Optimization of 3D Hydrofoil Using a Cavitating Lifting Line Method

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Ing. L. Dipilato[1], Ing. M. Farnesi[1], Ph.D. C. Ramirez[2], Ing. B. Pineiro-Aramburu[2], Ph.D. R. Lanos[2]
Ing. T. Gaudiot[2] and Prof. G. Lombardi[3]

[1] CUBIT s.c.a.r.l., 56023 Navacchio, Cascina (PI), Italy. Web: http://www.cubitlab.com

[2] Syroco, 13002 Marseille, France. Web: http://www.syro.co

[3] Dept. of Civil and Industrial Engineering, University of Pisa, 56122 Pisa, Italy.

ABSTRACT

Cavitation is a complex phenomenon that inevitably takes place in high-speed foiling. As such, designing a hydrofoil specifically for supercavitation is mandatory when striving for high speeds, but doing so with common engineering tools is slow and inefficient. To achieve the World Sailing Speed Record, Syroco and Cubit had to research more advanced and faster tools and processes to design the most efficient foil for the sailboat that will be used for the world record.

Initially, the optimization of a high-efficiency 2D supercavitating profile was performed using an optimization loop that used an efficient Finite Volume Method (FVM) simulation setup for hydrodynamic performance evaluation coupled with structural Finite Element Analysis (FEA). However, despite the optimized FVM setup, a 3D optimization loop with 3D FVM simulations is unfeasible because of the prohibitive computational costs of 3D FVM. For this reason, ways to bypass 3D FVM have been explored for an optimization loop able to study and optimize 3D wings.

This article introduces a new method for optimizing 3D supercavitating foils using a custom lifting line code called the Cavitating Lifting Line (CLL). The CLL accounts for cavitation nonlinearities and provides results with significantly reduced computational time compared to optimized FVM setups. This accelerated approach enables multi-level optimization, considering hydrodynamic, structural, and feasibility constraints, and allows for convergence towards the most efficient design. Our method represents a breakthrough in efficient optimization for high-speed sailing foils and has potential applications in other fields requiring 3D hydrodynamic optimization.

Keywords: Foil; optimization; cavitation; lifting line method; FVM.

1. INTRODUCTION

Designing a high-performance speed craft, aiming to set the World Sailing Speed Record, is a challenge that requires optimization procedures with innovative approaches that can obtain the desired performances while coping with computational costs and component feasibility.

In the context of the speed record, different optimization loops have been carried out in Syroco. Previously, an optimization of the 2D profile as described in Farnesi (2021) was carried out using an Finite Volume Method (FVM) solver for hydrodynamic performances and a Finite Element Method (FEM) solver for structural validation. Although an optimized setup was achieved (Mariottini, 2023), it was clear that Computational Fluid Dynamic (CFD) with FVM would become a bottleneck for 3D optimization.

For this reason, a lifting line code that takes into account the effects of cavitation has been developed. Some previous explorations on the subject were carried out by Vernengo (2017), showing the potential of the method for supercavitating hydrofoils. The code that was developed uses a modern approach to lifting line codes, implementing methods as described in Phillips (2000), to efficiently tackle the problem of solving the lifting line problem for arbitrary wing shapes.

The resulting method proves to be effective for preliminary design and shows good coherence with higher fidelity methods, making it a good candidate for optimization evaluation.

This paper describes the development of an optimization method that uses the lifting line code for hydrodynamic evaluation to achieve an exponential speedup compared to 3D FVM optimized setup, allowing for a more elaborate and accurate optimization loop.

2. OPTIMIZATION LOOP ARCHITECTURE

The present optimization loop consists of four key components: an optimization algorithm, a design generator, a performance evaluator, and a constraint evaluator. modeFRONTIER is used to manage the software and execute the optimization algorithm.

The design generation is handled with a Python script, using a custom wing parametrization that uses b-spline curves to describe the leading edge and trailing edge of the hydrofoil, as well as other macro-parameters, to allow for a detailed geometry description without introducing unnecessary parameters that can make the design space size blows up.

