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Elisa Berrini, Bernard Mourrain, Regis Duvigneau, Matthieu Sacher, Yann Roux

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GEOMETRIC MODEL FOR AUTOMATED MULTI-OBJECTIVE OPTIMIZATION OF FOILS

ELISA BERRINI[a,b], BERNARD MOURRAIN[a], REGIS DUVIGNEAU[a], MATTHIEU SACHER[c] AND YANN ROUX[b,d]

[a]Université Côte dAzur, INRIA Sophia Antipolis Méditerranée
2004, route des Lucioles - 06902 Sophia Antipolis, France
e-mail: elisa.berrini@inria.fr, bernard.mourrain@inria.fr, regis.duvigneau@inria.fr

[b] MyCFD - 29 avenue des frères Roustan, 06220 Golfe-Juan, France
e-mail: yann@mycfd.com, elisa@mycfd.com

[c] Naval Academy Research Institute - IRENAV CC600, 29240 BREST Cedex 9, France
e-mail: matthieu.sacher@ecole-navale.fr

[d] K-Epsilon - 1300 route des Crêtes, 06560 Valbonne, France
e-mail: yann@k-epsilon.com

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Abstract. This paper describes a new generic parametric modeller integrated into an automated optimization loop for shape optimization. The modeller enables the generation of shapes by selecting a set of design parameters that controls a twofold parameterization: *geometrical* - based on a skeleton approach - and *architectural* - based on the experience of practitioners - to impact the system performance. The resulting forms are relevant and effective, thanks to a smoothing procedure that ensures the consistency of the shapes produced.

As an application, we propose to perform a multi-objective shape optimization of a AC45 foil. The modeller is linked to the fluid solver AVANTI, coupled with Xfoil, and to the optimization toolbox FAMOSA.

1 INTRODUCTION

Automatic shape optimization is a growing study field, with applications in various industrial sectors. As the performances of a flow-exposed object can be obtained accurately with CFD (Computational Fluid Dynamics), small changes in design can be captured and analysed. To exploit these performance analysis capabilities, it is important to have a precise and efficient control of the geometry of the objects.

To improve the form of a design in order to increase its performances, a precise shape consistency control is essential when performing deformations. Naval architects need to use shape quality preserving tools to modify hulls or appendages while avoiding non-realistic forms.

The coupling of a flow solver, an optimization algorithm and a quality preserving shape modeller is the basis for an efficient automatic shape optimization loop.

We propose a parametric modeller tool with a new approach for shape deformation, integrated into an automatic shape optimization loop with a flow solver, AVANTI, and an optimization toolbox FAMOSA. The methodology presented here has the ability to generate valid forms from an architectural point of view thanks to an innovative shape consistency control based on architectural parameters. Controlling shapes by architectural parameters allows reducing the number of degrees of freedom of the shape optimization problem. They also introduce a physical and a design meaning into the optimization process.

The approach proposed allows using directly a CAD model based on a NURBS [1] representations in the modeller tool. The methodology developed can be applied to any shape that can be described by a skeleton, e.g. hulls, foils, bulbous bows, but also wind turbines, airships, etc.

This paper presents the general methodology of parametric modeller and an example of application to the shape multi-objective optimization of a AC45 foil, with general form parameters (main lengths, angles, etc.) and local form parameters (foil chord lengths, twist, etc).

2 RELATED WORK

The coupling of a flow solver to a modeller and an optimization algorithm methodology is widely used [2, 3, 4, 5].

Recent technological progress allows running quasi-automatically the CFD solver and post-processing the relevant results of the computation. Optimization algorithms demonstrate their efficiency in solving problems with a large number of degrees of freedom and where the objective function values are difficult and costly to evaluate. However, less efforts have been dedicated to the development of efficient parametric modellers.

Shape deformation for ships or appendages is a relatively recent approach. Classical deformation techniques such as Free Form Deformation (FFD) and morphing, created for 3D animations purposes, have been applied to ship shape optimization [6, 7] (FFD) and [8] (morphing).

Morphing is limited to known bounds of shape variations, the exploration of possible optimal shapes is reduced to a given number of shapes.

FFD can be very efficient if used with a small number of degrees of freedom to control the whole shape of the object. However, local perturbations can be performed only with refinement of the areas of interest, therefore increasing the number of degrees of freedom. FFD does not take into account any architectural parameters when deforming an object, leading possibly to non-realistic results.

