Optimization for sail design

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Abstract

The aim of the paper was to research the use of optimization to increase the performance of sails. The modeFRONTIER tool from Esteco was used to streamline the overall process, and to have access to a wide range of high-performance algorithms. The paper presents the process followed by Cape Horn Engineering (CHE) to test and then refine their methodologies. Considerations are then given about using these methods into sail design for the Volvo Ocean Race and America's Cup.

1 Introduction

Sailing yacht design has reached such a level of refinement that a formal optimization process is expected to provide the necessary advantage to reach a new performance level. Sails are the engine of a yacht, and as such are one of the major design research area. The flow characteristics (large separation, viscous effects) around the sails and their structural behavior (large deformation) makes this a very challenging area. Fitting the optimization in an already tight design schedule of the most-involved sailing yachts is also a challenge. The paper will first look a 2 dimensional cases, this forms the basic understanding. it will then go on applying the same ideas on 3D geometries. This while keeping the link. A multi-objective optimization was performed on several VO70 sails; both in reaching and upwind conditions, and presented in section 6.2.

2 Nomenclature

2D	Two Dimensions
3D	Three Dimensions
CAD	Computer Assisted Design
CFD	Computational fluid dynamic
CHE	Cape Horn Engineering
CPU	Central Processing Unit
DoE	Designs of Experiments
FSI	Fluid Structure Interaction
GA	Genetic Algorithm
NSGA	Non-Sorted Genetic Algorithm
NURBS	Non-Uniform Rational B-Spline
RANSE	Reynolds Averaged Navier-Stokes Equations
RSM	Response Surface Models
STEP	Standard for the Exchange of Product Model Data
y^+	Dimensionless wall distance

3 Flying / Design Shape

Sails are soft structures that deform under load. Optimization of the shapes can take two ways (see figure 1); optimize the design shape (the undeformed shape), this needs a FSI capability to deform and compute the deformation and flow around the sails. The second way is to optimize the flying shape, this removes the need of FSI computations, but may result in a shape that is unfeasible.

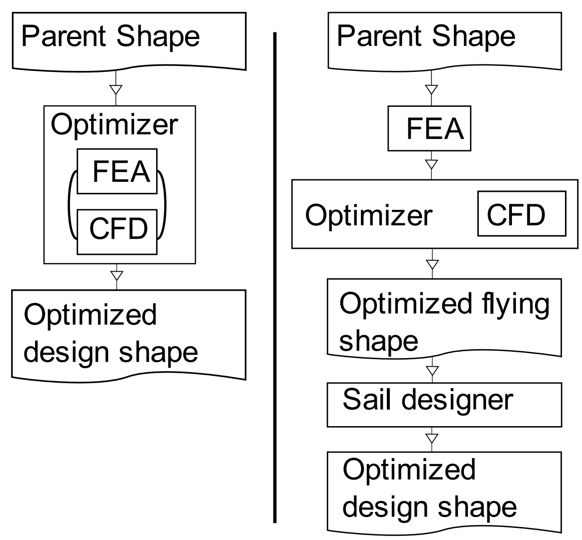

Figure 1: Flying/Design shape optimization

The major difference is in the computational cost of the simulations; the option on the left requires a FSI coupling to be done for every design. This increases computation time by a factor of 5. Sails are quite unstable, so putting the structural part of the computation outside of the optimization makes the loop far more robust. The other difference is in the type of output; the first option will give us the optimized design shape, this can be built directly. The second option requires the sail designer to find the structure and its design shape, that after deformation will give the optimized flying shape.

4 2D optimization

Three dimensional effects are important in sail designs, therefore two dimensional studies are of limited interest. However, being much faster to solve than 3D studies (in the order of 1 to 10), they have been used extensively at the beginning of the project to test, benchmark and compare a range of modeFRONTIER's setup.