The performance evaluator needs to evaluate the efficiency of a given design which is then used as the optimization objective. As previously mentioned, 3D FVM simulations for supercavitating wings are prohibitively expensive, and therefore inefficient within an optimization procedure. For this reason, a custom lifting line code able to account for supercavitation was developed to accelerate the exploration of the design space.

Finally, regarding the constraint evaluator, we are interested in manufacturing feasibility, which can be easily checked for with a Python script, and structural feasibility. Usually, as in Farnesi (2021), Finite Element Analysis (FEA) would be used for this kind of scenario. However, since FEA is orders of magnitude more expensive than the lifting line code used, a custom bending equation solver was used to evaluate structural feasibility to avoid being the bottleneck for the optimization loop.

2.1 **Performances Evaluation: Cavitating Lifting Line**

The lifting line code developed, called Cavitating Lifting Line (CLL), is based on the Viscous Lifting Line described by Vernengo (2017), and has been improved to take into account additional supercavitating profile data.

The lifting line implementation is mostly implemented with numerical methods described by Phillips (2000), which involves calculating the effect of each horseshoe vortex in the panel discretization of the wing onto specific collocation points distributed along the wing, forcing the no-penetration condition on those points.

The lifting line equation is solved iteratively, and the position of the collocation points is updated depending on the performances of the 2D section with a similar approach to Vernengo (2017), eventually converging to a specific position distribution.

Once this inner loop converges, the bound vortex shape is adjusted to the current effective angle of attack distribution, and the inner loop is run again. This outer loop is repeated until the bound vortex shape converges, which improves the accuracy of the method for more irregular wing shapes.

The performances are then evaluated by integrating the lift spanwise to obtain the total lift of the wing, while drag is computed as the sum of "viscous drag" (i.e., the drag from 2D section hydrodynamic characterization) and "induced drag" (i.e., the component of lift that is projected in the flow direction due to the induced angle of attack).

2.1.1 Characterization of 2D Profiles

The CLL requires knowledge of the hydrodynamic performances of the 2D profile employed for the hydrofoil to compute the profile's performances used for the lifting line calculations, and thus it's necessary to compute with 2D FVM the performances of the profiles used in the CLL.

As an example, Figure 1 shows the lift coefficient as a function of the angle of attack of a generic supercavitating airfoil.