Engineering dedicated CAD software provides parametric design features, allowing the user to build parametrized models such as *Catia*^{TM}, *Grasshopper* for Rhinoceros 3D$^{\mathrm{TM}}$ or *CAESES* from Friendship System$^{\mathrm{TM}}$. This method allows generating shapes easily, but all of the parameters are lost when saving the model in a standard format such as IGES or STEP. This represents a limitation for automatic linking with solvers (CFD, structural analysis, etc.) or optimization algorithms.

Specific software have been developed during the last decades for ship applications. One of the most widespread is CAESES^{TM} form Friendship Systems^{TM}, allowing the user to modify imported geometries using advanced geometrical parameters [9]. Similarly, a ship dedicated tool Bataos [10] allows to modify the shape of sections of the hull described B-Spline curves with predefined functions.

These tools are based on geometrical control of shapes. Architectural parameters are computed on the deformed geometry and can be included as constraints, but they do not directly control the shape modification.

3 PARAMETRIC MODELLER

To obtain smoothly deformed shapes, we propose a novel modeller tool based on a generic methodology to modify shapes with architectural constraints. To achieve this objective, we use a twofold parametrization of the shape that allows describing a broad class of objects in the same way. We base our method on a generic skeleton concept to describe the geometry, completed by specific architectural parameters according to the studied shape.

3.1 Shape parameterization

3.1.1 Geometrical parameterization

We consider the skeleton as a set of curves composed of a *generating curve* and *section curves*.

The purpose of the generating curve is to describe the general shape of the object. For airfoil based shapes, the trailing edge is an ideal choice, as is the keeline for a hull.

The sections are similar to the classic architects line plan, describing more precisely the outlines of the object around the generating curve. Each section curve is identified on the generating curve by a local coordinate system, an origin and a rotation, allowing to know its position and orientation. Section curves are computed as the intersection between the studied object and a family of cutting planes. The cutting planes are defined to be normal to the tangent vector of the generating curve at the corresponding point adjusted with the rotation associated to the section.

The generating curve and the section curves are represented as B-Splines curves with a given number of control points [1]. To create those curves we use a fitting process, inspired by [11] using a small number of control points (e.g. ≤ 10). A good level of approximation of the original model is ensured, the average normalized relative distance between the intersection curves and the B-Spline section curves is kept under 10^{-5}.

Fig. 1 illustrate the skeleton of the AC45 foil. We illustrate also the skeleton obtained for the hull of a sail boat.