4.1 Implementation

4.1.1 Geometry

Simulations are modeling the flow past two sails (*jib* and *mainsail*) and the mast (see figure 2). Each sail is parametrically defined as B-splines with 7 control points (see figure 3). This approximates well typical sail sections, and enables a wide range of deformation. The mast was parameterized in a similar way.
This parameterization is used to replicate the parent model to be tested. To reduce the amount of variables, a morphing approach is then used. This reduces the number of variables to 4 per sail (see figure 3); leading edge entry angle, draft (maximum thickness position), camber (thickness to chord ratio) and twist (local angle of attack). Figure 4 presents a flow chart of the optimization steps.

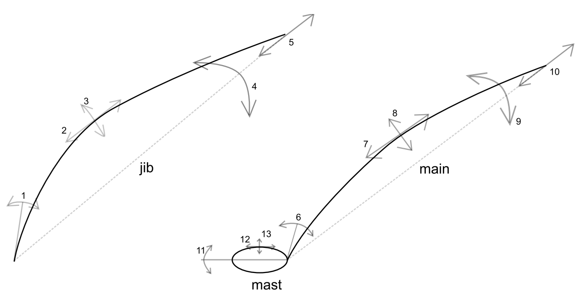

Figure 2: Variables used in the optimization

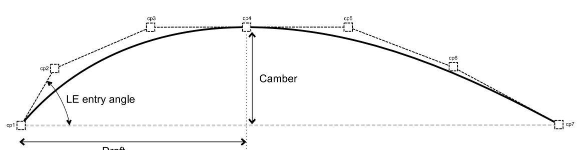

Figure 3: 2D Parametric model

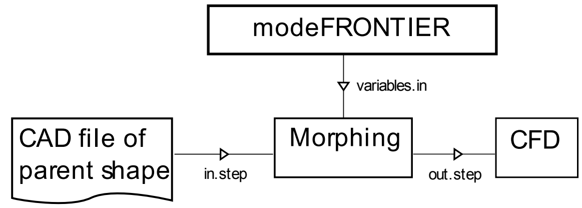

Figure 4: Flow chart of the morphing

4.1.2 CFD model

The 2D computational domain is meshed with approximately 80000 polyhedral cells. The boundary layer is modelled with wall functions. Using wall functions is appropriate when optimizing overall shapes; in the case of mast designs a more accurate definition of the boundary layer is required. The flow is solved using RANSE solver. A complete solution (meshing + solving times + reporting) takes less than 30min (single CPU computations).

4.1.3 Optimization

As explained above, sails shapes are optimized using 8 variables in total. The overall sail forces can be decomposed into lift and drag forces (wind axis) or in driving and side force (boat axis) (see figure 5). Two objective functions are used: first the maximization of driving force, and second the minimization of side force. Optimization is carried out using the NSGA-II algorithm.

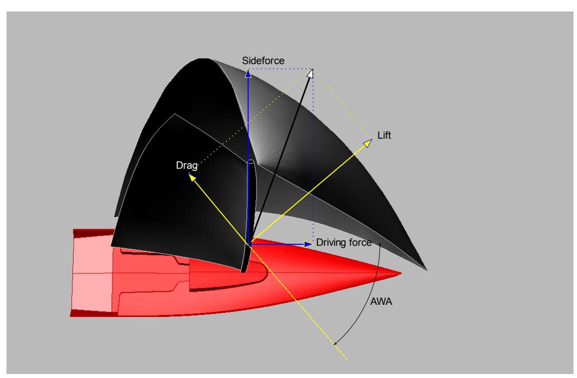

Figure 5: Sail forces

4.2 Results

Pareto fronts for two wind conditions (here, two wind angles) are shown in figure 6, it presents results for one parent shape, better shapes are found towards the bottom-left side (more driving force (-FX), and less sideforce

(FY)). Results are presented for two wind conditions (two angles of attacks), an angle of 13.3 degrees is on-design (black), while an angle of 18.0 degrees is off-design (red). For the off-design point, the optimization is able to produce a new shape that will generate 12% more driving force for the same sideforce. Optimizing the on-design shape is more difficult, and only a increase of driving force of 1.5% is reached.