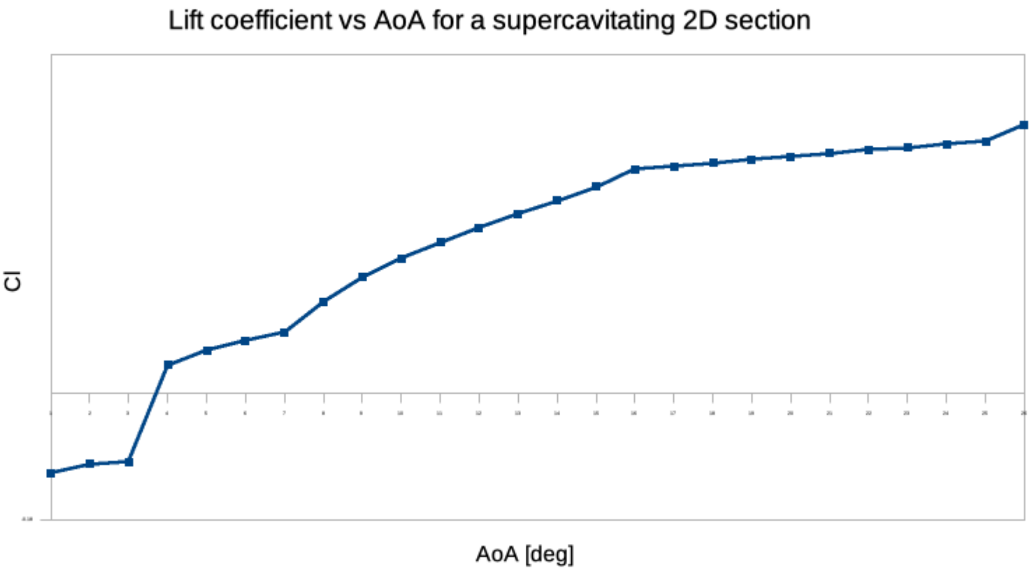

Figure 1: sample curve of lift coefficient vs. angle of attack

The curve can be thought of as a piecewise linear function and therefore can be represented with acceptable precision using a small number of points. However, in order to properly describe the transition zones, the position of the changes in slopes is necessary. To ensure the zones of slope change are properly described, 20 computational points have been run to describe the performances of the profile, using an uneven distribution to increase the resolution where the slope change is expected.

With 20 points per profile, it was required to detail a cost-effective but precise procedure, so that the CPU time saved using the CLL was not used by the profile characterization. In the same way, it was considered important to design an automatic procedure that would allow efficient feeding of the database in the future.

The Rayleigh-Plesset cavitation model, which implements the full Rayleigh-Plesset equation for cavitation, is considered to be the most accurate, but is expensive as it requires a very fine time step to converge, and some numerical oscillations can make the setup diverge, making it unreliable for automatized characterization procedures.

For this reason, the cavitation model described in Singhal (2002), denoted "Singhal cavitation model", has been adapted for use in Star-CCM+, and after tuning the setup to the new cavitation model we found a strong agreement in the results among the two cavitation models with a computational time reduction to about 20% of a Rayleigh-Plesset setup.

The Star-CCM+ implementation of the Singhal model is slightly more expensive than the basic Rayleigh-Plesset implementation, but it has a much weaker dependence on strong time derivatives, typical of the first timestep of a simulation, meaning that it can allow for an overall smaller timestep and absorb numerical oscillations with more ease than Rayleigh-Plesset, making it overall more stable and less expensive. (Incerpi, V. (2021)

2.1.2 3D Validation of the CLL

To validate the operation and accuracy of the CLL tool, a comprehensive validation campaign was carried out. The objective of this campaign began by verifying that the CLL could correctly predict the behavior of a sub-cavitating wing and then was extended to verify the behavior of a supercavitating wing in both sub-cavitating and supercavitating regimes.

For this last stage, the results obtained with FVM of different wing shapes previously designed in the context of the speed record were used. From this comparison, the results were coherent and in agreement with the FVM results.

As an example, Figure 2 shows the geometry of two wings tested with both FVM and CLL with different aspect ratio. The comparison in the behavior prediction obtained for each of the wings, for four different angles of attack, by the two methods, is shown in Figure 3 and Figure 4, respectively.

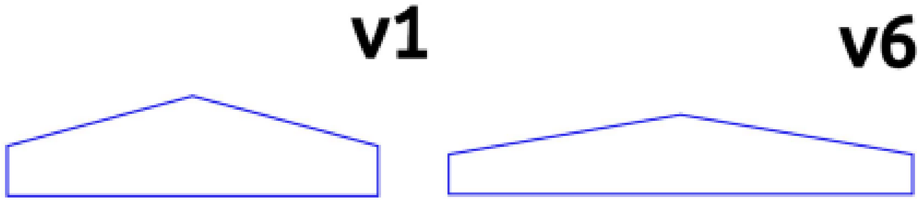

Figure 2: test wings used to measure the effects of aspect ratio

As can be seen, there’s a slight offset in the values predicted by the CLL and the FVM simulations, but they are consistent (errors under 5%) and get increasingly accurate towards high lift coefficient angles (i.e., supercavitation), which is where the efficiency is at its highest and thus near the optimization target, increasing accuracy near the global optima. (Dipilato, 2022)