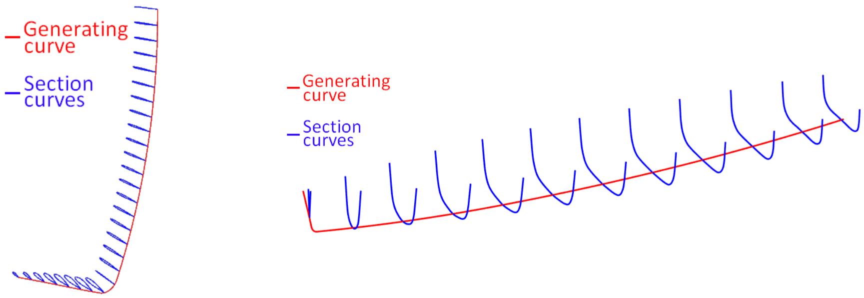

Figure 1: Skeletons of the AC45 foil and the hull of a sail boat

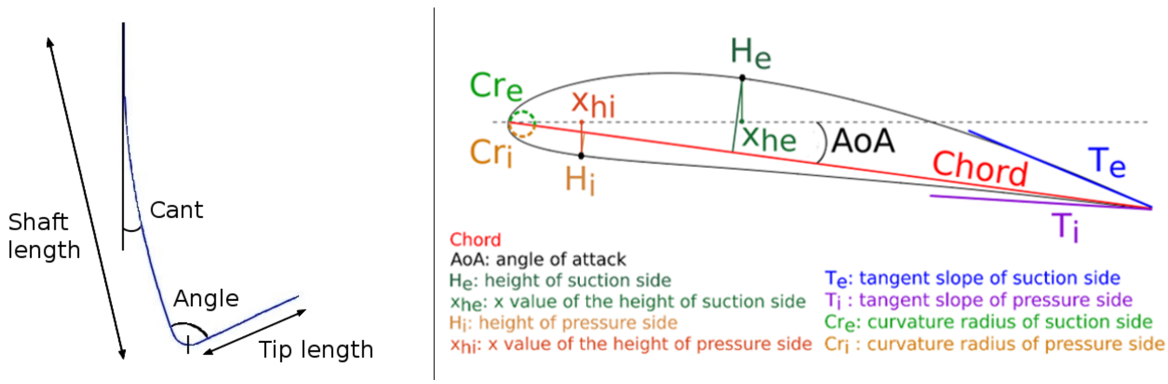

Figure 2: Generating curve and section curve parameters

3.1.2 Architectural parameterization

We define a set of architectural parameters on the studied object according to the design practice and effects on the object performance. The strategy of our modeller is to control the whole shape through these parameters.

Both the generating curve and the section curves have an independent set of parameters. Parameters of the foil are illustrated in Fig 2.

We introduce an *observer function* ϕ that computes the set of parameters P on a given geometry G: $\phi : G \longrightarrow P$. For the generating curve the parameters are real and finite values whereas sections describe parameters as a function along the generating curve, thus defining ϕ in an infinite dimensional space.

In practice ϕ is represented with B-Spline curves B_ϕ passing through the section parameter values according to their position on the generating curve.

The control points of B_ϕ will be used to control the value of the sections parameters. The number of control points of B_ϕ is chosen to be way smaller than the total number of sections of the skeleton. This allows drastically reducing the number of parameters that control the shape of the object and that are used in an optimization loop. In addition, the modification of a B-Spline curve can ensure a smooth distribution of the parameters, preserving the fairness of the object.

3.2 Shape deformation

Our goal is to compute smooth shapes corresponding to a given set of architectural parameters. Therefore, deforming an object corresponds to finding a new geometry G that matches a given set of architectural parameters P. Referring to the definition of the observer function ϕ, we need to compute an inverse problem: $\phi^* : P \longrightarrow G$.

The shape G is described with a skeleton made of B-Spline curves. The idea is to compute new values of the coordinates of B-Spline curves control points until the new skeleton parameters reach the target ones. The new coordinates of the B-Spline control points are the solution of a non-linear constrained minimization problem, built with four terms, as described below.

1. E_{param} measures the distance between the current parameters values and the target ones.
2. E_{shape} is introduced to ensure consistency control by measuring the distance between the current geometry and the original one.
3. The third term allows taking into account specific constraints F for the studied object, usually position or tangency constraints. These constraints are defined for each section and are not necessarily the same for all sections.

   For example, an airfoil has a smooth connection between the suction and pressure faces thanks to a tangency constraint: the tangent at the leading edge of both sides has to be orthogonal to the chord vector.
4. The last term H controls the overall smoothness of the shape by introducing stiffness between successive control points of the section or generating curves. We add correction terms to control respectively C^1 and C^2 properties of control points.

The proposed minimization system is :

$$\min_{\mathbf{c}_i} E_{param} + \varepsilon E_{shape} + \sum_k \lambda_k F_k^2(\mathbf{c}_i) + \sum_l \mu_l \, H_l(\mathbf{c}_i) \tag{1}$$

where $\mathbf{c}_i$ represents the control points of the generating curve or a given section of the skeleton. The system (1) is solved for the generating curve and for each section curve independently.

The definition of the problem (1) is well adapted to Sequential Quadratic Programming (SQP). We start with an initial value of ε, usually 1, and the original curve as the starting point of the algorithm, then we decrease ε at each iteration and start the SQP again with the last computed curve. The algorithm stops when the value of the objective function reaches a fixed threshold. λ_k and μ_l are chosen small, usually 10^{-4}.

4 AC45 FOIL MULTI-OBJECTIVE SHAPE OPTIMIZATION

In the recent years, new high-speed boats were developed using foils. The purpose of a foil is to lift the hull of the boat above water surface. The hull resistance (friction and wave making

Figure 3: Illustration of the AC45 on the Groupama Team France sail boat, *Credit:* ® *Eloi Stichelbaut / Groupama Team France*

drag) is decreasing, allowing to reach very high speeds.

For sailing yachts, the foils are built as an "L" shape with a vertical part countering the sails forces, and a horizontal part supporting the yacht weight. While sailing, the foil allows the yacht to fly as shown in Fig. 3. However, to maintain this flying state, the stability of the foil is a critical aspect for both safety and performance. Designers have to manage numerous parameters in order to produce a foil with a low drag, but high stability.

