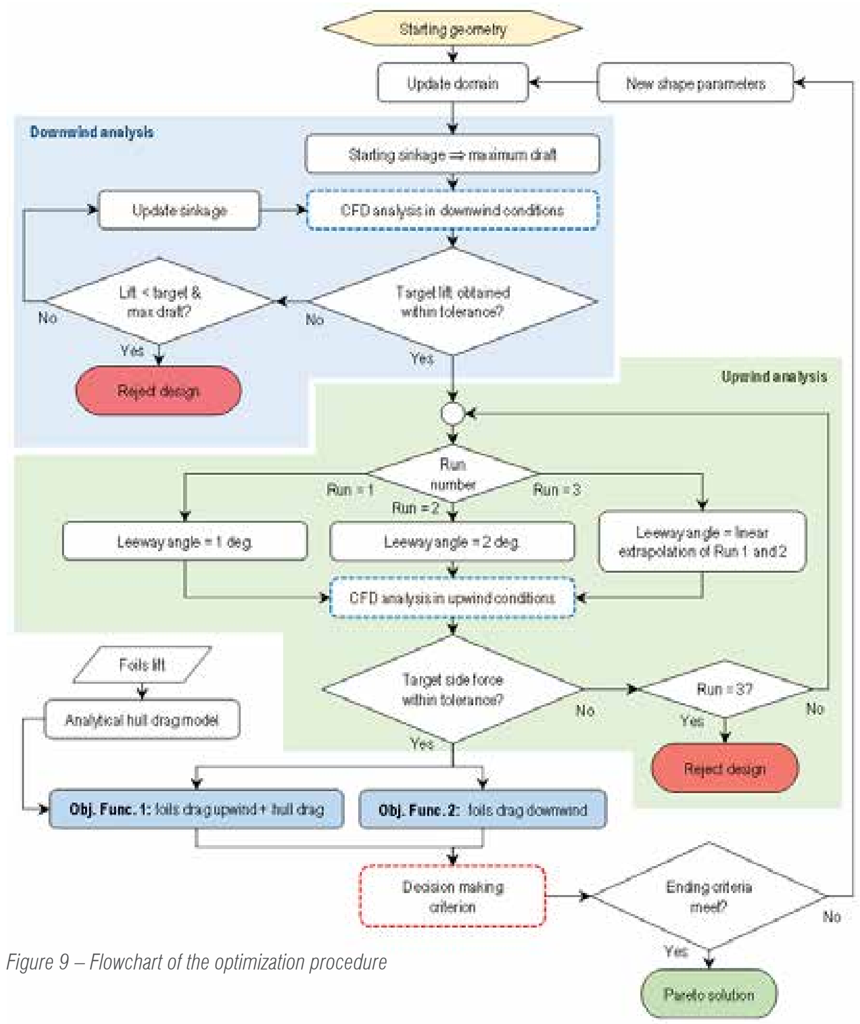

Figure 9 – Flowchart of the optimization procedure

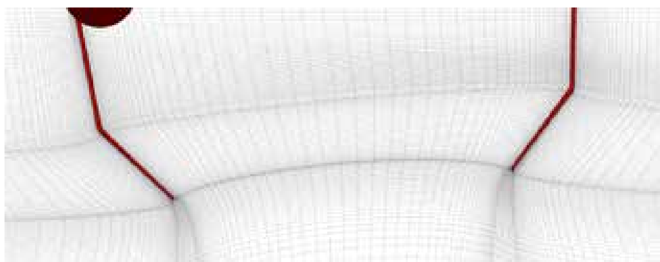

Figure 8 – Detail of the computational domain

Optimization procedure

A two-objective optimization procedure was setup. The defined targets were the minimization of the hydrodynamic drag of the boat, excluding the rudders, in upwind and downwind sailing conditions. The workflow implemented followed the scheme reported in Figure 9. The starting reference geometry is updated each cycle, by the morphing procedure described above, according to the design variables selected by the decision making criterion. The candidate evaluation is managed by a script procedure written in Scheme language. The analyses in the two sailing conditions are performed in sequence. The upwind analysis is run if the downwind analysis was successful. In downwind sailing the boat is expected to be fully lifted up from the water by the foils. Configurations not able to generate sufficient lift are rejected. In upwind sailing, the boat is only partially sustained by the foils. The drag component of the hull, to be summed to the foils drag in the objective function, is evaluated including in the modeFRONTIER environment a node that executes the analytical hull drag model developed in form of a Scilab function. The optimization algorithm adopted was the MOGA-II, a proprietary version of the Multi-Objective Genetic Algorithm.