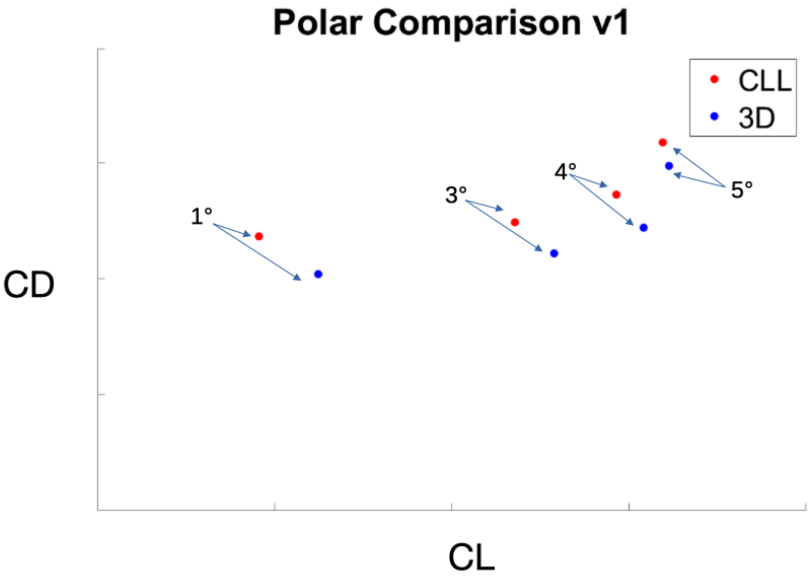

Figure 3: polar curve for v1 wing, low aspect ratio. Each point corresponds to a different angle of attack.

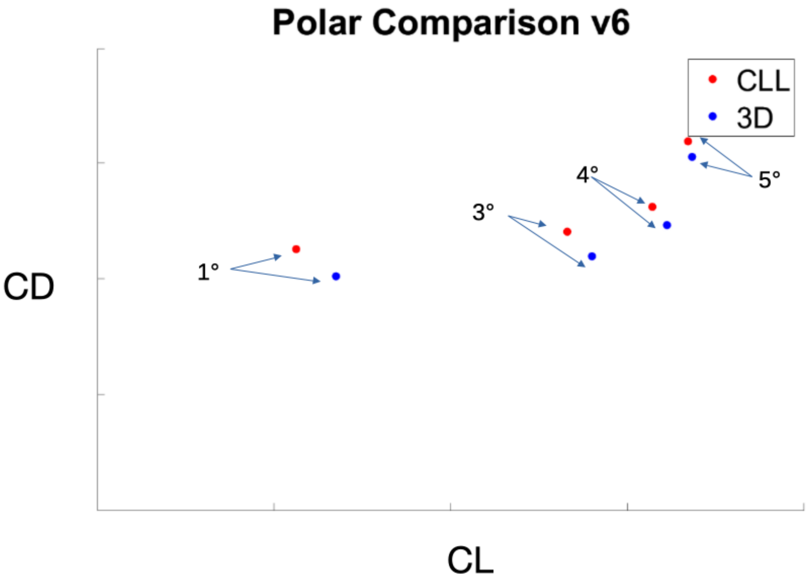

Figure 4: polar curve for v6, high aspect ratio. Each point corresponds to a different angle of attack.

2.2 3D planform parametrization

To describe the planform of the 3D hydrofoil and optimize it efficiently, the number of parameters has been minimized. All those parameters have been adimensionalized by the span.

The parameters used during the various optimizations are as follows:

- Planform parameters that changes the planform of the foil, the wing is assumed at first of constant
    - b : span of the foil

  - c_r : chord at the root of the foil, expressed as a percentage of span b ($\frac{c_r}{b}$);
  - $\lambda = \frac{c_t}{c_r}$: Taper: defined as the ratio between the tip chord (c_t) and the root chord;
  - Leading edge : b-spline defined with one control point and two parameters, tension ($\boldsymbol{\tau}_{LE}$) and tangent angle ($\boldsymbol{\alpha}_{LE}$) at the root of the spline;
  - Trailing edge : b-spline defined with one control point and two parameters, tension ($\boldsymbol{\tau}_{TE}$) and tangent angle ($\boldsymbol{\alpha}_{TE}$) at the root of the spline;
  - Λ_m - Sweep: sweep angle measured as the angle of the line from the leading edge at the root and the leading edge at the tip;
- "3D" parameters that have effects on the wing geometry in 3D
  - AoA : Angle of attack of the foil;
  - Twist distribution around the leading edge;
  - Dihedral distribution along the span;