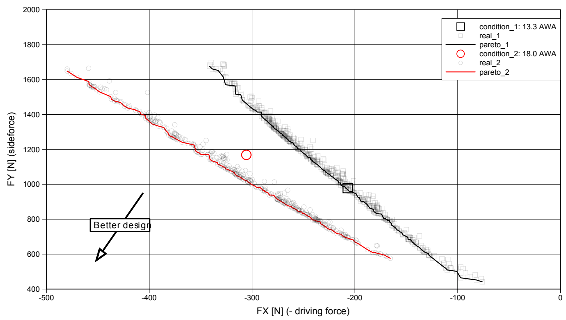

Figure 6: 2D results

section	amount
main draft	-10%
main camber	+55%
main twist	-1.56°
main entry angle	-4.92°
jib draft	-8%
jib camber	+114%
jib twist	+1.80°
jib entry angle	+7.08°

Table 1: Amount of changes to reach optimum for the off-design condition

The morphing deformations applied to the parent shape to generate the optimum shape are shown in table 1; the camber needs to be drastically increased and the camber moved forward for both sails, with an increased twist for the jib, this is typically what would happen in sailing while bearing away from the wind. (the off-design condition is at a wider wind angle than the on-design).

5 3D optimization

5.1 Implementation

An optimization is carried out to find the best flying shape for a predefined sailing condition (boat attitude and wind conditions); the sail is assumed to be rigid so no FSI coupling is needed.

5.1.1 Geometry

The parent geometry is generally a sail that is currently being used (tested) on the boat, or at an advanced stage of conception. The sail-designer provides us with the design shape and its structure. The flying shape (i.e. deformed) is found by running a single FSI coupling.
A morphing methodology is used to generate new shapes, that have similarity to the parent shape.

Compared to a parametric model, the morphing model has one main advantage; it reduces the number of variables needed. (by around 4-5 for a sail model). This affects the speed of the optimization and the quality of the final sail surface. The goal of the morphing is to generate a realistic sailing shape. The range of transformations and capabilities of the morphing model were closely developed with a sail designer. This has lead us to our current model that uses 5 horizontal (spanwise) sections per sail (see figure 7).
One weakness of the morphing could be that it cannot vary far away from the parent shape; this is thought to be adequate since the sail-designer has already reached a good optimum.

5.1.2 CFD model

The CFD model is the full model currently used in all sails aerodynamic studies at CHE. Hull, deck, mast and sails are included. The fluid domain is discretized using around 2.5M polyhedrals cells. Prisms are grown from all wall boundaries to correctly model boundary layers with the help of wall functions.
A commercial RANSE solver is used to solve the flow. Convergence of forces is reached in around 300 iterations (steady state) for shapes with low level of separation (upwind cases). On 4 CPUs partitions this takes around 3hrs. With the current level of modeFRONTIER's license (20 concurrent design); 160 designs per day or 1120 designs can be solved.

5.1.3 Optimization

Variables
Reducing the number of variables has always been at the forefront of the priorities during development, current sail design softwares need around 80 variables. In typical cases, where general dimensions are known (mast length, boom length,...), 20% or those variables can be fixed. However this is still far too many. The approach taken with the morphing enables to reduce drastically the number of variables. First versions were run with 12 variables. The range of shapes seemed adequate, however the optimizer could not find a better shape. After more

studies on other projects and conversations with the sail-designer; it was deemed interesting to incorporate sections at 25 and 75% of the sails to increase the range of shapes. This gives 5 sections per sail, with 3 variables per section this gives 15 variables per sail. Twist variables were limited to 3 per sails since non-smooth distribution are unrealistic. Along with fixing the bottom section of the jib (constrained because of deck design) and the top of the jib (section is flat and small); this reduces the total number of variables to around 20 depending on the particular sail design.

Objective functions

The optimization's goal is to generate a sail shape that will improve the speed of the boat. Figure 5 describes the forces and moments acting on a sailplan, of main interest in the fact that increasing driving force will also increase the sideforce and therefore the heeling moment. A yacht has a limited transversal stability (that counteracts the heeling moment).
In the present project, it is assumed that a higher boat speed will be reached if the sail-set generates more driving force or less heeling moment. This requires two objective functions:

- Maximize driving force.
- Minimize heeling moment.