Solutions

The time elapsed to complete the evaluation of one valid design, using the coarse mesh, ranged between 15 and 20 minutes on a workstation equipped with 20 CPU. The time required for the morphing action was less than two minutes. More than 400

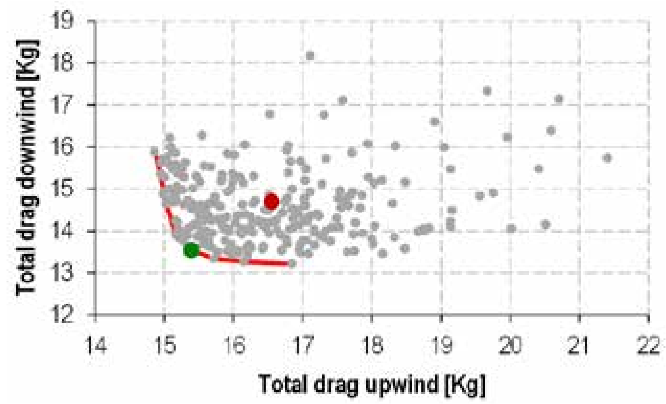

Figure 10 – Pareto solution of the final two-objectives optimization

evaluations were performed in three days. Among them about 40% of the design candidates were rejected because of failure in the minimum lift requirement criterion. The solution obtained is reported in Figure 10. The green point on the Pareto front is the optimum solution which was considered the best compromising design. The red circle refers to the starting baseline geometry which was built roughly referring to existing designs. The estimated drag reduction in upwind sailing is 7% (hull plus foils) while in downwind is 7.9%.

The selected optimum was verified in downwind conditions (only) using the fine mesh adopted for the grid sensitivity evaluation. The RBF solutions were applied to the fine baseline grid (the method is meshless) to obtain the fine mesh of the optimum geometry. The analysis also allowed to verify if the evaluation of the improvement is confirmed. The results of this verification is summarized in Table 1. The improvement was overestimated by only 0.24% confirming the coarse grid, despite the lower absolute accuracy it involves, to be suitable to correctly drive the optimization process toward the optimum.

Table 1 – Performance improvement verification of the selected optimum

Mesh	Baseline Kg	Optimized Kg	Drag reduction %
Coarse	14.7	13.54	7.89
Fine	13.99	12.92	7.65

Conclusions

A design procedure, based on multi-objective optimization, has been presented. The core of the method is the parameterization of the geometry implemented by a mesh morphing technique based on Radial Basis Functions. The foils of an A-Class catamaran have been optimized at two sailing conditions. A multi-objective optimization, using genetic algorithms, was setup within the modeFRONTIER environment. The analysis of candidates was implemented by a script procedure executed within the ANSYS Fluent CFD solver. The target of design was the minimization of drag in the two operating conditions.

An important conclusion concerns the evaluation of the geometric parameterization strategy. Strongly constrained configurations usually require the adoption of a CAD based procedure in order to gain the required flexibility in implementing shape parameters and constraints. The mesh morphing setup, by using RBF Morph, implemented in this work demonstrated its capability to face complex and strongly constrained parameterization problems providing the possibility to exploit the several advantages associated to a mesh morphing approach (no re-mesh required, high robustness, high parallelizability, meshless properties). The possibility to combine several RBF solutions and to define each amplification factor according to any formulation able to account for external constraints offer large flexibility in setting up complex combinations of shape parameters. The high parallelizability feature, furthermore, extend the potentiality of the method providing the possibility, within HPC environments, to setup optimization configurations that involve large computational domains. The workflow, furthermore, showed to be very robust. The rejected solutions concerned only designs not able to fulfil the requirement of sustain the boat in downwind sailing.

The optimization process led to a Pareto front on which a compromising design, that improved the performance of a reference geometry by 7% in upwind conditions and by 7.9% in downwind, has been selected. The starting geometry was generated roughly referring to existing designs. Further margin of improvements might be explored enlarging the design variables space and including the a irfoil in the optimization process.

In order to speed up the process, a very light mesh (less than one millions of hexahedral cells) was used in the optimization workflow. It was, however, observed a difference in the estimation of the performance improvement of the selected optimum, comparing the percentages of drag reduction computed using the coarse with a very fine grid, of only 0.24%, indicating the adoption of a so coarse mesh to provide a very efficient compromise between computational costs and optimization trend evaluation.

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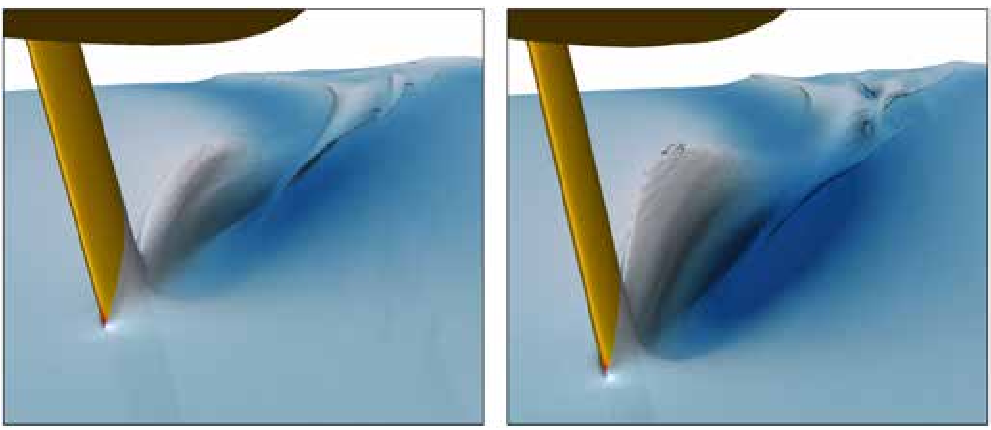

Figure 11 – Free surface in downwind sailing by baseline (left) and optimum (right)