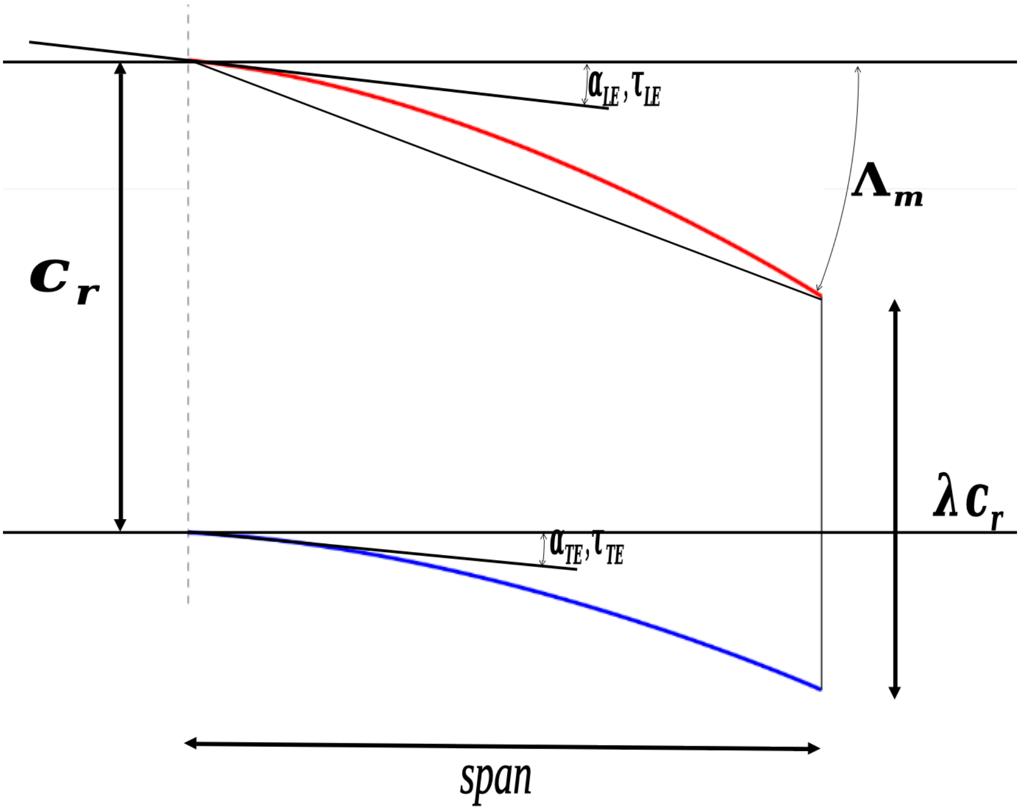

Figure 5: Wing parametrization

2.3 Structural Evaluations: Bending Equation

As shown in Farnesi (2021), a profile that will achieve good performances in the supercavitating regime often consists of a very thin design that has poor structural strength.

Similarly, the design of a 3D wing must be carefully verified in structural terms. For example, high aspect ratio wings are generally more efficient than low aspect ratio wings but have much worse structural performances. An uncontrolled optimization procedure will generate wings that are structurally unfeasible.

To evaluate the structural performances of the wings during the optimization, a bending equation solver was implemented that takes as input the properties of the profile, the geometry of the wing, and the load conditions as exported from the CLL, returning the expected displacements and stresses, to check against the properties of the material used for the wing.