We consider here the AC45 foil. This type of foil is "one-design" meaning that its shape is the same for all AC45 boats. For this application, we aim to optimize the shape of the AC45 foil in order to decrease its total drag while keeping stability as high as possible. The foil performances are computed with the potential flow solver AVANTI coupled with XFoil.

The AC45 foil is currently used by the Groupama Team France sailing team for the 35^{th} America's Cup. In such a context, the performance of the foil is essential. An illustration of the sail boat flying thanks to the foil is shown in Fig. 3, one foil in the water (right) and the other one visible in the retracted position (left).

4.1 Numerical methods

4.1.1 AVANTI

AVANTI, the flow code used in the present study, is developed and commercialized by the company K-Epsilon. AVANTI features multiple different methods for flow solving (e.g. vortex line method, particle method, panel method, etc.) [12, 13].

The method used here is a vortex line method with solved wake. AVANTI is coupled to XFoil in order to incorporate the flow behaviour such as laminar transition, and stall.

The foil is represented with a finite number of elements, i.e. airfoil sections given by the skeleton. For each element a local velocity, a local Reynolds number and a local angle of attack is computed. Each element has an associated XFoil database containing the lift and drag of the section for a given range of angles of attack.

AVANTI uses this database to find the lift of each element of the foil according to its current

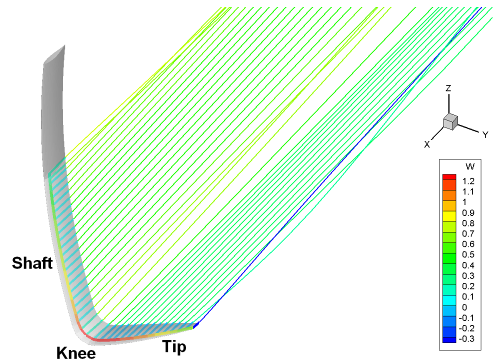

Figure 4: Illustration of the wake and vortex line on the AC45

local angle of attack. Then the lift is converted to a local vorticity. The wake is imposed with the computed gradient of vorticity then solved. These steps are repeated until convergence thanks to a direct iterative method, which is able to find a stationary solution.

As inputs, AVANTI requires a 2D point cloud description of the sections with its the 3D position given with points and quaternions. These files are generated automatically by the parametric modeller.

In our specific case for AC45 foil study, only the underwater part of the foil is simulated. The influence of the free surface is taken into account with an anti-symmetry plane model. This model is a satisfying approximation for high speed. As [14] suggests, with a Froude number greater than 1, an infinite Froude number free-surface condition can be used. In our case, the Froude number is around 5.45.

We illustrate in Fig. 4 the wake computed with AVANTI and the vortex lines. The vortex line is located at 25% of the aft of the leading edge along the foil. From the vorticity repartition colormap, we see that the parts of the AC45 which generate most of the force allowing to lift up the boat are the knee and the tip.

The reference frame is defined as follows: X is in the opposite direction of the flow, Z is in the vertical direction (oriented upwards) and Y is horizontal, perpendicular to X.

4.1.2 FAMOSA

The robustness of the optimization algorithm is critical to solve realistic problems. Therefore, derivative-free methods have been preferred to more efficient but fragile gradient-based approaches.

Evolution strategies mimic the natural evolution laws to simulate a population of individuals that progressively converges to the optimum. In this paradigm, each individual is characterized by a set of parameters and its ability to survive is proportional to its performance. These methods, although expensive, are noticeable since they are able to avoid local minima thanks to random operators.

FAMOSA toolbox features the PAES algorithm [15], which is a particular evolution strategy, which has been adapted to the context of multi-criterion optimization. In that case, the ability of an individual to survive is not related directly to the criteria values, but to the concept of dominance, introduced by the economist Pareto. In short, an individual is dominating another one if it has a better performance according to all criteria. This algorithm generates an archive of non-dominated individuals, which is used to determine the ability of a new individual to survive and have offsprings.

4.2 Performance criteria

We choose to define the foil performances with two criteria computed with ARAVANTI.