Constraints

Sensible limits are put on the input variables, therefore constraints on the output values are not required. However optimizing constraints were found useful to refine the Pareto front in areas of interest.

Algorithms

From preliminary studies, the NSGA-II algorithm was found to be very adequate in all optimizations. This was therefore chosen as the basic optimization method.
The Normal-Boundary Intersection Method coupled with NLPQLP (NBI-NLPQLP) was also tested, however it lacks robustness and parallel efficiency (linked to number of variables) for the current application.
Considering computational capabilities and the number of modeFRONTIER's licenses (20 parallel licenses), an initial population of 60 designs was used (generated using a SOBOL distribution). Using 40 or 80 designs did not show gains in efficiency. The number of generations needed to reach the Pareto front varies, but 20 generations has been the maximum so far. The optimization is stopped once a suitable convergence is reached.

Surrogate models

For some optimization cases, the use of surrogate models can greatly reduce the computing time. Kriging and Radial Based Functions (RBF) algorithms were tested. Correlation between the CFD points and the surrogate model for a range of DoEs is shown in figure 8, it shows that to achieve a good correlation, a large number of designs (more than 500) need to be tested. This is due to the amount of variables, which is considered to be higher than optimal for typical application of surrogate models. Surrogate models were therefore not used in these studies.

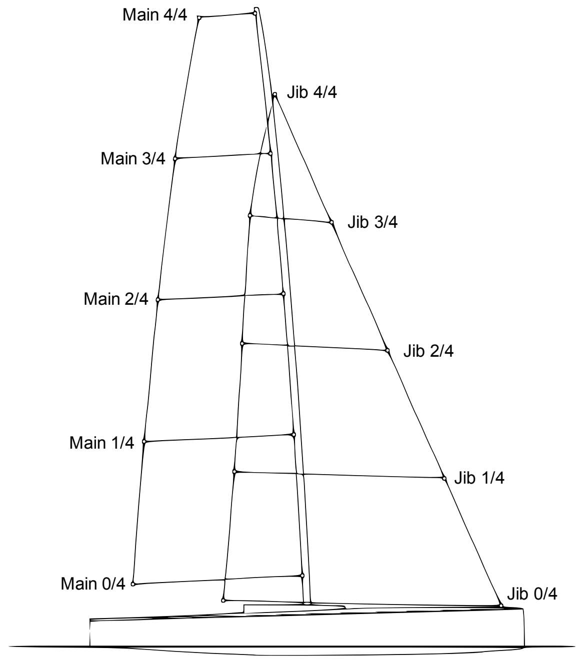

Figure 7: 10 sections model

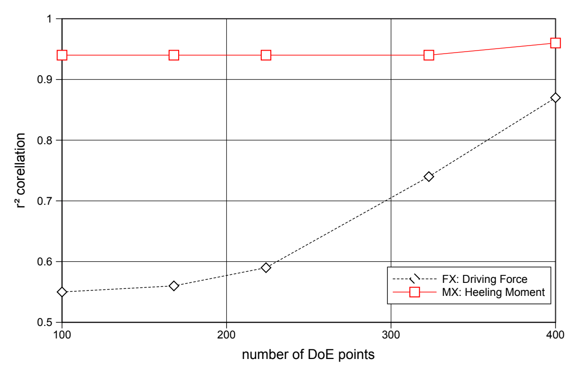

Figure 8: Corelation varying the number of DoEs (RBF algorithm).

5.2 Results

Pareto front results for a jib and mainsail sail set are shown in figure 9, the morphing changes made on the parent shape are presented in table 2. They show that a sensible gain in performance (5% more driving force for the same heeling moment) can be found by using the methodology described above.