Although the bending equation is not as accurate as a full FEA, the validation of the optimization procedure showed that this structural prediction is sufficient to establish a constraint criterion in the design of a 3D supercavitating wing. In this way, infeasible wings are quickly discarded, without this stage becoming a bottleneck in the optimization procedure.

2.4 Optimization Algorithms: modeFRONTIER

modeFRONTIER is the coordinator of the optimization process that is used in this work. Acting as the unique control module it allows the coordination and interaction of the different required tools. While the optimization algorithms are running, modeFRONTIER handles the execution of software and scripts, the exchange of inputs and outputs, and compliance with the optimization constraints.

In general, the optimization procedure defined in this work seeks to optimize the parameters that characterize the behavior of the hydrofoil and that maximize its efficiency. It was specifically decided to target efficiency since we are interested in minimizing drag for a given lift.

The parameters used and their ranges are deduced by a sensitivity analysis performed with the DOE generation of modeFRONTIER. This allowed us to understand the hydrodynamic and structural effects of each parameter, as well as understand which parameters are important for the optimization and which ranges are meaningful.

Since the lift of a given wing is unknown a priori, the procedure is to run an initial CLL simulation, and subsequently scale the wing up or down as needed. In this way, the target lift is achieved which, if efficiency is optimized, will also achieve minimal drag.

The optimization loop, as mentioned previously, is a multi-leveled optimization. An outer optimization loop attempts to optimize a subset of parameters, specifically the parameters describing the planform of the wing, while an inner loop optimizes the 3D parameters. The architecture allows for very efficient optimization of the planform since the optimization of the 3D parameters, whose effect varies largely depending on the planform parameters, is left to a sub-loop.

As for the optimization algorithm, the MOGA-II and PilOpt algorithms were explored, as well as a combination of the two on two different levels. The MOGA-II, known for its simplicity and robustness, is able to explore the design space more broadly than other algorithms, offering a good efficient exploration.

PilOpt is a multi-strategy hybrid algorithm, which is a much more direct algorithm that offers better exploration of the design space, converging in fewer iterations than other algorithms with similar properties.

Because of the overall negligible computational costs of a single loop, the MOGA-II algorithm was chosen for improved robustness and better exploration of the design space, which in turn allowed for a better understanding of the impact of the geometrical parameters.

3. RESULTS

The optimization procedure developed is fast and allows for very quick prototype development, and hydrofoil optimization for different operating conditions.

To explore the design space better, only the objective (maximizing efficiency) was taken into account at first without any design restrictions imposed, and the constraints were later added to the optimization.