1. The total drag F_x of the foil in the reference frame. A low drag increases the total performance and speed of the boat.
2. A stability criterion, represented by $\frac{\partial F_z}{\partial z}$, where F_z is the total force in the z direction of the foil. The aim of this criterion is to ensure that the boat will stay at a fixed z height thanks to a self adjusting F_z balancing the vertical movements of the foil.

Computations are performed with a fixed F_y given as the opposite force to balance the force applied by the sails on the hull. F_z is also fixed to counter the weight of the hull and be able to lift it up. The speed of the yacht is set to 22 knots. ARAVANTI solves for the leeway and rake angles of the foil, until computed forces converge to the imposed forces.

F_x is computed during the simulation, and we aim to decrease it as much as possible. In the reference frame we used, F_x is oriented along the negative x direction. Thus, the sign of F_x will be negative, but we can consider the absolute value to compare the foil performance.

To compute the second criterion, we estimate $\frac{\partial F_z}{\partial z}$ with finite differences. We vary the foil displacement by a small Δz and compare it to the the computed F_z. To be stable, the foil has to generate a F_z opposed to the direction of the displacement. Thus the ratio $\frac{\partial F_z}{\partial z}$ has to be negative and as large as possible. For example, if the boat is riding too high above the water surface, the foil force F_z has to decrease in order to make the whole system lower.

The aim of our study is to reduce the total drag of the AC45 as much as possible while keeping stability criterion as large as possible.

4.3 Shape parameters

Deformation of the foil shape is decomposed into general form parameters (generating curve parameters) and local form parameters (section curve parameters), as illustrated in Fig. 2. We have identified the most relevant parameters that influence a foil performances as: the tip length, the angle between the shaft and the tip, the cant angle, the local chord and twist of sections. Five parameters are used to control the chord along the foil, and five others to control the twist.

These parameters are obtained with the *observer function* representation B_ϕ described in the section 3.1.2.

To generate a new CAD from the original CAD model, our tool takes on average 12 seconds to build the skeleton, 5.1 second for the generating curve deformation and 5 seconds for the section curves deformation. There is no need to build a new surface around the skeleton, as AVANTI does not require a continuous surface as an input. On average, AVANTI takes 20 seconds to perform the computation of the two criteria and post-process the result.

The PAES algorithm does not require limits to parameters variations. A starting point and an initial step length is defined to explore the domain. Then, the search direction is oriented towards the best results found, until the algorithm converges to the Pareto front.

4.4 Results

We illustrate in Fig. 5 the Pareto front obtained. The performances of the AC45 are identified with the orange triangle. The blue points represent an initial distribution of shape parameters along a domain around the initial shape of the AC45. The distribution follows a Latin Hyper cube model. The green points represent the path of the PAES algorithm to converge towards the Pareto front. Finally, the red points are located on the Pareto front.

On the Pareto front we identified 4 foils labelled F1, F2, F3, F4 illustrated in the Fig. 6 to 9.

The resulting shapes demonstrate the capability of the modeller tool to generate geometrically valid forms. The shapes of the foils on the Pareto front tends towards much thinner forms than the original AC45 foil to limit drag. The tip length is longer, in order to counterbalance the loss of lift induced by smaller airfoils. Larger cant angles observed in all four foils improves the stability criterion without impacting the drag. We can notice that the upper part of the foil, above the water surface, is not modified by the shape optimization. Indeed, this part of the foil does not impact significantly the performance criteria.

The structural properties of the four foils can be discussed: such thin shapes can lead to structural deficiencies. Moreover, we did not introduce a criterion to avoid cavitation phenomenon.

This study highlight the importance of multi-physics optimization. Taking into account structural properties of the shapes will lead to more feasible shapes. The current results are relevant according to the geometric and hydrodynamic criteria chosen.

5 CONCLUSION

This paper presents a method for smooth shape deformation with a generic skeleton-based approach. The twofold parametrization, geometrical and architectural, demonstrates its capability to generate simulation-suited models. Our parametric modeller allows to explore the domain of possible shapes in an efficient way and to determine improvements of the design that are architecturally relevant.

As shown by the experiments, we are able to improve the hydrodynamic performances of a AC45 foil in an efficient and automatic way.