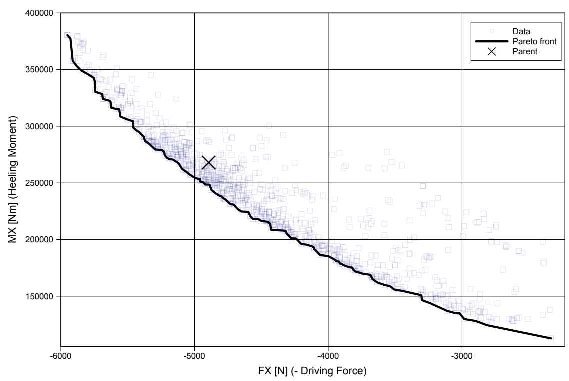

Figure 9: 3D results

section	amount
jib camber14	-2.4%
jib camber24	-4.6%
jib camber34	+0.9%
jib draft14	-10.7%
jib draft24	-13.5%
jib draft34	+4.3%
jib twist24	-1.5°
main camber04	-1.3%
main camber14	+0.4%
main camber24	-2.4%
main camber34	-3.5%
main camber44	-1.3%
main draft04	-35.3%
main draft14	-13.9%
main draft24	-11.1%
main draft34	-9.5%
main draft44	-12.6%
main twist04	-3.7°
main twist24	-4.3°
main twist44	-1.0°

Table 2: Amount of changes to reach optimum

6 The optimization in the design process

A short description of fitting the above optimization methods in the design process is presented here. Applications to two particular projects are then described.

6.1 Implementation

The two major requirements for such a tool to find its place in the design process are accuracy and robustness; they are needed to make sure that a better sail shape is found each type the system is run. Since optimization already regroup a large number of programs and steps, building a robust enough system is not an easy task. The first step was to choose a robust optimization algorithm that also does not requires a large amount of user input. This is why surrogate models were discarded in favor of a full genetic algorithm approach (albeit expected to be slightly slower). The user input and user knowledge is too high to make it robust. The use of modeFRONTIER also makes sure of a robustness from the optimizing part.

The underlying CFD (meshing, solving) methods, along with the geometry generations, need to be throughly tested and validated.

Typical sail development in large projects (Volvo Ocean Race or America's cup) spans over a large period of time (2 years), it usually begins at the commissioning of the design and continues until the middle of the race. So time constraints are not one of the main requirements. For the reader's informations, the current setup is described next. To reach a good optimum, around 1000 designs are needed; using 20 parallel licenses, running 1000 designs requires 50 steps. One CFD point is solved in 3hrs, so in total 150hrs, a bit less than a week. The current setup is therefore able to optimize one sail-set per week; increasing the number of modeFRONTIER's licenses would enable to solve 3 designs per week (or 1 design every 2.3 days).

Another major point is that the optimized shape is an optimized flying shape. It is then the sail-designer's job to produce a design shape and structure that will deform to this flying shape. Optimization could converge to unrealistic shapes, however with correct input variables and using the morphing technique, such problems have been avoided so far.

The way optimization is used is heavily influenced by the type and programs of the boats. Two particular examples, that CHE has been involved in, are presented next.

6.2 Volvo Ocean Race

The Volvo Ocean Race is a round the world race, starting in Spain and finishing in Russia. Weather conditions (wind and waves) are varying from calm to very rough. On these boats (21.5 m long), sails have to cover a large range of wind conditions. The major requirement is generate sail-sets (number is limited by the rule) that cover well the whole conditions. So it is more about testing a large number of concept designs than optimizing a particular predefined designs. Parametric studies have proved to be very interesting since it enables to cover more ground and gain knowledge faster. However once a sail-concept is adopted, sensible gains are only achievable through optimization.

6.3 America's Cup

The America's Cup is the oldest active trophy in international sport, and the most prestigious in the sport of sailing. It is raced by match-race (one against one) between two buoys (upwind + downwind). Weather conditions are regulated; this implies that the variation in wind conditions are small. The sails concepts are limited, the designs are therefore more refined. Optimization is therefore an important tool; and should prove to be successful.

7 Conclusion

An optimization tool for sail design has been described. Its application to real cases has been found to be successfull. Comments about its use in the design process have been given, however the present tool was too late to be used in the through the whole design process for Volvo 2008. The system is in place to be used in the next Volvo Ocean race and America's Cup.
Flying shapes are optimized using a full genetic algorithm approach. This has proved to be a robust and accurate method. A complete optimization requires around 1000 designs to reach an adequate optimum.