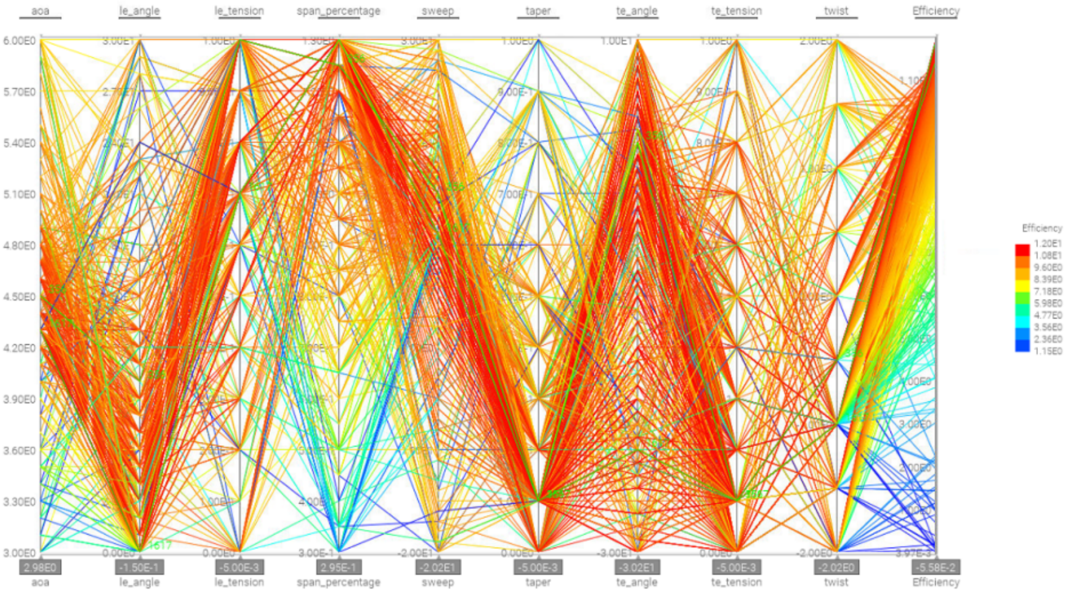

Figure 6: parallel coordinates plot for design exploration

After the first optimization, the parametrization was slightly changed, by removing parameters whose optimal value was found, coupling multiple parameters into a compound one, and introducing new parameters altogether.

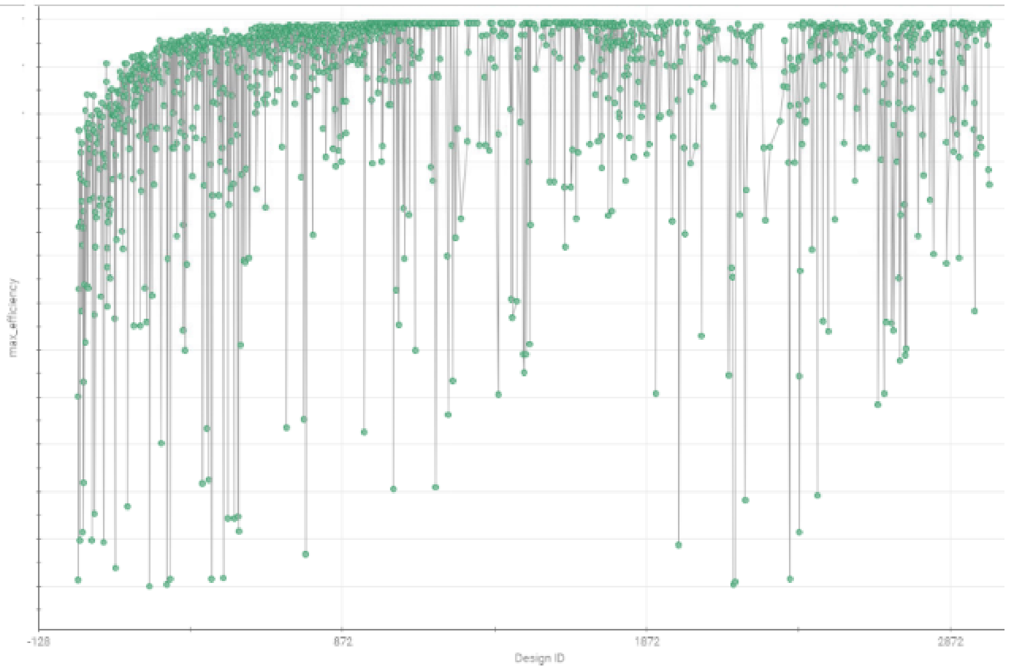

Figure 7: efficiency convergence of the designs

In general, a good convergence of the optimization was always found, with a clearly defined design boundary. Figure 7 shows an example of the history of the efficiency obtained during one of the runs. In this case

The optimizations run with the constraints mostly converged to low aspect ratio wings since they greatly reduce the stress at the root as opposed to more elongated designs. However, the aspect ratio achievable found is higher than expected by what was conjectured by Farnesi (2021).

Some notable results of the later optimizations for our specific targets include the impact of the curvature at the trailing edge. Both the trailing edge and the leading edge are described using a tangent angle at the root and the tension at the root for the parametrizing spline. In general, we found that high tensions and low tangents at the root for the leading edge are optimal, the shape of the trailing edge doesn't have a direct impact on efficiency, but only indirectly impacts it for chord distribution. As such, a general family of optimal wings has a curved LE for its good hydrodynamic properties, while the chord distribution is mostly controlled by an almost flat trailing edge.