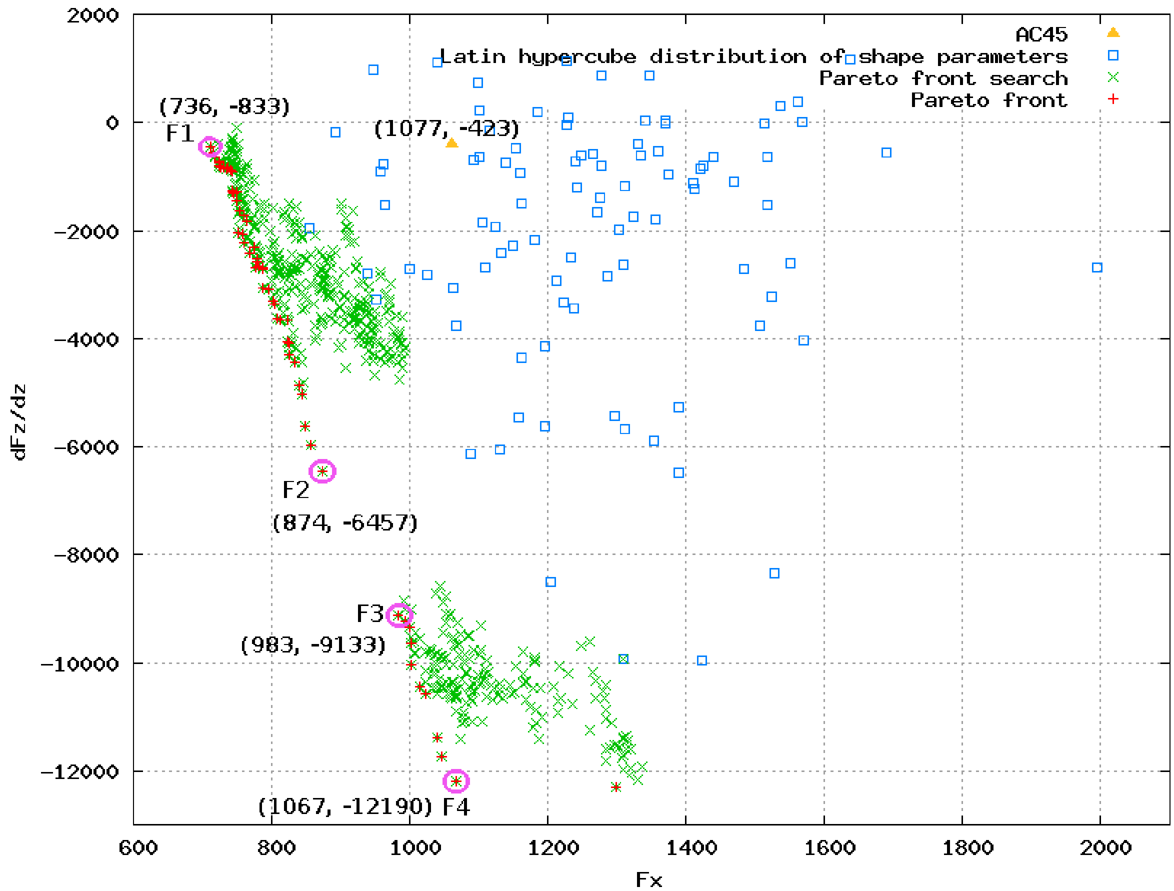

Figure 5: Pareto front of the AC45 foil shape optimization.

We also implemented a technique to reconstruct with accuracy a 3D surface around the deformed skeleton that we did not describe here. With this feature, the parametric modeller can also be linked with different types of flow or structural solvers.

Further work will focus on including multi-physics criteria in the optimization loop. We will also focus on handling more complex geometries with the skeleton representation. Section curves with multiple components and branching curves will be possible.

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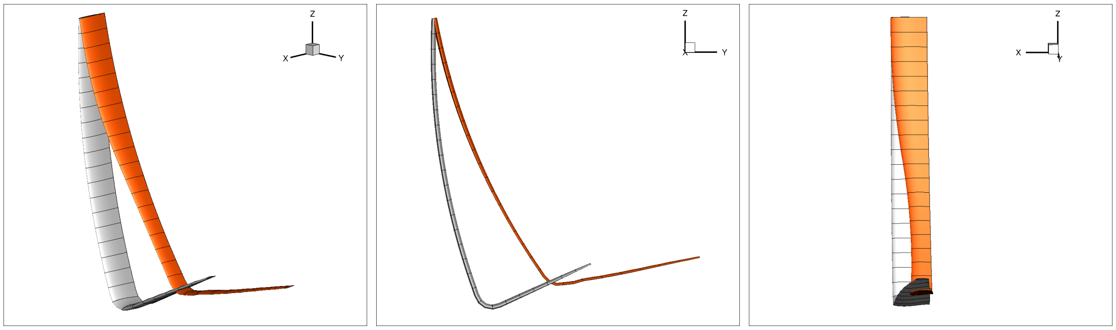

Figure 6: Views of the foil labelled *F1*

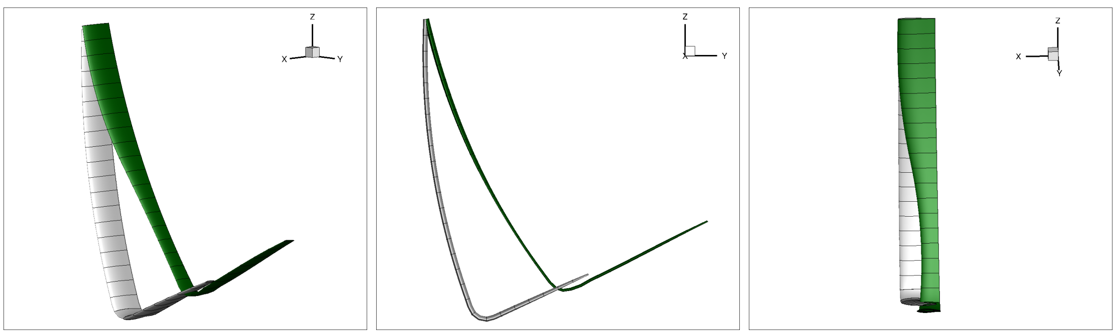

Figure 7: Views of the foil labelled *F2*

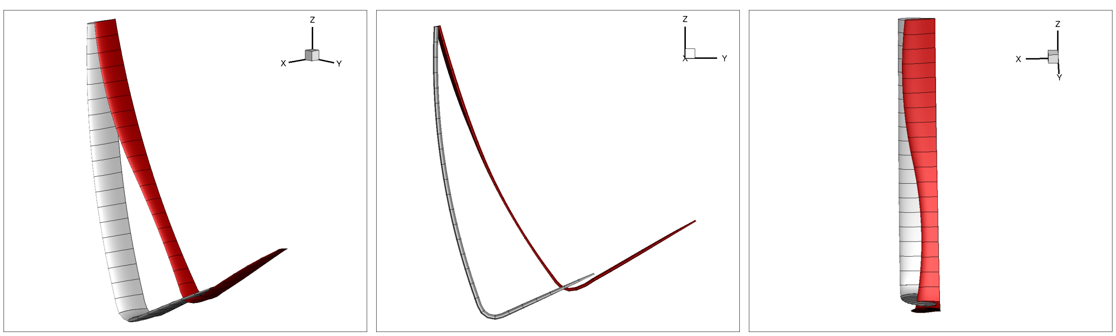

Figure 8: Views of the foil labelled *F3*

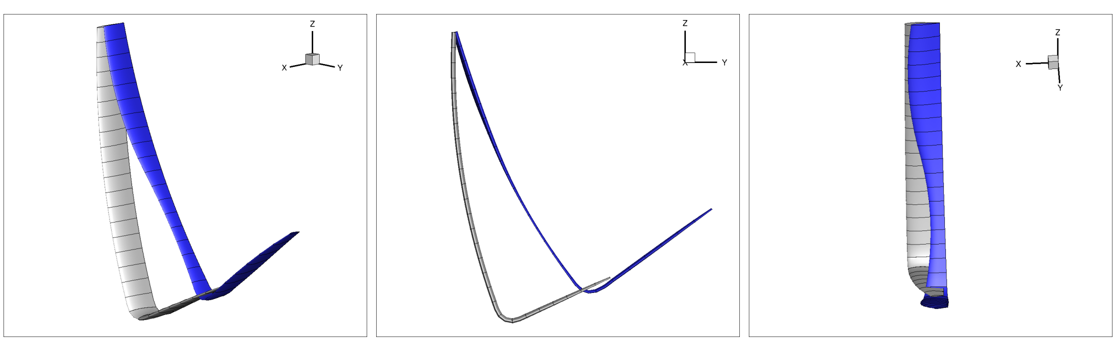

Figure 9: Views of the foil labelled *F4*