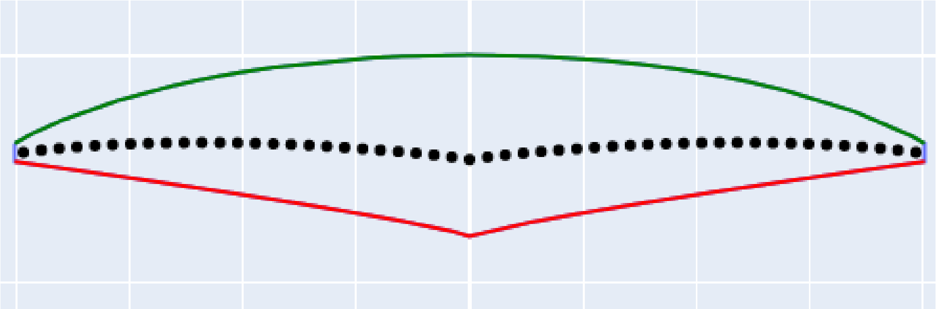

Figure 8: example of one possible wing design family

Other notable results are regarding the taper ratio and twist angle relationship. In particular, since most of the drag comes in the form of viscous drag, having a pseudo-elliptical lift distribution doesn't impact much the efficiency. For this reason, the optimizer found that relatively higher aspect ratios with negative twist angles worked better to reduce the loading of the wing at the tip but still feature an elongated wing.

4. CONCLUSIONS

The great accuracy to computational costs ratio of the optimization setup described makes it a good general global optimization procedure, able to quickly and efficiently converge to the global optimum. Although different results were obtained in each optimization cycle, on average it can be said that the optimization achieved an improvement of around 40% compared to the lowest efficiency points that are part of the Pareto front.

With the optimization cycle that uses the MOGA-II algorithm, we were able to explore features that allowed us to efficiently optimize the planform and 3D parameters of a wing, which additionally allowed a fast convergence.

The CLL proved to be reliable enough to be used for all the hydrodynamic evaluations during the optimization procedure. On top of this, the extensive validation, both on the preliminary designs and on the optimized designs, proves that the CLL can also be used for conceptualization and to simulate the hydrodynamic behavior for dynamics simulations of sailboats accounting for cavitation.

Because of the assumptions made for the CLL, and for the lifting line in general, the CLL works adequately for subcavitating and supercavitating wings, but has subpar performances in partial cavitation, due to the intrinsically unsteady nature of the partial cavitation regime.

The main disadvantage of the current optimization loop is that even though it can converge very quickly to the global optimum, the low fidelity of the models used makes it hard to converge precisely to a definitive optimal wing design. To further improve the accuracy of the optimum that is found, a local search with FVM can help converge to an optimal design in a fraction of the time it would have taken to carry out the whole optimization with FVM.

If it is considered that during a MOGA-II optimization an average of 20 designs per generation are considered, and about 150 generations are evaluated, it can be said that an optimization loop needs approximately 3000 hydrodynamic performance evaluations. With optimal numerical settings for a 2D FVM simulation, the computation time required is about 3% of the time of a similarly optimized 3D FVM simulation. If a 2D simulation costs approximately 2h, a 3D simulation will cost approximately 65h, considering an equivalent number of processors.

With this in mind, it can be said that an optimization loop using FVM will cost approximately 65*3000 computing hours. In the same way, it can be said that an optimization loop that uses the CLL, and for which 20 2D simulations need to be carried out once, will cost 2*20 hours of calculation, plus something like 250h if time is considered. of evaluation of the CLL on the total of the evaluations. It can be concluded that performing the optimization cycle using the CLL costs only 0.15% of the time that would have been required if the FVM method had been used. Again, it is worth mentioning that time savings were allowed by the fact that around 15 optimization cycles were performed.

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